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Additive manufacturing technology in construction projects

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3D concrete printer
Printing techniques
Simplify3D
Mach3

ABSTRACT

Additive manufacturing, widely known as 3D printing technology, has taken the world by storm, capturing the attention of researchers, engineers, architects, and investors alike. With the ability to transform a mere drawing into a physical object, 3D printing can change the game in various industries. However, the challenge lies in implementing this technology effectively with limited resources. That's where this study comes in - it sheds light on the breakthrough projects produced by a 3D concrete printer. From the iconic university structure to stunning furniture for interior and exterior spaces and even a small-scale village. This study showcases the possibilities of 3D concrete printing technology. By delving into practical techniques such as design, software manuals, slicing model methods, and visual appearance, this study provides valuable insights for anyone interested in this groundbreaking technology. The practical techniques in the printing process related to design, software manuals, slicing model methods, and the visual appearance of a specific model will be discussed.

1. Introduction

The success of rapid industrialization in different parts of the world can be attributed to the automation processes that have enabled faster and more cost-effective production. In this context, it's important to note that the construction industry, despite its unique challenges, is also benefiting from increased automation. This trend is particularly significant as it has the potential to reduce labor and construction time, enhance quality, and minimize environmental impact. However, the concrete construction sector has not experienced the same level of automation as other industrial sectors due to the material's unique properties. The introduction of three-dimensional printing in 1987 as a rapid prototyping method has opened up new possibilities for the industry, and this study aims to shed light on these developments.

Numerous three-dimensional printing techniques are available, but additive manufacturing (AM) remains the fundamental principle. This means that the technology adds material layer by layer, which differs from traditional manufacturing methods that subtract material. It is widely believed that AM and 3D printing have driven a shift in design and fabrication, owing to their unique ability to produce highly customized and geometrically complex products using various materials. This shift in how objects are designed and fabricated presents significant opportunities for the building and construction industry. Industry. There has been a growing trend in recent decades of publications related to the application of 3D printers in the construction industry. This is evident from Figure 1.

Over the past few years, several well-known buildings, bridges, and architectural icons have been constructed using on-site 3D printing technology. This trend has been gaining momentum since 2014 [2], [3], [4], [5], [6]. These accomplishments provide valuable insights into the full potential of 3D printing technology in construction projects. Thanks to automation and software technology advancements, 3D printing has become more effective. Moreover, this technology is considered environmentally sustainable since it can utilize various materials in construction, including recycled materials and zero-waste additives. The process of 3D printing in construction begins with a 3D CAD model of the object, which is saved in ".STL" format. Next, the model is sliced into layers using Simplify3D software, and the sliced model is saved as a “.Gcode” file. Finally, 3D concrete printers use Mach3 software to control the printing of components. Figure 2 illustrates this process presented here above.

Printing components or entire buildings with 3D printers can be achieved using either gantry systems or robot systems, as shown in Figure 3**Error! Reference source not found.**

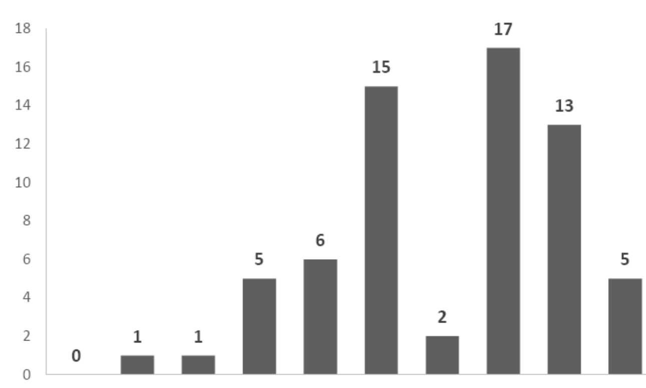

Figure 1. Publication rate of filtered articles on 3DP in architecture [1].

