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*Research Article*

# Research Progress of Concrete 3D Printing Technology and Its Equipment System, Material, and Molding Defect Control

**Yanhua Zhao [1,2] Wei Meng,[2] Peifu Wang,[3] Dongqing Qian,[4] Wei Cheng,[1] and Zhongqing Jia[1]**

[1]*Laser Institute, Shandong Academy of Sciences, Jinan 250103, China*
[2]*School of Mechanical and Electronic Engineering, Shandong Jianzhu University, Jinan 250101, China*
[3]*Jinan Special Equipment Inspection Institute, Jinan 250100, China*
[4]*Hangzhou Optimax Tech Co., Ltd, Hangzhou 310000, China*

Correspondence should be addressed to Yanhua Zhao; zyh@sdjzu.edu.cn

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The traditional construction technology not only has environmental friendly problems such as noise and dust but also has resource-saving problems such as large template quantity and low construction accuracy. In addition, the traditional construction technology has an insurmountable technical bottleneck in the construction of special-shaped buildings. Building 3D printing technology can effectively overcome many problems existing in traditional construction technology and provide unlimited possibilities for the construction of special-shaped buildings. Concrete 3D printing technology is one of the most important technical categories of building 3D printing. In this study, the research status and progress of concrete 3D technology were reviewed from the aspects of equipment system, materials, defect control, and application scenarios. On this basis, the development foreground was prospected.

## 1. Introduction

*1.1. Building 3D Printing Technology.* Additive manufacturing technology has become an important part of modern product development and manufacturing process. This technology is to manufacture the target component by layer-by-layer superposition of materials, and its forming process is shown inFigure 1. Compared with the traditional manufacturing method of material removal, this new "bottom-up" manufacturing method has many advantages, such as no template, rapid intelligence, and precision molding [2]. With the deepening of the research on additive manufacturing technology, the range of printed materials has been gradually expanded, and the application of additive manufacturing technology has also been expanded from the manufacturing industry to the construction industry.

Building 3D printing technology is the application of additive manufacturing technology in the construction industry. The molding principle of building 3D printing technology is the same as that of additive manufacturing technology of metal or organic materials. The three-dimensional model of the target building is established in the computer, and a series of processing is carried out on the model. The slice file with equal thickness is formed along a certain direction, and then, the slice file is modified and improved to generate the numerical control program. Finally, the mechanical device is controlled by the numerical control system to print layer by layer, and the building is accumulated to form the building [3]. At present, the building 3D printing technology is mainly divided into four categories [1]: (1) layered overlay construction technology of concrete: the technology originates from a construction method proposed by Pegna [4], which is suitable for the layer-by-layer accumulation of cement materials and the realization of various free forms. After continuous exploration by many scholars, the concrete 3D printing technology is finally developed, and the printed object is shown in Figure 2(a). (2) Bond overlay construction technology of

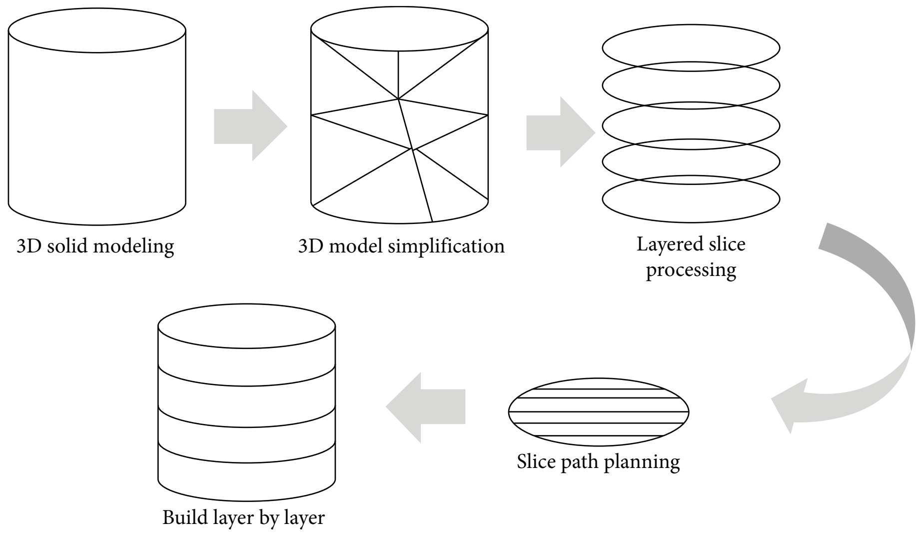



Figure 1: Forming process of additive manufacturing technology [1].

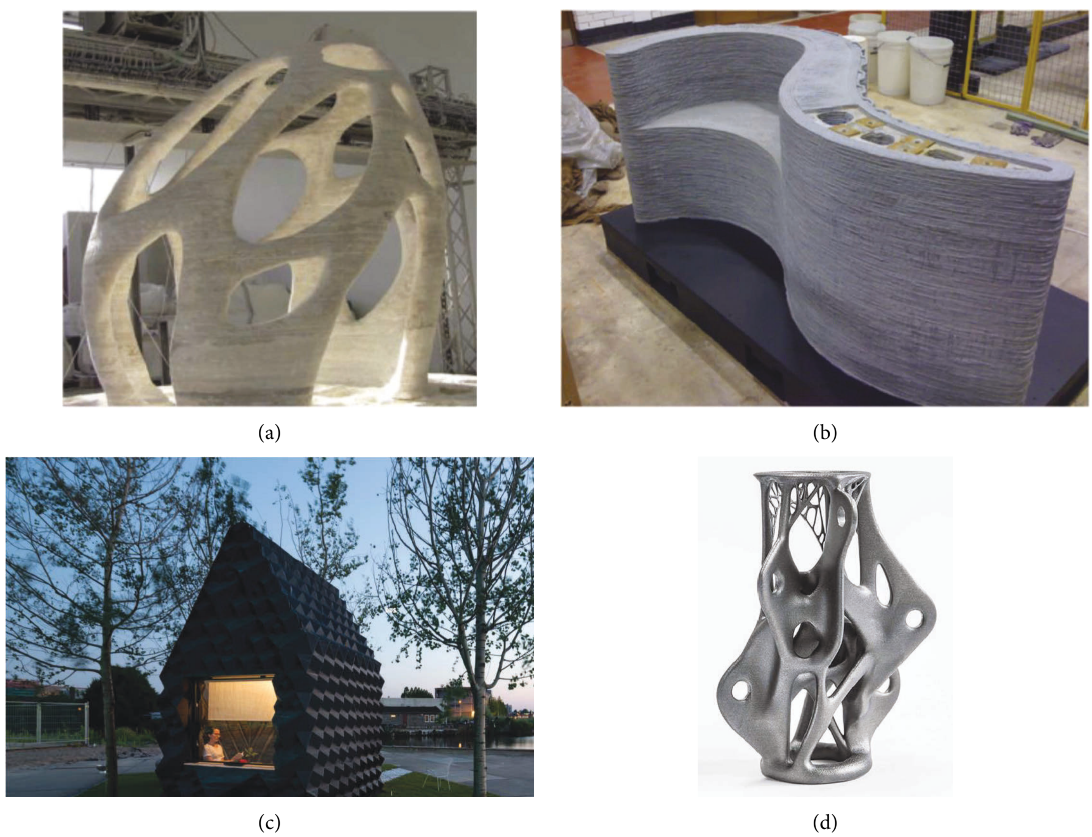



Figure 2: Printed work display of building 3D printing technology ((a) concrete printed back chair, (b) sculpture superimposed by gravel, (c) DUS Company printed riverside office by plastic fiber, and (d) ARUP Company printed steel structure) [5, 6].

sand and gravel: the typical representative of this technology is the D-shaped technology proposed by an engineer of Monolite company. The sand and gravel are bonded layer by layer through the binder extruded from the nozzle, and finally, the printing of the target component is realized, and the printing object is shown in Figure 2(b). (3) Molten overlay construction technology of metal, the Dutch MX3D Company, and the British ARUP Company use this technology to realize the rapid manufacturing of building truss and steel structure, which has the advantages of high printing accuracy and small molding quality, and the printed object is shown in Figure 2(c). (4) Melt bonding construction technology of plastics or other materials: the technology is represented by the super-large FDM printing technology of DUS Corporation in the Netherlands [5]. Because organic materials such as plastic fibers have the advantages of melting and molding, the technology is widely used in rapid prototyping and complex structure manufacturing and other fields, and the printed object is shown in Figure 2(d).

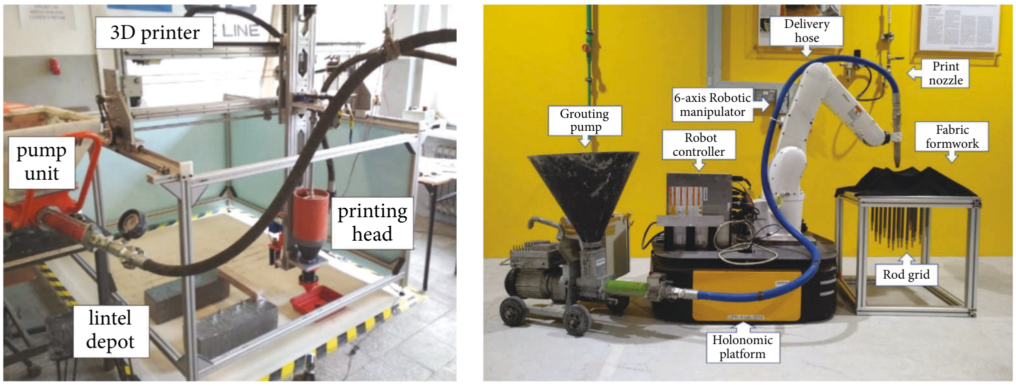
*1.2. Concrete 3D Printing Technology.* Although there are many kinds of building 3D printing technologies, only the concrete 3D printing technology can adapt to the traditional concrete construction habits and is easy to achieve large-scale printing. The more simple and rapid support method in the printing process makes the concrete 3D printing technology a widely used building 3D printing technology. Many research institutions and enterprises have carried out research on it, mainly focusing on the research of concrete materials, the development of printing equipment and system, the quality, and path optimization of printing molding [7]. The concrete 3D printing technology is derived from a construction method of free-form components based on the layer-by-layer superposition of cement materials proposed by Pegna in 1997 [4]. The free-form printing is realized by selective deposition of sand and silicate cement materials, then the printed components are steam cured, and finally the printing process is realized. In 2001, Khoshnevis et al. [8] proposed the construction printing technology of "Contour Crafting." In 2007, Paul et al. [9] improved the contour crafting and proposed "CC-cable-suspended." In 2008, Lim et al. [10] proposed a similar technology based on concrete jet extrusion pile forming, named "Concrete Printing." In recent years, 3D concrete printing technology has increasingly become the forefront of academic and industrial circles. Many institutions and enterprises have participated in this research, which has promoted the technology from experimental research to industrial application.