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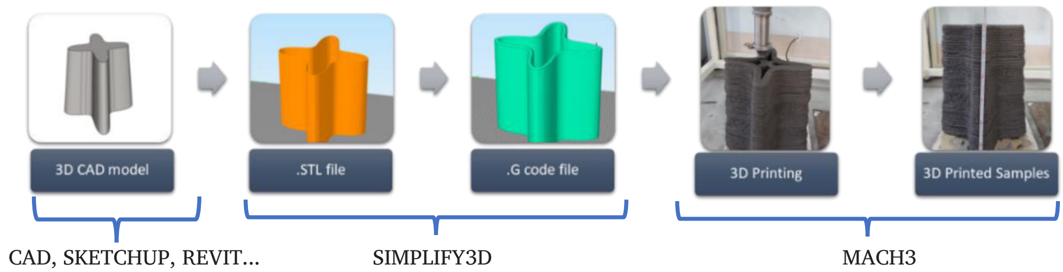


Figure 2. Steps of the printing process [7].

(a) Robot system [8] (b) Gantry system [9]

Figure 3. Types of concrete printers.

Given the constraints of limited printers, technology issues, and budget, the question remains how to effectively utilize and implement 3D concrete printing technology. Therefore, the techniques of additive manufacturing technology will be revealed through highlighted projects produced using 3D concrete printers. The highlighted projects, which include the University icon and exterior furniture, are presented in detail. The practical techniques involved in the printing process, such as design, software manuals, slicing model methods, and the visual appearance of a specific model, will be discussed. Based on the research results, recommendations have been provided that can serve as a reference and guide for applying 3D concrete printing technology in the construction field.

2. Materials and methods

2.1. Materials

For this research, the binder component was formed using ordinary Portland cement (OPC) by Chiffon PC40 and fly ash (FA) by the Haiphong thermal power plant. This combination was chosen due to the success of cement-based materials that many researchers have developed. [10], [11], [12], [13], [14], [15]. Commercially available natural and crushed sand were used in this research. Polypropylene (PP) fibers were added to the concrete mix to reduce shrinkage during the printing and hardening. The main properties of the PP fibers are listed in Table 1.

Table 1. Properties of PP fiber.

Tensile strength	500 MPa
Modulus	6000 MPa
Diameter	35+/-5 μm
Length	12 mm
Specific density	0.910 kg/l

Vis-concrete 3000M, a superplasticizer, was used to adjust the workability of the fresh concrete. Figure 4 presents the materials used for mixing concrete in this research.

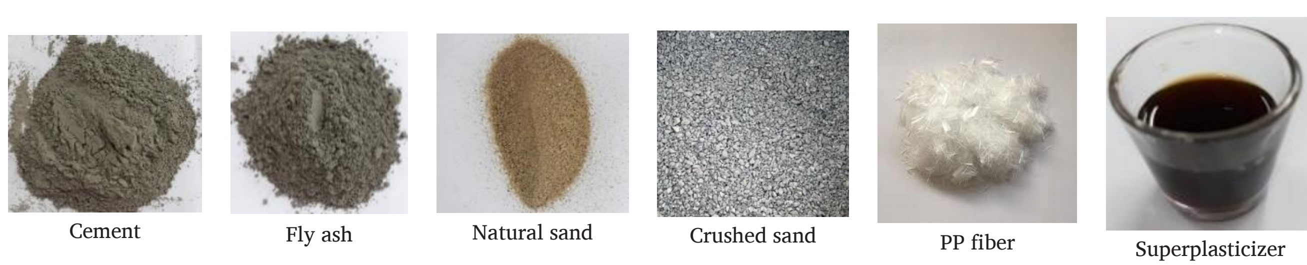


Figure 4. Materials used for mixing concrete.

2.2. Mixture proportions and rheological requirements for printable concrete

The authors of this research highly value practical methods in both the laboratory and on-site, based on the approaches and achievements of previous authors[13], [16], [17], [18]. To that end, the author has proposed a mix proportion design process that uses coefficients and slump value, as shown in Figure 5. This approach is intended to be constructive and to offer a practical mix design solution for 3D concrete printing technology.

The slump height of the concrete cylinder is a crucial factor in assessing the yield stress and buildability of the tested concrete. Therefore, the authors of this research have chosen a cylinder mold with a height and diameter of 80 mm based on the previous research by author [19]. This approach is intended to ensure the testing process is effective and reliable.

The consistency of the concrete cylinder slump measurements, which ranged from 8 to 28 mm, and the lack of deformation after the mold was lifted away, as demonstrated in Figure 6, provide constructive evidence that the concrete has sufficient solid ability. Based on a significant slump test that is shown in **Error! Reference source not found.**, according to the design process presented, many printed products have been successfully performed.

The rheological properties of printable concrete are critical for determining the success of the printing process and are highly dependent on the input printing parameters. The extruded material must be placed in thin layers to minimize the initial gravity-induced stress during the deposition process because the thickness is small compared to the printed object height scale.

For a given layer to be stable after deposition and its shape to be controlled, it is necessary to achieve an adequate yield stress quickly. This initial yield stress must be strong enough to sustain the gravity stresses induced by the deposition process. Figure 8 illustrates the development of yield stress over time.

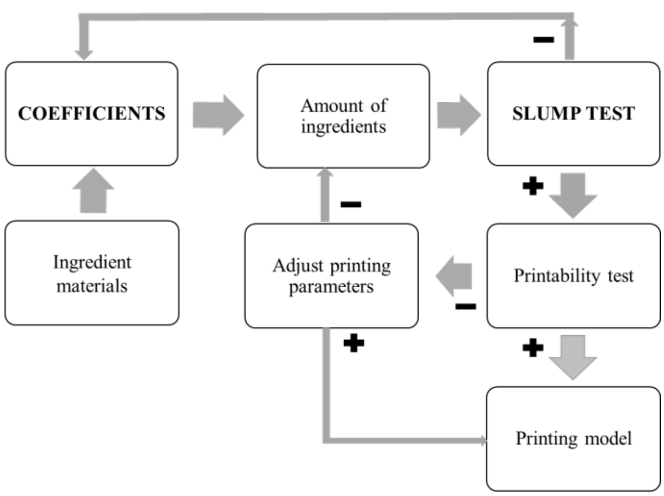


Figure 5. Mix proportion design process.

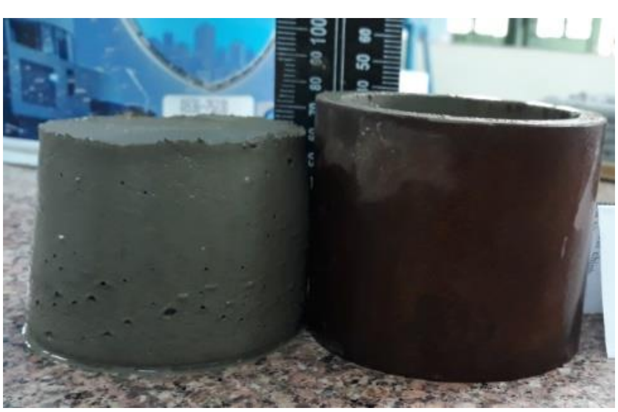


Figure 6. The slump of the sample.

Figure 7. The slump of the sample.

Table 2. Mix proportions.

Project name	Cement	Fly Ash	Water	Natural sand	Crushed sand	PP Fiber (%)	SP (%)
University Icon	1.0	-	0.32	0.5	0.5	0.25	0.4
Furniture	0.5	0.5	0.32	0.5	0.5	0.25	0.4

(Note: Binder = Cement and Fly Ash; values in Table are ratios of each ingredient to binder)

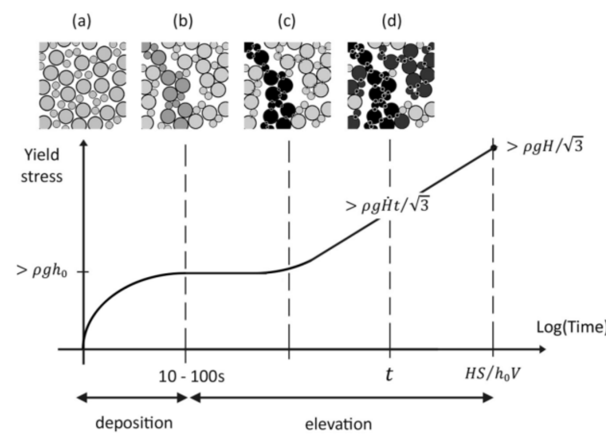


Figure 8. Network(s) of interacting cement particles along with yield stress evolution and target requirements[20].

(Note: h0 is the layer thickness. H is the final object height. S is the contour length. V is the nozzle velocity, and ρ is the printed material density.)