*1.3. Article Structure.* In summary, concrete 3D printing technology has significant technical advantages to overcome the disadvantages of traditional construction technology. With the development of relevant research, concrete 3D printing technology will inevitably move from laboratory to actual production and construction. In this study, the equipment system, concrete materials, molding defect control, and application scenarios of concrete 3D printing technology were reviewed. The introduction of concrete 3D printing equipment system mainly focuses on three parts: frame structure, control system, and feeding and extrusion system. While introducing the working principle of each subsystem, it is analyzed and deepened with research examples. The introduction of concrete materials mainly focuses on the enhancement of the performance of printing concrete materials by the addition of various fiber materials, admixtures, solid wastes, and other materials and developing a variety of new printing concrete materials. The introduction of molding defect control mainly analyzes the generation principle of various defects and summarizes the related methods to improve defects through the enumeration and classification of defect examples, so as to improve the molding quality of printing components. The application scenarios mainly summarize the engineering application of concrete 3D printing technology through the application of concrete 3D printing technology in practical engineering. Finally, the development trend of concrete 3D printing technology is prospected from three aspects of equipment, material, and process.

## 2. Concrete 3D Printing Equipment System

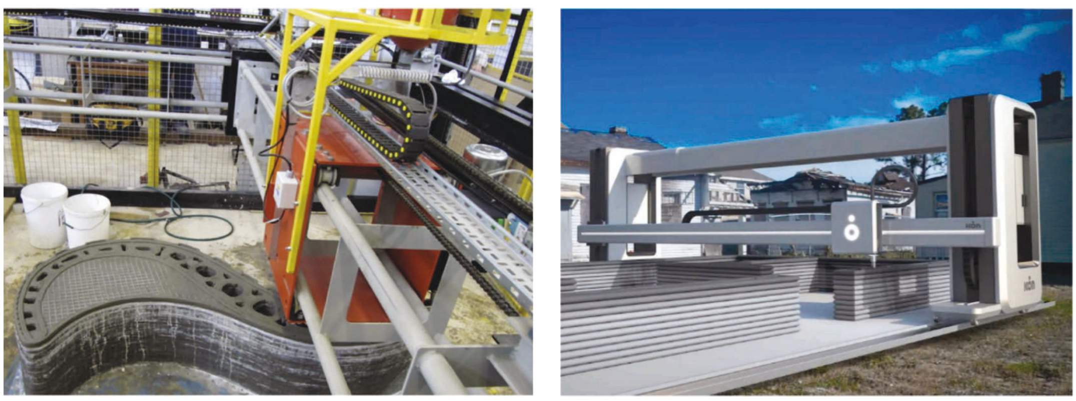
The concrete 3D printing equipment system consists of three parts: frame structure, control system, and feeding and extrusion system. The frame structure is responsible for the support and movement of sprinkler head device in space. The control system controls the movement of the printing device and the extrusion of concrete. The feeding and extrusion system is responsible for mixing concrete evenly and then conveying it to the extrusion mechanism and extruding the concrete through the screw. Figure 3 shows two groups of common concrete 3D printing systems. From the figure, we can clearly see the components of the concrete 3D printing equipment system, such as the feeding pump, the feeding pipe, the frame structure, sprinkler head device, and the computer control system. The feeding and extrusion system, frame structure, and control system of concrete 3D printing equipment system are introduced in detail. The working principle and common structural dimensions of each part of the concrete 3D printing system are discussed and deepened.

*2.1. Frame Structure and Control System.* The frame structure mainly provides support for the movement and positioning of the sprinkler head device in space, which requires the frame structure to have a relatively large bearing capacity. Due to the different size and accuracy requirements of the printed building, the size requirements of the frame structure are also different. The frame structure is generally divided into mechanical arm structure, gantry structure, and truss structure. Compared with the mechanical arm structure, the gantry structure and truss structure have the advantages of high overall stiffness, strong bearing capacity, simple control, and high stability [13]. Although the above three kinds of frame structure can realize the functional requirements of concrete 3D printing system for frame structure in theory, the mechanical arm structure is limited in printing size, and it is difficult to realize the one-time printing of large-scale target buildings. Truss structure and gantry structure are easier to realize the construction of large-scale frame structure. At present, the frame structure in the actual construction process of concrete 3D printing is mainly gantry structure and truss structure, and the frame structures are shown in Figure 4. The size of the two frame structures is based on the size of the span as the classification standard, but the detailed size classification of the two structures is slightly different. The different load-bearing tons of the gantry correspond to different spans, and the different cross-sectional areas of the truss correspond to




(a) (b)

Figure 3: Examples of concrete 3D printing system [11, 12].



(a) (b)

Figure 4: Frame structure. (a) Gantry structure [14] and (b) truss structure [6].

different spans. When the actual construction process can be based on the size of the target building to select the size of the corresponding frame structure span size, commonly used gantry structure and truss structure size are shown in Table 1. Gantry structure and truss structure, the achievable construction size is still very limited. For large target buildings, the solution of partial printing and assembly is still used. When applied to actual production and construction, it requires coordinated calculation in many aspects, which increases time cost and technical challenges for the construction process. Therefore, the development of printing framework for large-scale target buildings and the integrated and efficient printing of large-scale target buildings are one of the important development directions of concrete 3D printing technology.

The control system is responsible for the motion of sprinkler head device on the frame structure and the coupling control of nozzle rotation and material extrusion [15]. Concrete 3D printing technology uses 3D modeling software (such as CATIA and SOLIDWORKS) to design the model and generate the target building model (STL file). Then, the professional 3D printing model processing software (such as Cura, Slic3r, and Skeinforge) is used to slice the specimen model with equal thickness to generate the path of each layer and convert the path into G code [3, 16]. The G code is input into the control system to achieve accurate and rapid printing process. Therefore, the control system plays a vital role in the whole concrete 3D printing system, and its functional requirements are also more stringent than those of other systems. The excellent control system should have the following characteristics. Firstly, it has high accuracy and stability, and at the same time, it has good speed regulation performance. Secondly, the drive control motor should also have good bearing capacity. In addition to these hardware conditions, the control system control program should be easy to write and modify and has a good human-computer interaction interface. Due to the different complexity of printing components, when printing complex target components, the simple control of X, Y, and Z with three degrees of freedom cannot meet the actual construction needs. The solution of multi-degree of freedom printing is generally divided into the following two kinds: one is to improve the

Table 1: Common dimensions of gantry and truss structure.

| | Small scale | Medium scale | Large scale |
|---|---|---|---|
| The span of gantry | 5–10 m | 12–36 m | 39 m above |
| The span of truss | ≤ 6 m | ≤ 12 m | ≤ 20 m |

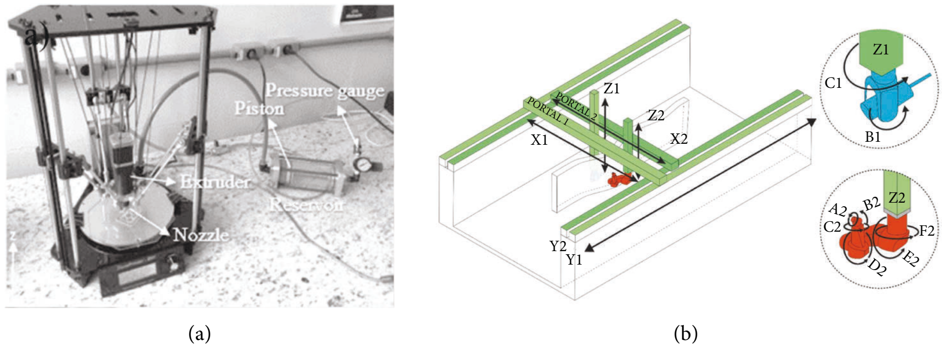



Figure 5: Multi-degree of freedom frame (a) [14] and multi-degree of freedom sprinkler head device (b) [17].

frame structure using more complex mechanisms to achieve multi-degree of freedom printing. The printing frame is shown in Figure 5(a), but the complex structure makes it also difficult to achieve large-scale printing and construction site installation and debugging. Another is on the basis of a simple frame structure, by improving the sprinkler head device to increase the number of overall freedom of the system, and the sprinkler head device is shown in Figure 5(b); because the sprinkler head device is improved, the frame structure is still relatively simple to build, so the method is more suitable for practical construction. In the printing process of three degrees of freedom or multi-degrees of freedom, higher performance requirements are put forward for the printing system. Starting from the above characteristics, and based on the general application of G code as the control code of motion controller in the concrete 3D printing technology, CNC (computer numerical control) system is very suitable for the performance requirements of concrete 3D printing technology on the control system. Compared with single-chip microcomputer and PLC system, CNC system can realize multi-coordinate linkage control, with high precision and good reliability. The position coordinates and processing path can be clearly expressed by G code to ensure that the printing process is fast and of high quality.

*2.2. Feeding and Extrusion System.* The feeding system is mainly composed of concrete mixer, power pump, and feeding pipe. The common feeding system is shown in Figure 6. The concrete mixer realizes uniform mixing of concrete mortar, and the pump provides power for concrete transportation. Concrete is composed of gel material, aggregate, water, and other components, resulting in large abrasion, and the loss of equipment is also obvious in actual production [18]. Therefore, when choosing the type of power pump, it is not only necessary to consider whether the pump can provide sufficient pressure but also necessary to consider whether the disassembly and repair of the pump body and the replacement of parts are convenient. At present, the use of peristaltic pump and screw pump as power pump is more common. Both pumps have the advantages of simple structure, low maintenance cost, and convenient disassembly.

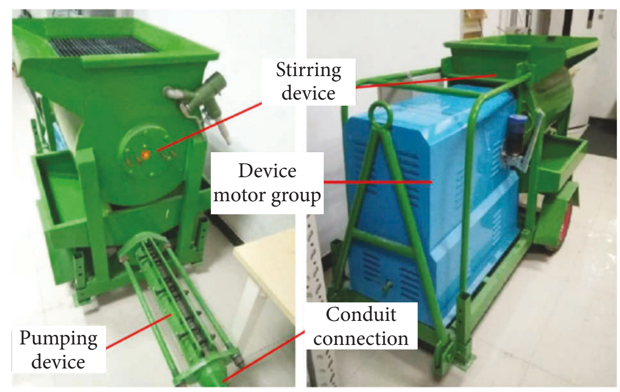
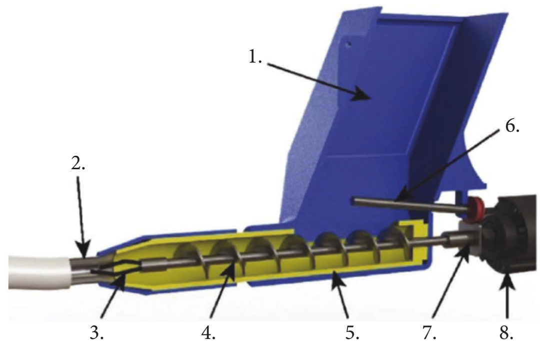



Figure 6: Examples of common feeding systems [1].

The extrusion system is mainly to solve the problem of uneven feeding caused by concrete pumping and improve the extrusion accuracy to achieve accurate printing. The common screw extrusion system is shown in Figure 7. When the power source is selected to pump, the transported concrete slurry will produce a certain pulse, which affects the whole printing process. Therefore, the problem of uneven feeding is solved by designing the storage bin of concrete in the extrusion system [20]. The shape and diameter of the extrusion nozzle are also important factors affecting the printing quality. The nozzle can be round, oval, and rectangular. In theory, the smaller the nozzle diameter, the smaller the “step effect” of printing, but considering the particle size of the concrete slurry and the printing efficiency of the actual production, the diameter of the extrusion nozzle should be selected according to the actual situation [21].