In addition, the critical height H_c, at which self-buckling is anticipated to occur in a slender vertical structure that is subjected only to its weight, can be expressed as follows:

$$H_c \approx \left(\frac{2.E.\delta^2}{3.\rho.g}\right)^{1/3} \quad (1)$$

Where:

E is the material's elastic modulus; ρ is the printed material density; g is gravity acceleration. δ is width filament.

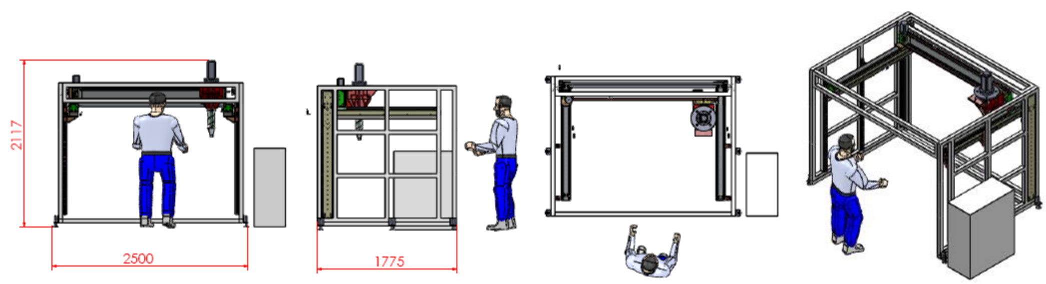
2.3. Concrete printer

Concrete printers are typically designed with either robot-based or gantry-based systems. The choice between these two systems is based on specific requirements, such as the required printing speed, flexibility, and conditions related to the production facility building. The main differences between robot-based and gantry-based 3D printing are primarily due to their distinct approaches to moving along the printed project.

Robotic arm printers are generally more mobile and versatile than gantry printers, and they can print specific designs that gantry printers may struggle with due to their 6-axis movement. However, gantry printers offer cost and stability advantages, and they can produce larger prints, including entire buildings, in one go. Additionally, gantry printers allow for non-continuous printing, which is necessary for printing entire buildings. A robotic arm printer is better suited for experienced operators, typically robot suppliers, who can print single elements with high complexity and detail. Meanwhile, gantry printers are better suited for large-scale projects and 3D printing of entire buildings. In this study, a gantry printer was operatted by author , as shown in Figure 9. The printer measures 2500 x 200 x 1800 mm (length x width x height) and can produce printed samples measuring 1500 x 1200 x 1200 mm (length x width x height). To control this printer, two generations of printers has been created to investigate the extrudability of concrete and Mach 3 software, which are used to control the printer, as shown in Figure 10.

The extruder is the most critical component of the printing equipment because it directly affects the extrudability of the materials. Extrudability refers to transporting fresh concrete to a nozzle with continuous filaments. There are two types of extruders commonly used in 3D printing: ram and screw, as shown in Figure 11. **Error! Reference source not found.** compares some of the main properties of these extruders.

Because of the simplicity of manufacturing the screw extruder, the authors employed a screw extruder for the printers. The extruders are illustrated in **Error! Reference source not found.**.



a) Design and dimension of concrete printer

(b) Overview of concrete printer and mixing/pump system

Figure 9. The concrete printer.

(a) Extruder

b) Small 3D printer

Figure 10. The concrete printer.

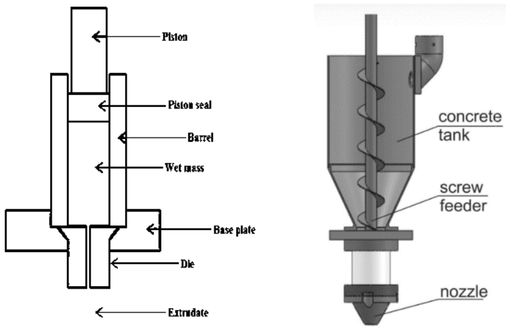


Figure 11. Typical types of extruders: ram and screw [21], [22].