With the development of 3D printing technology of concrete, the requirements for the shape and structure of printed parts are becoming more and more complex. The conventional sprinkler head device is sometimes difficult to meet the needs of production, so many scholars begin to pay attention to the design and innovation of sprinkler head device. Xu [1] proposed a variable size sprinkler head device. The sprinkler head device consists of four isosceles triangle plates. Driven by an external motor, the four isosceles triangle plates carry out relative motion, resulting in a gap between the four isosceles triangle plates and




(1.Silo 2.Nozzle 3.Nozzle gasket 4.Screw 5.Conveying rod
6.Vibrating rod 7.Coupling 8.Motor)

Figure 7: Examples of common extrusion systems [19].

realizing the change in nozzle diameter. The structure diagram of the sprinkler head device and the isosceles triangle plate is shown in Figure 8. Yu et al. [22] proposed a particle bed 3D printing method, in which the special binder was deposited on the particle bed powder by the nozzle according to the specified path, and the above process was repeated continuously according to the printing model. Finally, the printing process was realized, which broke away from the limitation of the diameter size of the extrusion nozzle on the concrete slurry particles, and provided a more free construction form for the construction of concrete 3D printing technology. The experimental equipment and principle are shown in Figure 9. Li et al. [23] attempted to improve the ductility of the printing body by adding steel wire to the printing body through the transformation of the sprinkler head device. That is, a wire feeding mechanism was added on the basis of the original sprinkler head device. Through this mechanism, the extrusion rate of concrete slurry and the conveying rate of steel wire were combined to print out the concrete slurry with steel wire, so as to improve the performance of the whole printing component. The wire feeding mechanism is shown in Figure 10(a). Hoffman et al. [11] installed a small manipulator on the original sprinkler head device that can realize clamping action to solve the automatic clamping and placement of support in the printing process. The manipulator can realize the rotation and movement of multiple degrees of freedom and increase the function of sprinkler head device. The structure of the manipulator is shown in Figure 10(b). With the development and utilization of similar devices, complex architectural design ideas and architectural forms can also be realized by 3D printing of concrete.

## 3. Material and Molding Defect Control

*3.1. Research Status of Materials.* The 3D printing concrete is mainly composed of gel material (reference cement), aggregate, water, and admixture, and its performance requirements are also different from those of ordinary concrete. The layer-by-layer construction method puts forward higher requirements for the printability of concrete materials. Printability refers to that the early printing layer can support the subsequent printing layer and has good bonding ability with the subsequent printing layer, so that the printing components will not collapse or deform. Printability is actually a comprehensive manifestation of the yield stress, thixotropy, and rheological properties of printing concrete [24], so the quality of printability directly affects the progress of 3D printing of concrete. Printability of 3D printing concrete materials is composed of critical failure time, interlayer bonding strength, drying shrinkage, strength, durability, and other performance requirements [25]. In the printing process, the printability of 3D printing concrete materials can show excellent mechanical properties and good thixotropy and fluidity. On the premise of ensuring printing efficiency and molding quality, low material cost is also the development direction of concrete 3D printing technology. For example, the slump test is used to test the working performance of ordinary concrete. Printed concrete materials also have corresponding test and evaluation methods. In the fresh concrete mixing state, the thixotropy and fluidity of concrete materials are tested. In the late maintenance stage of printing components, mechanical tests such as compressive strength, tensile strength, and flexural strength were carried out according to the actual working state of printing components [26]. The printability of concrete materials was comprehensively evaluated through thixotropy, rheology, and mechanical properties of printing components under fresh mixing state of concrete materials.

To meet the requirements of printing concrete materials mentioned above and develop more suitable concrete materials for 3D printing, many experts and scholars have made attempts in the aspect of aggregate doping ratio, aggregate type, or admixture type of printing concrete materials, such as improving the cement-sand ratio and water-cement ratio, doping steel fiber to enhance the strength of concrete, or adding different types of admixtures (such as water reducing agent, plasticizer, retarder, and coagulant) [14, 27]. This study summarizes the research and development of printing concrete materials from three aspects: the enhancement of mechanical behavior of printing concrete materials, the improvement of rheological properties and fluidity of printing concrete materials, and the development of low-cost and low-carbon printing concrete materials.

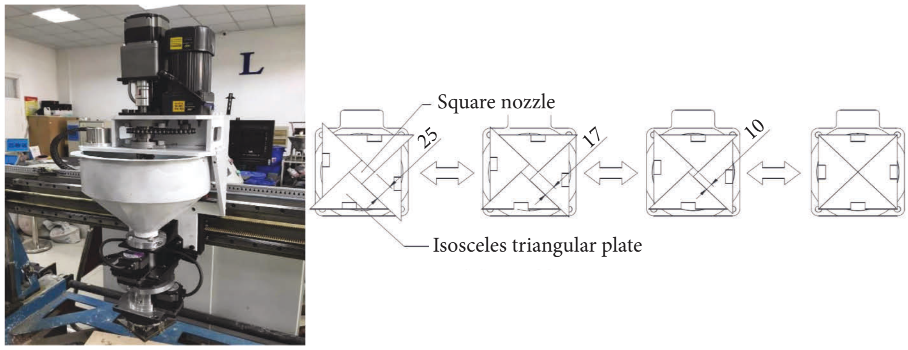



FIGURE 8: A variable size sprinkler head device and deformation principle [1].

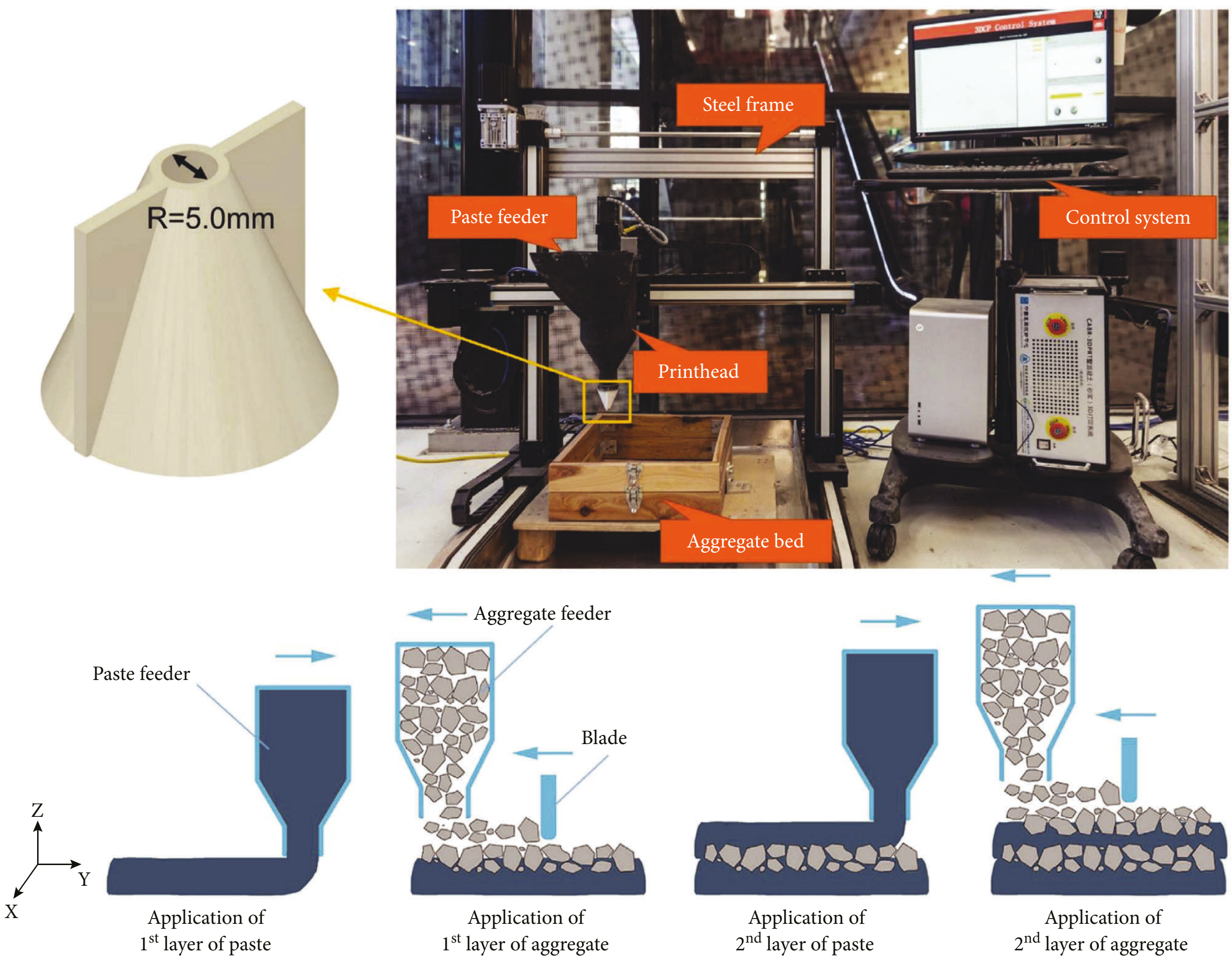
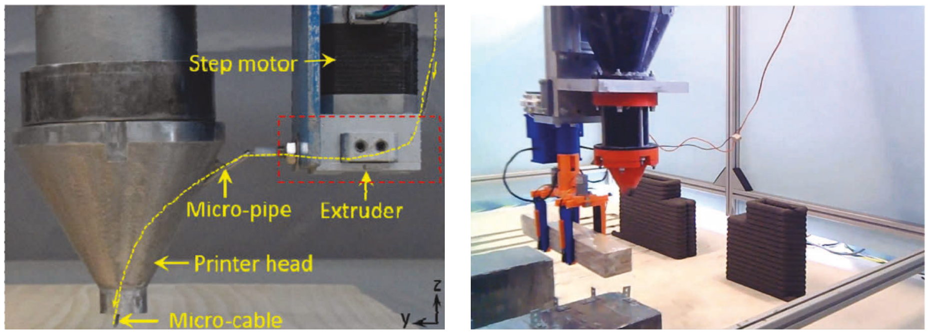



FIGURE 9: Particle bed 3D printing experimental device and principle [22].

*3.1.1. The Enhancement of Mechanical Behavior of Concrete Materials.* 3D printing concrete materials are composed of gel materials, aggregates, water, and additives. When the mixing ratio of basic materials is changed or doped with fiber materials, the performance of 3D printing concrete materials will also change [28, 29]. Sun et al. [30] obtained a kind of ultra-high performance concrete suitable for 3D printing construction by changing the material mixing ratio of concrete, doping steel fiber, and adding water reducing agent. This kind of concrete nonuse coarse aggregate and the compressive strength and flexural strength are better than those of ordinary concrete materials. Because the addition of steel fibers not only has good toughness but also helps to improve the adhesion of adjacent printing layers as a 3D




(a) (b)

Figure 10: Sprinkler head device feeding mechanism (a) [23] and sprinkler head device manipulator (b) [11].

printing material, and the performance is very suitable for large-scale concrete 3D printing projects. Chu et al. [31] developed high-strength fiber-reinforced concrete (HSFRC) and studied the effects of nanoparticles, carbon fibers, steel fibers, and glass fibers on its performance. The results show that the addition of nanoparticles and fibers can improve the rheological properties of the concrete, and the addition of steel fibers has lower extrusion pressure and higher shape retention ability of printing components than that of carbon fibers and glass fibers. The addition of appropriate amount of nanoparticles is conducive to the enhancement of interlayer bonding, thereby improving the bonding strength between layers of printing components. The doping of carbon fibers, steel fibers, and glass fibers enhances the compressive strength of printing components, among which the strengthening effect of steel fibers is the most obvious. The compressive strength of printing components doped with steel fibers can reach more than 120 MPa. The printing shape of samples and the compressive strength of the samples doped with different fibers (0-plain, 0-CF0.5, 2-CF0.5, 4-CF0.5, 4-SF0.5, 4-GF0.5) are shown in Figure 11.