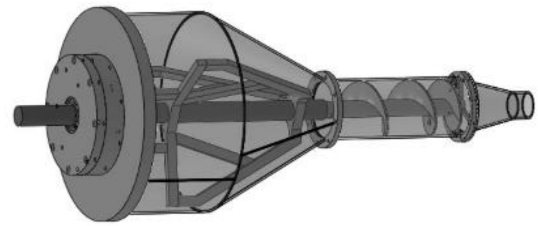


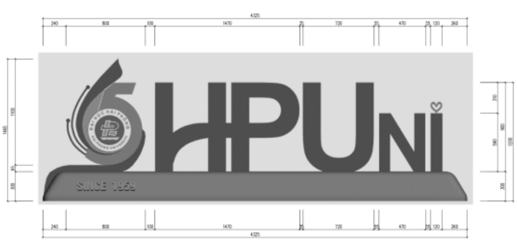
Figure 12. Diagram of extruders.

Table 3. Comparison between ram and screw extruders [23].

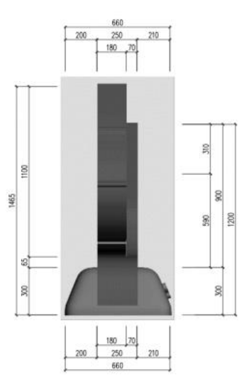
Type	Properties	Requirements for cementitious materials	Applications
Screw	Continuously feed into the extruder—the jamming of larger particles between the barrel of the hopper and the screw.	Homogeneous and high flowability. High thixotropy accelerators.	More suitable with fine aggregates.
Ram	Discontinuously feed into the extruder—jamming problem in the transition region from Barrel to Die.	Greater viscosity, Lower flowability, and higher yield stress.	Suitable for concrete with large aggregates, such as concrete.

2.4. Design model of the Construction projects

This study will present and analyze two highlighted projects as the following contents. The first one is the University icon, designed with a total length of 4325mm, a width of 660mm, and a height of 1465mm. The icon includes six components on the base. The dimensions are in detail, as in Figure 13.



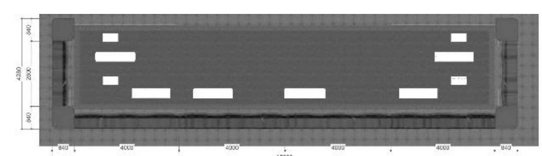
a) Front view



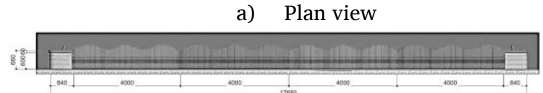
b) Side view

Figure 13. University icon design model.

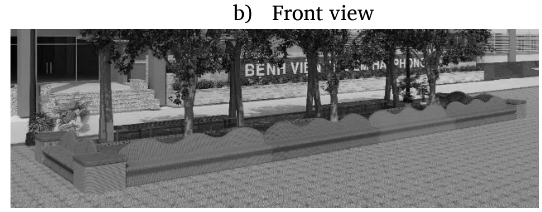
The second one is outside furniture designed for a total length of 26,24m. The benches and tables' dimensions are in detail, as in Figure 14.



a) Plan view



b) Front view



c) Overview

Figure 14. Benches and tables design model.

3. Results and discussion

The designers will consider separating the entire model into components based on the whole designed option. There are some rules to divide a complete model into components that can be successfully printed:

- The printer limits the dimensions of the components.

- In changing slope, the Leaning angle must be considered based on the printing speed and layer height but not exceed 50o as shown in Figure 15 .

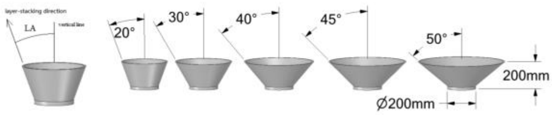


Figure 15. The leaning angle tests. [24]

- The location of the separated surface model should be at the changing slope position.

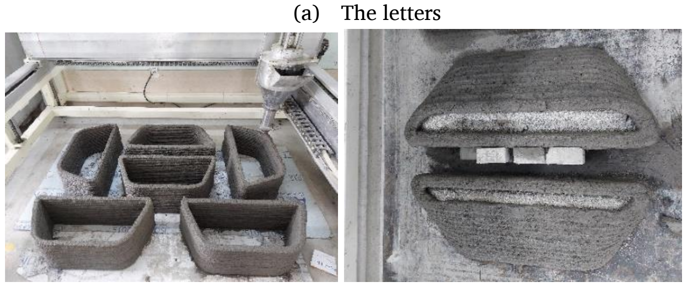
A temporary support method can be used for the complex components, which affects how the whole model is divided.