Arunothayan et al. [32] developed a kind of high-performance fiber-reinforced 3D printing concrete (UHPFRC). The concrete material is the basis of reference cement and aggregate. It is doped with 1%–2% copper-coated steel fiber and shows excellent performance in compressive strength and fracture modulus (MOR). In the process of fracture, it will follow the flexural hardening behavior. At the same time, it is found that the diameter of the nozzle will affect the arrangement direction of the fiber to a certain extent. When the nozzle with 10 mm diameter is used for printing, the best fiber arrangement distribution is obtained. The development of the concrete material is conducive to printing slender and complex structures through concrete 3D printing technology, replacing the traditional reinforcement method. The compressive strength of printed samples with different fiber doping ratios (F1-D30-S30, F2-D30-S30) and conventional pouring samples (F0-D30-S30) is shown in Figure 12.

Ding et al. [33] studied the effect of polyethylene fiber on the anisotropic behavior of concrete materials under bending state. The experimental results show that with the addition of polyethylene fiber, the failure of the sample is no longer concentrated in the weak interface, and the bending strength of X, Y, and Z directions is significantly improved. After the bending strength reaches the peak, the related properties of concrete materials are directly related to the fiber content. The microstructure of fiber-reinforced 3D printing sample was analyzed by SEM. It was found that a certain number of fibers were broken and some fibers were pulled out from the cement matrix under three directions of loading, indicating that the addition of polyethylene fibers enhanced the ability of specimens to resist failure deformation. At the same time, the arrangement direction of polyethylene fibers was the key factor to improve the ultimate strength and post-peak performance of fibers. The microstructure of concrete materials with polyethylene fibers is shown in Figure 13.

Yu et al. [34] developed a printing concrete material with high ductility by adding engineering gel composites (ECCs) to concrete materials and used this new type of concrete material to print a 1.5 m high, 150 layers of twisted columnar building. Engineering gel composite (ECC) is a kind of gel material reinforced by adding fibers, which has high tensile strength and bending strength. The concrete material added with this kind of material also has high tensile strength and bending strength. The research and development of this printing concrete material are expected to eliminate the dependence of concrete building engineering on steel bars. The twisted columnar buildings printed by this concrete material and the fluidity and hardening deformation varying with time are shown in Figures 14(a) and 14(b).

*3.1.2. The Improvement of Rheological Properties and Fluidity of Concrete Materials.* Li et al. [35] studied the influence of fly ash and silica ash on the working performance and mechanical properties of 3D printing cement-based materials by mixing fly ash and silica ash in single and complex forms. Experiments show that the incorporation of fly ash can improve the fluidity of materials and reduce the printability of materials, while the effect of silica ash is opposite. For the setting time, whether single or mixed, materials will prolong the setting time. The influence on the fluidity and setting time of cement-based materials is shown in Figure 15. Wang et al. [36] studied the effects of aggregate, plasticizer, and latex powder on the properties of 3D

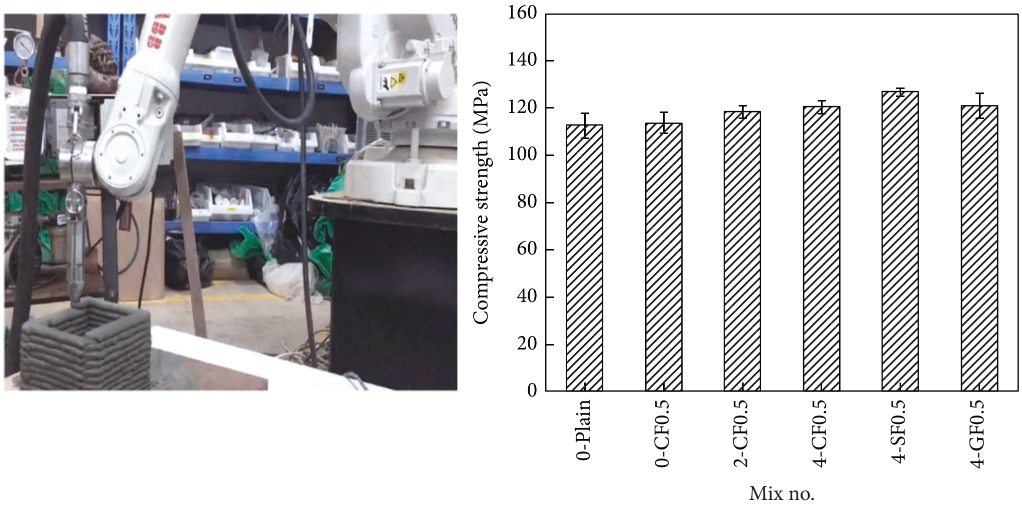



Figure 11: Shape and compressive strength of 3D printing concrete sample [31].

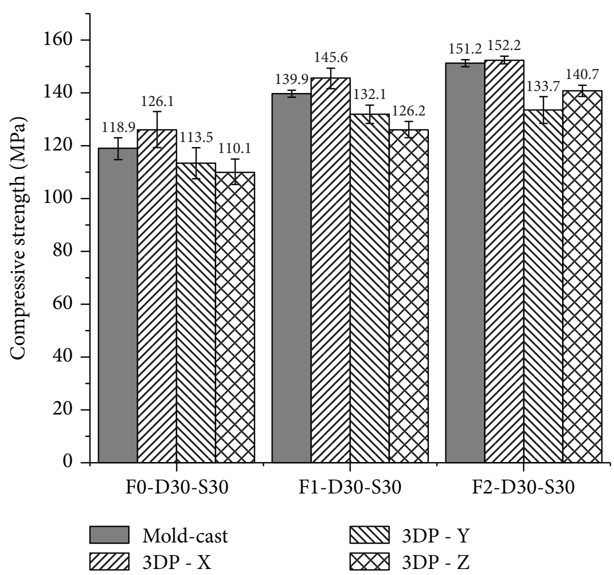



Figure 12: Compressive strength maps of printed sample and conventional cast sample with different fiber doping ratios [32].

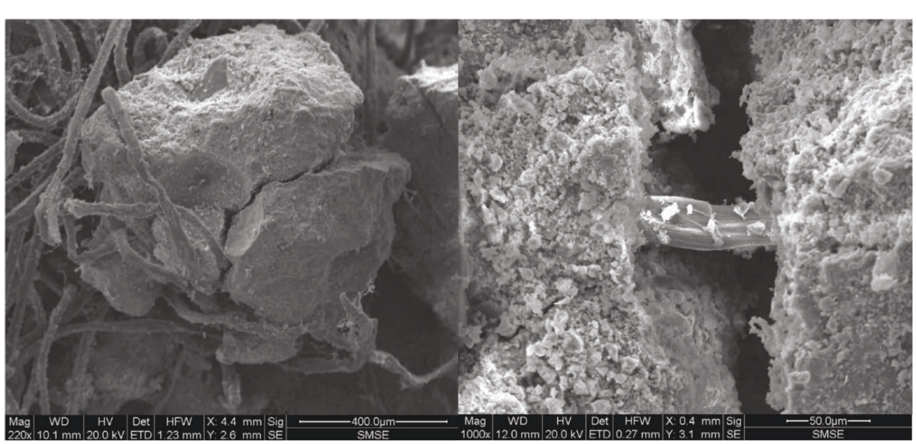


Figure 13: Microstructure of concrete material with polyethylene fiber [33].

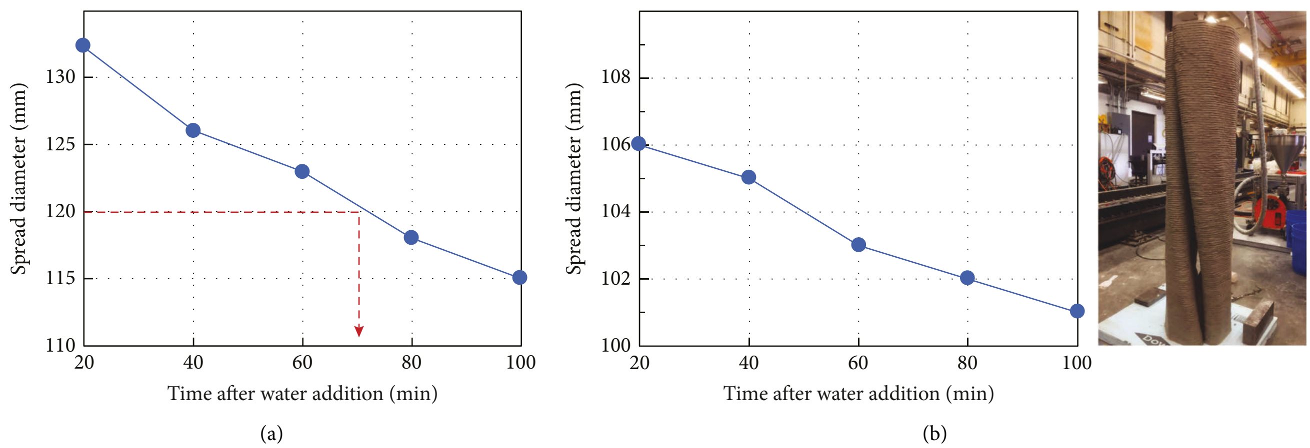



Figure 14: Time-dependent fluidity (a) and degree of hardening deformation (b) of concrete materials and twisted columnar building [34].

printing concrete. The results show that the apparent viscosity, thixotropy, and yield stress of printed concrete increase significantly with the increase in plasticizer content. With the increase in latex powder content, the apparent viscosity, thixotropy, and yield stress of printed concrete decrease first and then increase. The influence of aggregate and plasticizer on printed concrete is shown in Figure 16.

Zhu et al. [37] explored the mixing of hydroxypropyl methylcellulose (HPMC) in printing concrete. The results showed that the fluidity and extrudate of concrete decreased with the increase in HPMC content, but the fluidity retention ability was improved. HPMC increased the printable time of printing concrete materials, and the concrete still had good extrudate after adding appropriate amount of HPMC. With the increase in HPMC content, the stackability is improved, and the shape retention ability of printing components under self-weight condition is enhanced. The apparent viscosity, yield stress, and plastic viscosity of the slurry are significantly increased. The thixotropy increases first and then decreases with the increase in HPMC content, and the printability is improved. The shape stability and compressive and flexural strength of concrete after HPMC doping are shown in Figure 17.

Zou et al. [38] used recycled sand prepared from construction waste as material, added sodium gluconate admixture to it, proposed a 100% recycled sand 3D printing concrete suitable for printing, and then verified the printability of 100% recycled sand 3D printing concrete from its fluidity, extrusion, opening time, and wet embryo strength. Experiments show that the addition of sodium gluconate improves the fluidity of the concrete, to achieve longer printing window time. The concrete has higher early strength than ordinary concrete materials, which is beneficial to the bottom printing of concrete slurry to provide sufficient support strength for subsequent printing. The fluidity of ordinary concrete and recycled sand concrete doped with different proportions of sodium gluconate is shown in Figure 18. Muthukrishnan et al. [39] studied the effect of base reaction on the early strength of printed concrete. The rheological properties of concrete materials were changed by adding magnesium aluminum silicate (MAS) and sucrose to obtain better early strength. The experimental results show that when the MAS and sucrose contents are 0.75 wt%, 1.0 wt%, and 1.5 wt%, respectively, the prepared printed concrete has good early strength and printability. The flocculation process generated by the base reaction inside the concrete material is shown in Figure 19.

*3.1.3. The Development of Low-Cost and Low-Carbon Concrete Materials.* Green low-carbon development concept has penetrated into our lives, and construction projects for green sustainable exploration steps have never stopped. Hosseini [40] summarized the recycling of waste plastics, waste tires, and coconut fibers in ordinary concrete materials, but the recycling of this type of waste materials is not only limited to ordinary concrete materials but also applied in 3D printing concrete materials. Qamar et al. [41] developed sulphoaluminate cement doped with industrial solid waste. The gel material has good performance in setting time, fluidity, and compressive strength and explores the use of lithium carbonate and boric acid to adjust and control the setting time of the gel material. The experimental results show that when 0.1 wt% boric acid and 0.05 wt% lithium carbonate are added and the water-solid ratio is 0.28, the gel material has better printing performance than ordinary concrete materials, and the production cost is only half of the ordinary concrete. The setting time changes after adding lithium carbonate and boric acid are shown in Figure 20. Khalil et al. [42] developed a kind of active magnesium oxide cement (RMC). Compared with traditional Portland cement, the carbon footprint of the active magnesium oxide cement is significantly reduced in the production and maintenance stage, which is a potential environmental protection building material. In addition, compared with the concrete pouring component, the 3D printed RMC component has higher compactness and nearly twice the high compressive strength. During the long specimen printing process (60 min), there is no fluid interruption or structural collapse. Even after accelerated carbonation, it still shows good shape

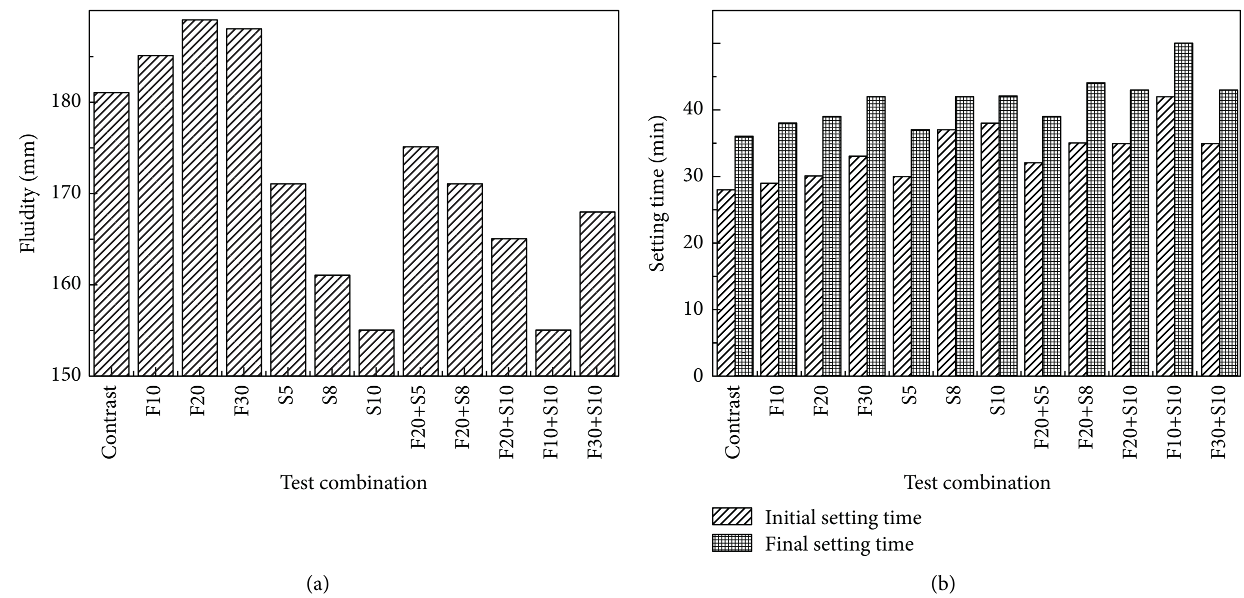



Figure 15: Effect of cement-based materials. Flowability (a) and setting time (b) [35].

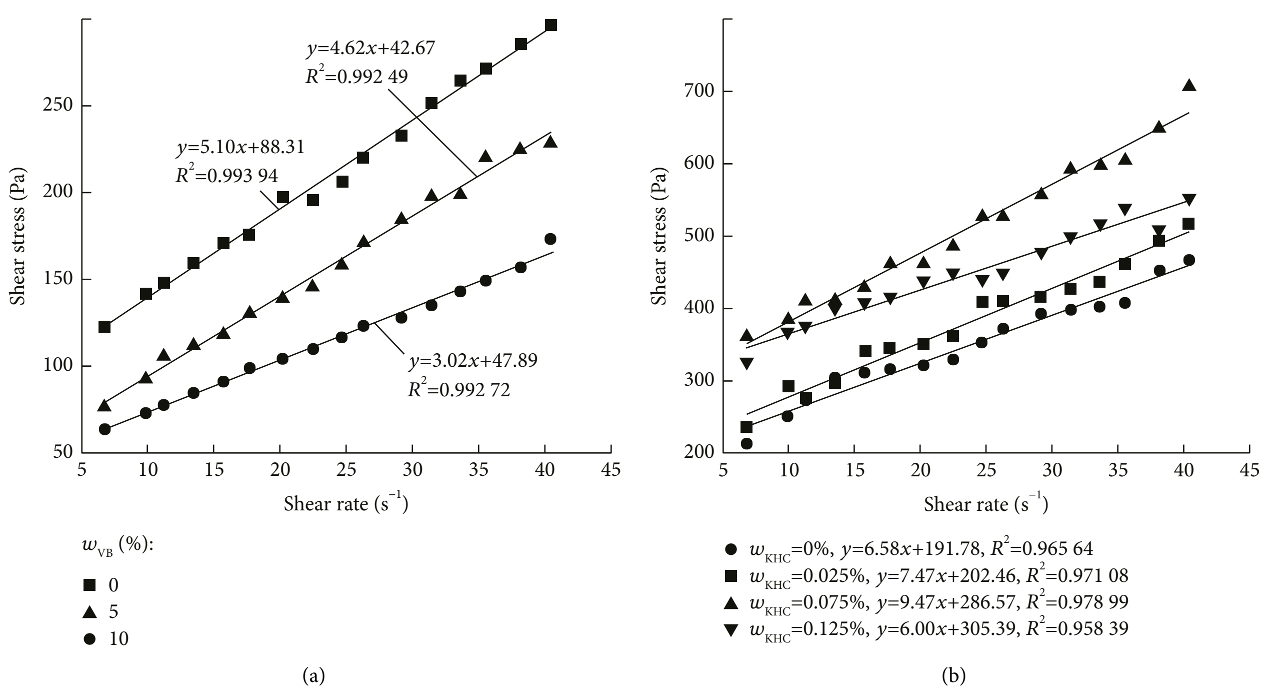



Figure 16: Effect of additional materials and additives on rheological properties of concrete, effect of aggregate (a), and effect of plasticizer (b) [36].

retention and overall integrity. Observation of surface and internal microstructure of casting components by 10 $\mu$m electron microscope is shown in Figure 21.

Craveiro et al. [19] doped waste wood into printing concrete and developed a nozzle device with variable mixing ratio of printing concrete. Compared with ordinary concrete materials, the concrete material doped with sawdust waste improves the thermal insulation performance of concrete materials on the basis of reducing the overall weight. The distribution of the physical section and section of the printed concrete member are shown in Figure 22. Alvarez-Fernandez et al. [43] used recycled slag as aggregate for printing concrete to prepare 3D printing concrete materials suitable for construction. By adding different proportions of slag, water, superplasticizer, and accelerator, the best strength, workability, and constructability were found. The experimental results show that the concrete material mixed with 20% recycled slag is very suitable for the printing

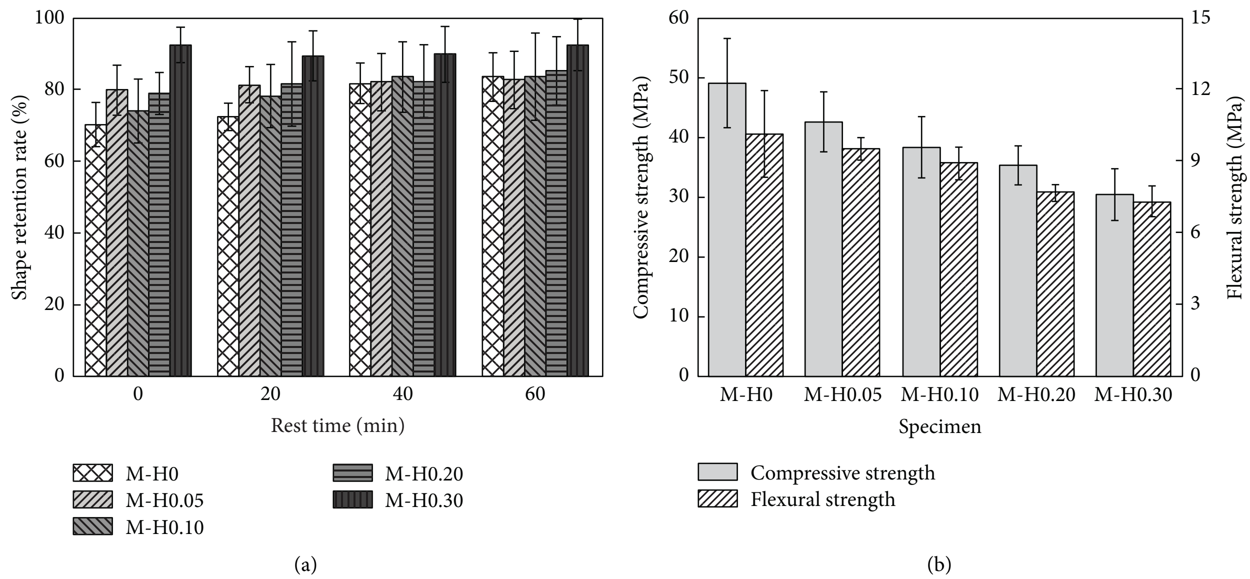



Figure 17: Changes in shape stability (a) and compressive and flexural strength (b) of 3D printing concrete with different HPMC contents [37].

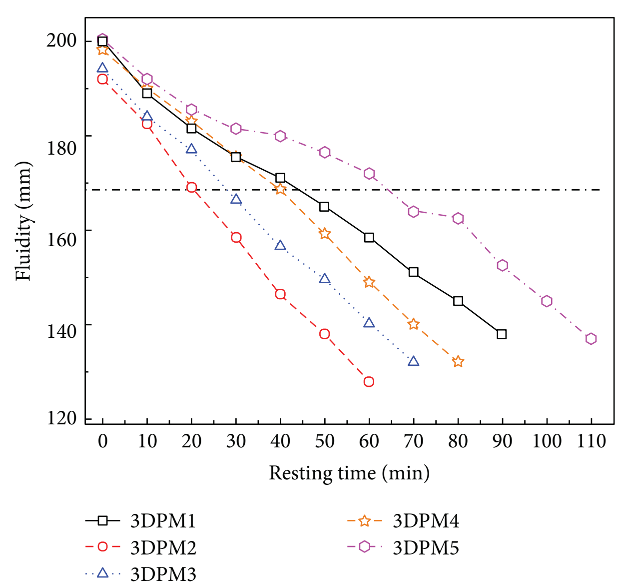



Figure 18: Flowability of ordinary concrete and recycled sand concrete doped with different proportions of sodium gluconate [38].

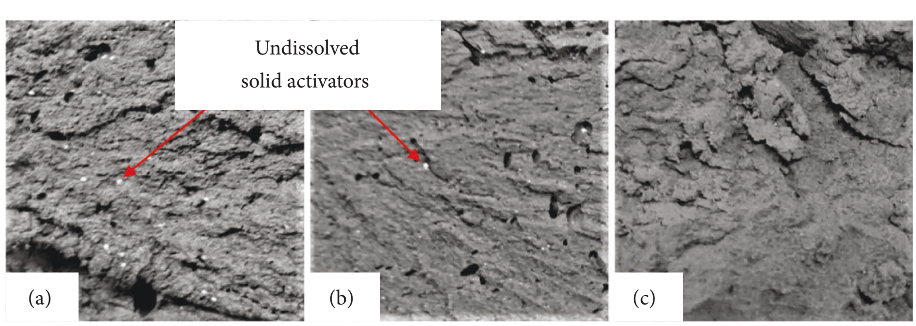
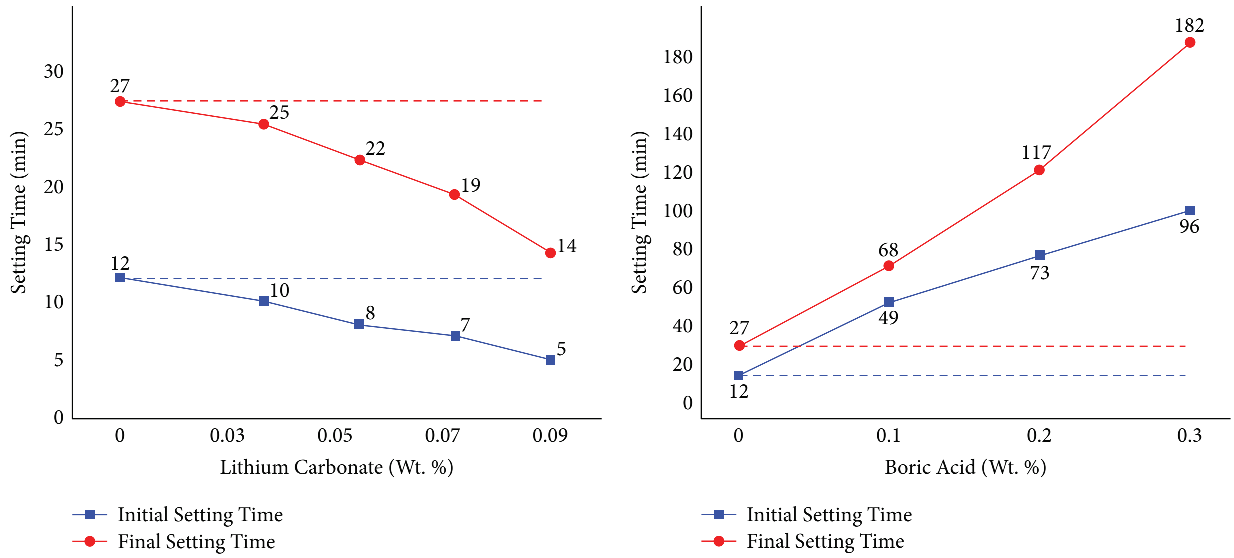



Figure 19: Flocculation process generated by base reaction in concrete materials [39].




(a) (b)

Figure 20: Setting time of sulphoaluminate cement doped with construction waste additives lithium carbonate (a) and boric acid (b) [41].

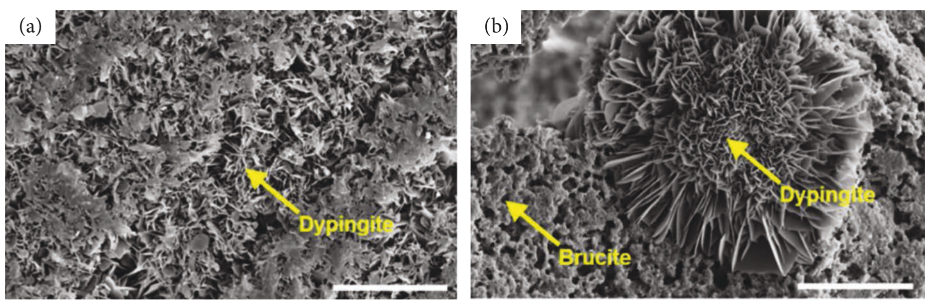
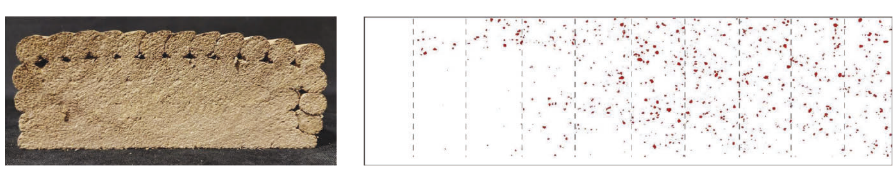



Figure 21: Observation of surface and internal microstructure of casting components by 10 $\mu$m electron microscope [42].



(a) (b)

Figure 22: Printing component section (a) and the distribution of sawdust waste (b) [19].

construction of 3D printing of concrete in terms of fluidity, extrusion performance, and compressive strength. In the construction process, superplasticizer and accelerator are used to enhance the interlayer bonding ability, which can achieve the construction effect that no additional support is needed in the whole printing process.

Ye et al. [44] developed an ultra-high ductility concrete (UHDC) to enhance the flexural strength of printed concrete by doping recycled rubber particles of waste tires into concrete materials. The experimental results show that the concrete material has good buildability in the fresh mixing state. The tensile strength and shear strength of the printed sample are slightly lower than those of the casting sample, but the bending strength of the printed sample is much higher than that of the casting sample, and the printed sample shows the smallest anisotropy in the bending strength. The compressive strength and bending strength of the concrete material are shown in Figure 23. Li et al. [45] developed a fiber-reinforced 3D printing concrete material made of seawater and marine sediments by adding glass fiber and basalt fiber to coral sand concrete. The concrete showed good printability in fresh state. The bending strength of the printing component was obviously due to the pouring component. The

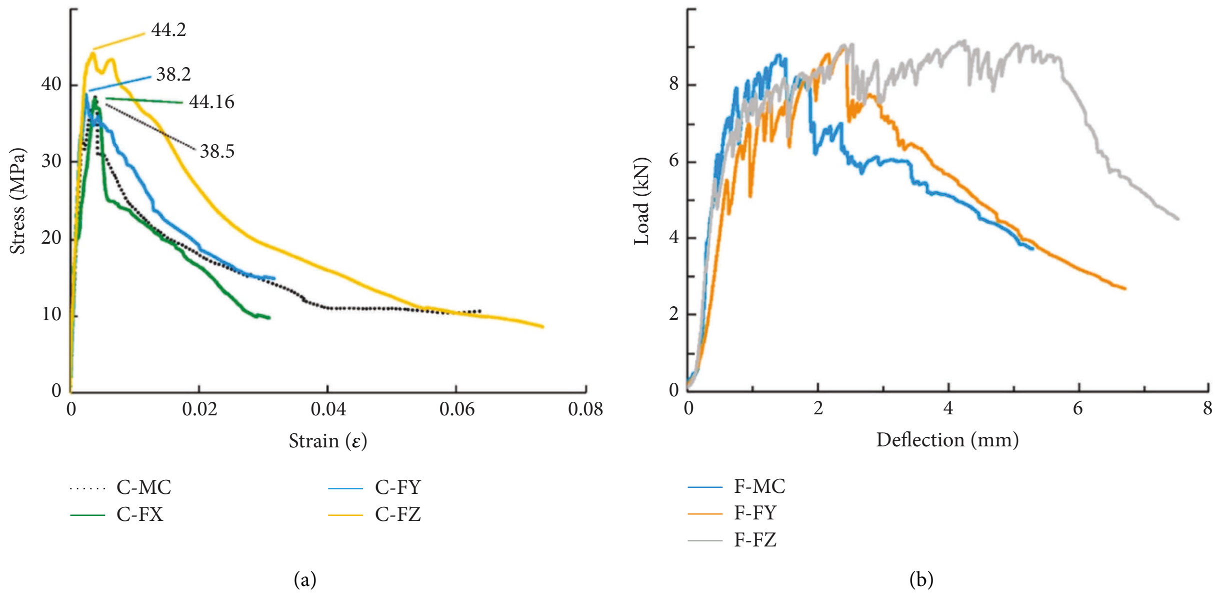



Figure 23: Compressive strength (a) and bending strength (b) of UHDC concrete [44].

compressive strength of the printing component was similar to those of the pouring component. The development of this marine sediment concrete material has great potential for the construction of remote islands and coastal areas and provides a better solution for the rapid green and recyclable construction of remote coastal areas in the future. The changes in bending strength and compressive strength of the printing component of this concrete material with the change in fiber ratio are shown in Figure 24.

### *3.2. Forming Defect Control of Concrete 3D Printing*

*3.2.1. Step Effect and Cracking Deformation.* The "step effect" means that there is a clear boundary between the layers after the concrete slurry layer is accumulated, and the outer surface of the step formation process is shown in Figure 25. In addition to the step effect, the printed components are often accompanied by overfilling, underfilling, and self-weight deformation. Although Khoshnevis et al. proposed a nozzle device with a wiper as early as 2001, the concrete 3D printing technology is called "Contour Crafting" [8]. This kind of nozzle with a wiper can reduce the step effect to a certain extent, but it is still not enough. In the printing process, the step effect will be at a low level when the number of lines to print a part is many enough to be fine enough, even if it is hard to see by the naked eye, it can be slightly felt only when touching the surface. However, when the number of extruded material lines is small or the particle size of the line is large, the step effect will become obvious, which can only be controlled using smaller nozzles and layer thickness to reduce the particle size of the extruded line [1]. Changing the shape and size of the printing nozzle will not only improve the defects such as step effect but also improve the mechanical properties of printed concrete component [46]. Nozzles with different shapes and sizes are an important means to solve the step effect in the 3D printing process of concrete. At the same time, in the late maintenance process of printing components, with the continuous volatilization of water, printing components will also have molding defects such as cracking and deformation [47]. Small cracks exist on the surface of printing components, and large cracks will seriously affect the working performance of printing components. The cracking of concrete components is shown in Figure 26. The shrinkage can be minimized by internal or external curing. Internal curing includes the use of shrinkage reducing admixture, saturated water lightweight aggregate, and adsorption fiber. External curing includes the application of water on the printing surface or the formation of film curing compounds, such as fog chamber curing. Any of the above measures can reduce the cracks in concrete and effectively protect the printing layer from the influence of shrinkage cracks, while avoiding the subsequent development of shrinkage cracks into structural cracks [11].

*3.2.2. Weak Surface between Layers.* In the process of concrete 3D printing, the forming method of layer-by-layer accumulation is easy to cause the weak bonding between layers, and there is no external vibration assistance in the forming process, and the weak bonding between layers becomes more significant. The weak surface between layers will lead to uncoordinated deformation and discontinuous mechanical properties of the structure, which is prone to fracture due to stress concentration. It is another major molding defect in the concrete 3D printing process [48, 49]. The printing structure water seepage caused by the weak surface between layers is shown in Figure 27. The formation of weak surface between layers is caused by the process factors, geometric factors, physical factors, and material factors [51]. In the process, it is difficult to coordinate the

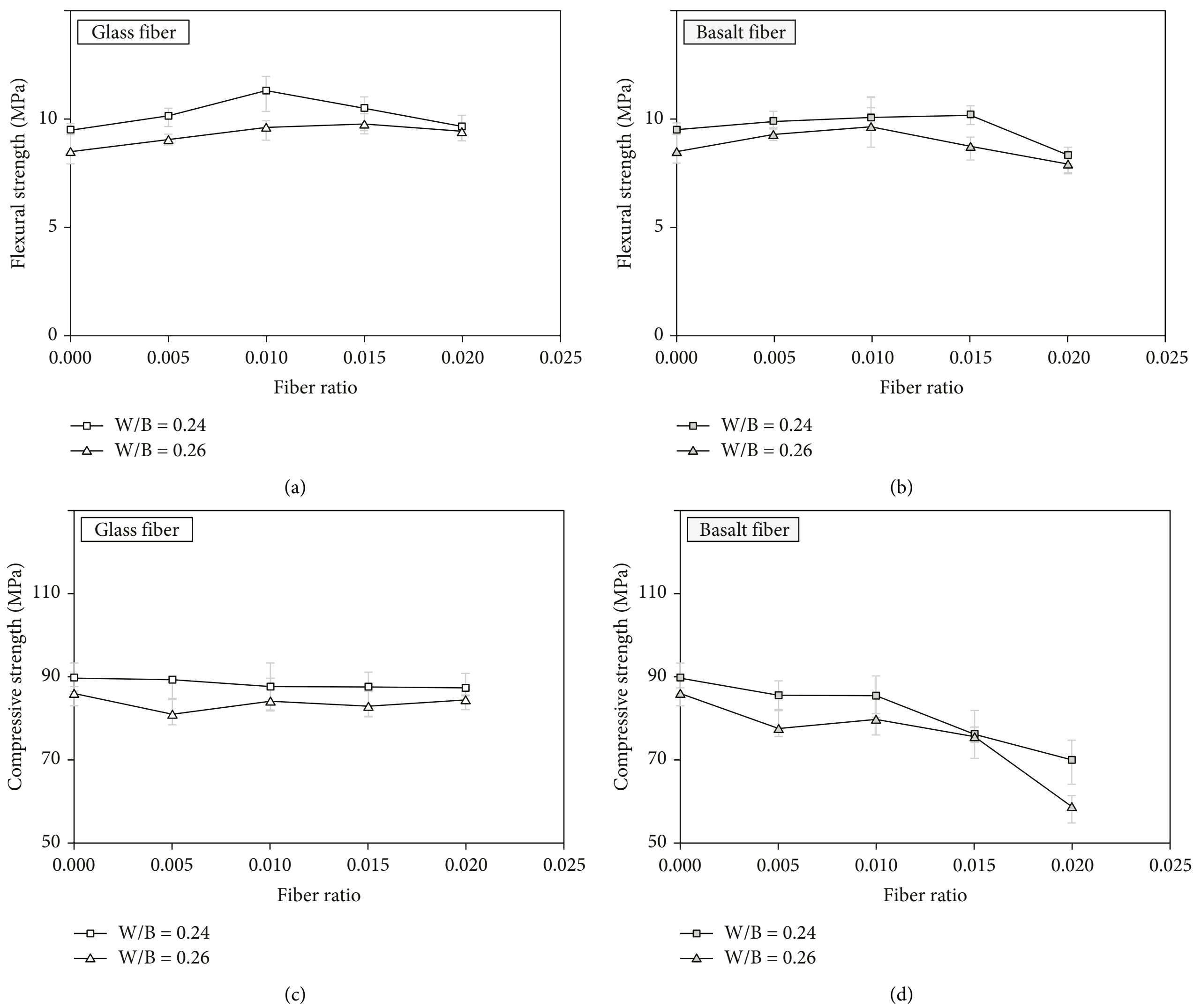



Figure 24: Flexural strength (a)(b) and compressive strength (c)(d) of printed components due to changes in fiber ratio [45].

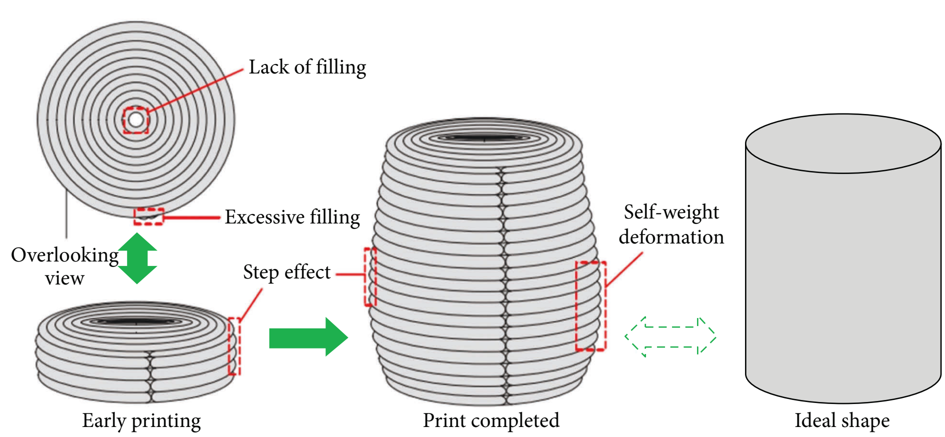



Figure 25: Step effect and other molding defects [1].

sprinkler head device moving speed with the extrusion speed of concrete materials. After the extrusion molding of materials, there may be water film between layers, which undermines the continuity of materials and reduces the bonding ability between adjacent printing layers. In terms of geometric factors, the widely used circular nozzle is

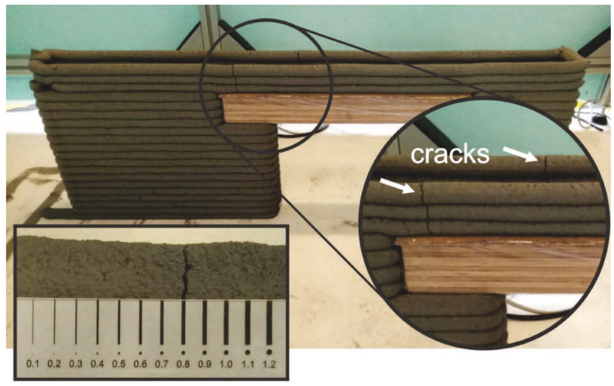



Figure 26: Cracks in printing components [11].

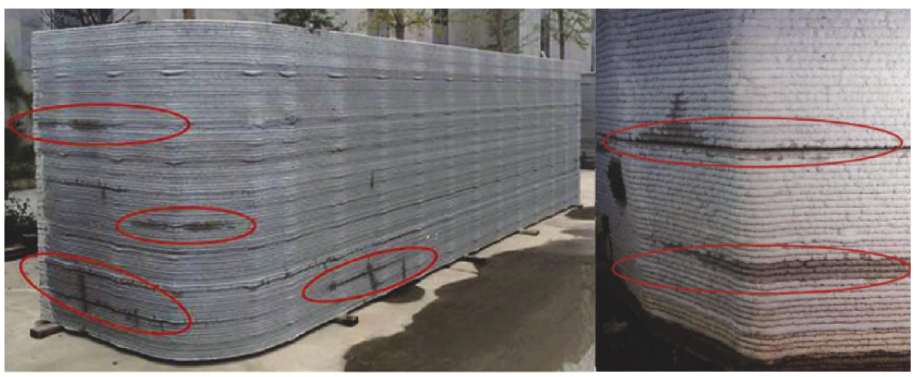


Figure 27: Water seepage caused by weak surface between layers [50].

beneficial to extrusion of concrete materials and avoids the dead angle, but the concrete slurry extruded by circular nozzle is easy to form voids between layers, resulting in defects. In terms of physical factors, the automatic molding process without tamping is not easy to eliminate bubbles and voids between the printing layers, resulting in weak bonding force between the printing layers. In terms of material factors, the continuous hydration and stiffness of early age cement and other gelling materials gradually increase, resulting in the decrease in the chemical activity of the surface of the printing material, and the interface between the adjacent two layers is more and more obvious, which reduces the bonding performance between the layers. The improvement method of weak surface between layers can be carried out from the following two aspects, namely, improving the printing path and optimizing the ratio of printing concrete or extrusion shape. There are two common print paths, parallel scan path and contour scan path, which are shown in Figure 28(a). Parallel scan paths consist of a set of parallel straight paths, also known as zigzag paths [53]. The contour scan path is composed of a series of offset lines of the contour [54]. When a single print scanning path cannot print the target component well, it can be considered to use different scanning paths in different parts according to the shape of the component, so as to achieve better forming quality. At the same time, adding appropriate admixture in the printing material can also improve the rheological and hydration of concrete materials, so that the bonding performance and strength of concrete printing materials are improved. For example, Sakka et al. [55] added 7.5% styrene-butadiene rubber polymer in cement-based materials, Li et al. [56] added 1.5% viscosity modifier (VMA) in cement-based materials, and Zareiyan et al. [57] optimized the ratio of printing cement-based materials. These practices and attempts can greatly improve the rheological properties of concrete materials, making concrete materials more in line with the construction requirements. In the process of concrete 3D printing, Wu et al. [50] smeared cement paste, fly ash paste, cement paste, modified acrylic acid, and emulsion on the interface between the layer and the layer to enhance the bonding strength between the layer and the layer of the printing component and obtained printing components with higher molding quality. The distribution of printing layer and interfacial agent in this method is shown in Figure 28(b).

## 4. Application of Concrete 3D Printing

At present, the relatively mature concrete 3D printing application mainly focuses on the plate, block, or column components with simple printing structure. This type of structure is moderately difficult to print and has strong practical significance, especially the plate and column components of various forms and sizes. Through the

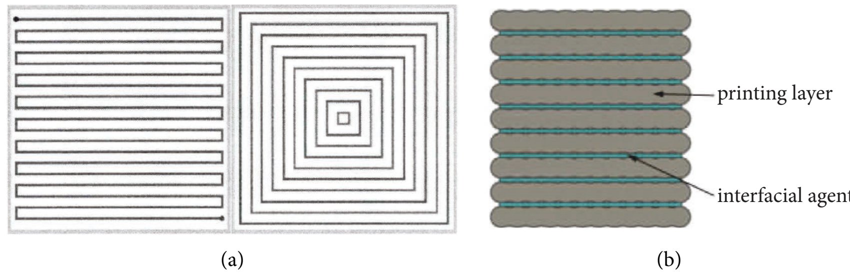



Figure 28: Parallel scan path and contour scan path (a) [52] and printing layer and interfacial agent distribution (b) [50].

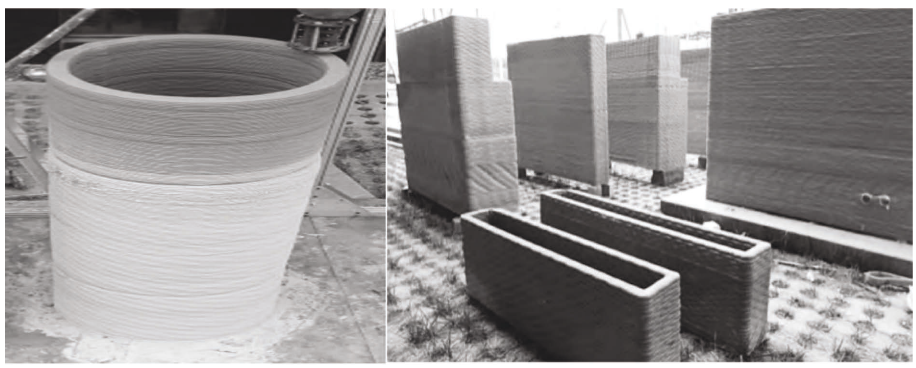


Figure 29: Concrete 3D printing wall and column [59].

Figure 30: Installation process and overall structure of concrete 3D printing bridge [60].

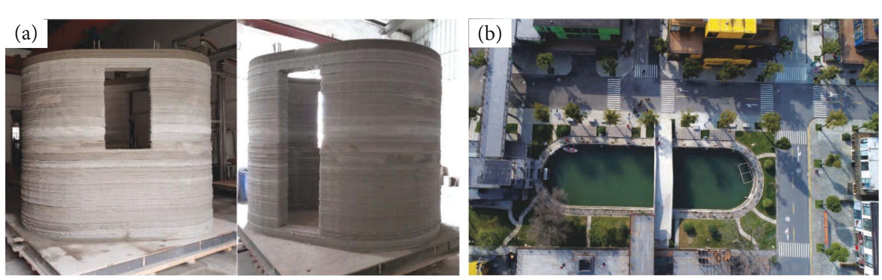



Figure 31: Concrete 3D printing room (a) [62] and concrete 3D printing walking bridge (b) [61].

installation and combination of the construction site, it can be well applied to the actual construction [58, 59]. The components of various shapes printed in the actual construction process are shown in Figure 29. Just printing these simple structures cannot show the superiority of concrete 3D printing technology compared with traditional

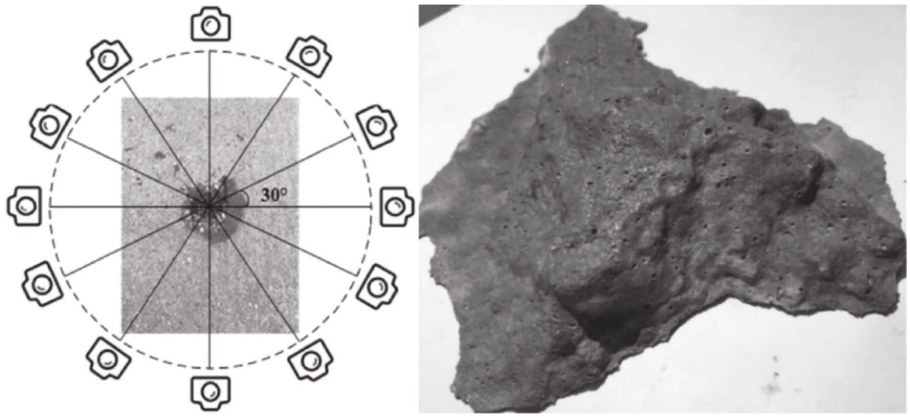



Figure 32: Photographing of pavement damage and concrete patch [64].

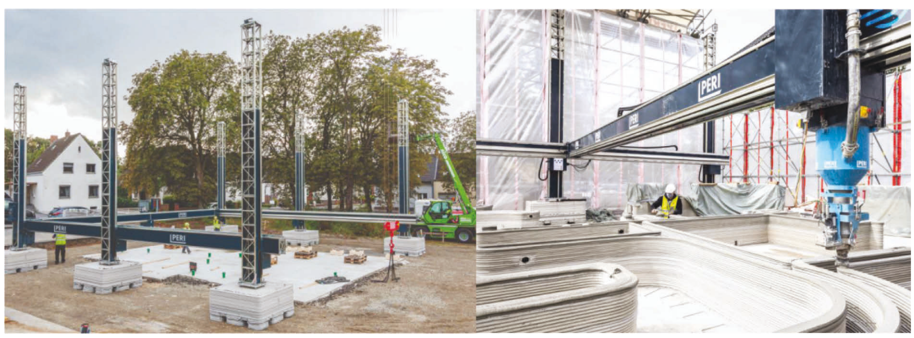


Figure 33: 3D printing house [66].

pouring technology and meet people's design ideas. Many examples of concrete 3D printing engineering applications have been carried out.

*4.1. Application of Bridge Engineering and Pavement Engineering.* Salet et al. [60] adopted the construction method of printing block-type bridge components and hoisting and installing prestressed tendons on-site and finally completed the construction of a bridge with length of 6.5 m and width of 3.5 m. The bridge used the synthetic epoxy-based material as the bonding material at the cross section, which can withstand the uniform load of 5 KN/m$^2$. The installation process and overall structure of the bridge are shown in Figure 30. The Center for Digital Architecture Research of Tsinghua University [61] built a concrete 3D printing walking bridge in Shanghai Baoshan with the self-developed machine arm as the printing mechanism. The walking bridge is 26.3 m in length and 3.6 m in width. The single arch structure is used to withstand the load. Compared with the bridge engineering of the same scale, the cost of the bridge is only 2/3 of that of the ordinary bridge. The aerial view of the walking bridge is shown in Figure 31(b). Zhang et al. [63] developed a recycled concrete 3D printed pavement slab, which improved the defects of conventional steel pavement slab in the project. The concrete pavement slab is superior to the conventional steel pavement slab in the manufacturing cost and can realize the recycling of resources, which is in line with the concept of sustainable development of green construction. Li et al. [64] proposed the application of concrete 3D printing technology in road repair. The damaged patch model was obtained by multi-angle road damage shooting, and the corresponding concrete patch printing and field repair were carried out according to the damaged patch model. The principle of defect acquisition and concrete patch is shown in Figure 32.

Figure 34: 3D printing of concrete landscape square [67].

*4.2. Application of Architecture and Landscape.* Xiao et al. [62] used recycled sand instead of natural sand in concrete materials, studied the performance of printing concrete doped with recycled sand and natural sand, and successfully printed a room of 2.5 m × 2.5 m × 3 m, which is shown in

Figure 31(a). Wang et al. [65] used concrete 3D printing technology to construct a novel coronavirus pneumonia prevention shelter, which was 7.3 m in length, 3.2 m in width, and 2.9 m in height and was composed of three main unit rooms. The production and installation process was automated, and all processes and operations could be completed by only 3–5 people. The technical characteristics of low labor density and high automation of concrete 3D printing technology show great technical advantages during such a special epidemic. The first 3D printing house in Germany built by PERI GmbH Company was constructed in Beckham City, North Rhine-Westphalia [66]. This two-storey 3D printing single house has an area of about 80 square meters per floor. The overall housing structure is printed at one time and no longer installed later. The frame structure and printing process of the building are shown in Figure 33. Xu et al. [67] used concrete 3D printing technology to build a landscape square with a total area of 5523.3 square meters. The whole process was automated without workers. The concrete 3D printing system was used to directly complete the printing construction of sidewalks, sculptures, seats, tree pools, flower beds, and retaining walls. The landscape square is shown in Figure 34.

## 5. Summary and Prospect

Based on the building 3D printing technology and concrete 3D printing technology, this study introduces the concrete 3D printing equipment system, concrete materials, molding defects, and control and summarizes and deepens the above contents through many research examples. As a new construction technology, concrete 3D printing technology can solve the problems of high energy consumption and high pollution in the traditional construction process, which is beneficial to promote the process of building energy saving and green development [68, 69]. Many advantages of concrete 3D printing technology have attracted a large number of domestic and foreign scholars to study this field. The continuous improvement of the above research has laid a solid foundation for the development of concrete 3D printing technology. The application of concrete 3D printing technology in practical construction is still in the initial stage. There are many problems such as large limitations of research results, difficult equipment upgrading of construction enterprises, and many influencing factors in the construction process, which restrict the further development of concrete 3D printing technology [70–72]. To solve these problems, the following three measures can be taken to promote the development of concrete 3D printing technology.

*5.1. Equipment.* At present, most of the 3D printing technologies of concrete use concrete mixing device to premix concrete slurry and transport it to the sprinkler head device. The construction of the target component is realized by layer-by-layer superposition of the extruded concrete slurry. The existing sprinkler head device can only achieve a single concrete extrusion function, or as mentioned above, it only focuses on changing the radial size of the extruded concrete slurry or the function of the sprinkler head device in clamping and handling. It does not pay attention to the further processing and strengthening of the extruded concrete slurry itself. The more complex and intelligent sprinkler head device can be designed. Through the combination of scrapers and struts, the printed concrete slurry is scraped and compacted to improve the molding quality of the printed components.

*5.2. Materials.* Although there are many researches on 3D printing concrete and many scholars and institutions have proposed a variety of 3D printing concrete materials, however, in the actual construction process, it is difficult to select the appropriate proportion of concrete for a certain project from many 3D printing concrete materials, which is a complex and arduous work. Therefore, it is necessary to summarize the existing research on printing concrete materials, form the printing concrete material system for different application scenarios, and then summarize the 3D printing concrete materials that can meet the general construction requirements and realize mass production and ready mixing, to minimize the operation steps of the construction site. At the same time, on the basis of the existing research on admixtures, the types of admixtures with better performance are explored and developed, such as more efficient water reducing agent, plasticizer, retarder, and accelerant.

*5.3. Process.* Compared with the traditional concrete pouring technology, the 3D printing technology of concrete eliminates the template engineering and the vibrating molding process in the construction and maintenance process and saves the cost of template and labor, which also puts forward higher requirements for the early strength and setting time of concrete material. At present, the main methods to improve the early strength and setting time of concrete material are still focused on changing the material ratio or adding admixtures in concrete materials. More extensive studies can be made on the interaction between nozzle extrusion speed and printing window time to explore the early strength changes in concrete materials with different printing speeds and printing window time. The support is also crucial in the printing process. The support mode of the existing concrete 3D printing system is mostly provided by the printing material itself. The windows and other structures with suspended parts of the building need to add auxiliary supports during printing, which is a very heavy work in the construction process. More simple and effective support solutions can be explored, and multiple support methods can be used in the printing process of complex structures to ensure the efficient printing process.

## Data Availability

The chart data supporting this systematic review are from previously reported studies and datasets, which have been cited. The processed data are available from the corresponding author.

## Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this study.

## Acknowledgments

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