3.1. The University icon

The printing process is guaranteed according to the steps shown in Figure 2. The components were printed with a 22mm circular nozzle. The height of each print layer is 10mm. The base is divided into eight segments and then assembled with adhesive. The pictures illustrate the printing process, as shown in Figure 16.

After completing the printing, all components were coated with paint according to the designed color. Then, the logo was transported by a specialized crane truck, erection, and connected to the completed icon, as captured in Figure 17.

(a) The letters



(b) The elements of base

Figure 16. Components printing.

Figure 17. Transportation, erection, and completion.

3.1. The Furniture

The printing process is also guaranteed according to the steps shown in Figure 2. The components were printed with an 18mm circular nozzle. The height of each print layer is 10mm. The Figure 18 illustrate the bench components are printing.

Figure 19 illustrate the process from the design pieces through the printing direction to the completed part of the bench components.

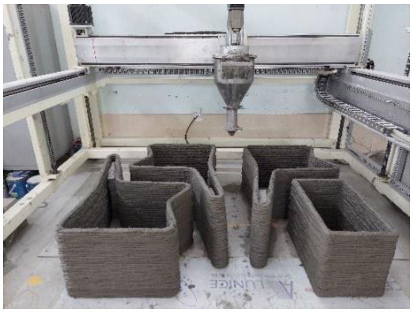
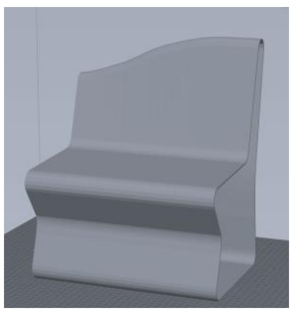
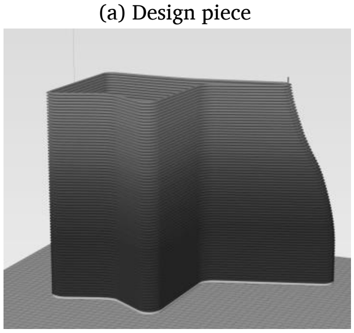


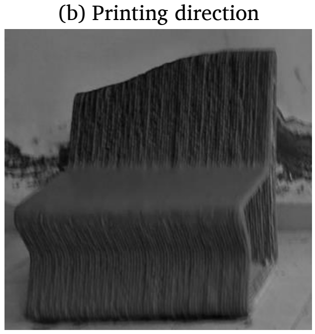
Figure 18. Components printing.



(a) Design piece



(b) Printing direction



(c) Completed piece

Figure 19. Printing technique process with Simplify 3D sofware.

Delivery and erection of the products were done in a few hours, and the finished products brought a fresh new look to the vibrant spaces in Hai Phong Children's Hospital, as shown in Figure 20.

Figure 20. Completed model.

4. Conclusions

Based on the results of the research projects presented herein with the 3D concrete printer at Haiphong University, some conclusions and suggestions are given:

(1) Additive manufacturing, with the employment of Simplify3D and Mach3, effectively slices and prints models, which the authors successfully investigated.

(2) The model's design is free in architecture, but the rules suggested in this research should be considered to guarantee the production quality in appearance and printability.

(3) The techniques revealed through the practical projects illuminated the process of creating a product with a 3D concrete printer, including design routine, division of the whole model into separate pieces, and printing process.

(4) Highlight projects presented in this study to enhance the application of additive manufacturing technology to the practice areas.

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CRediT authorship contribution statement. Author Pham Thi Loan: Methodology, Investigation, Funding acquisition, Formal analysis.

Declaration of competing interest. The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1]. M. Žujović, R. Obradović, I. Rakonjac, and J. Milošević, “3D Printing Technologies in Architectural Design and Construction: A Systematic Literature Review,” *Buildings*, vol. 12, no. 9, 2022, doi: 10.3390/buildings12091319.

[2]. L. Stinson, “World’s largest 3D-printed building completed in Dubai.” [Online]. Available: https://archive.curbed.com/2019/12/30/21035765/world-largest-3d-printed-building-dubai-apis-cor

[3]. L. Alter, “3D printed house displayed at Milan Design Week.” [Online]. Available: https://www.treehugger.com/green-architecture/3d-printed-house-displayed-milan-design-week.html

[4]. 3dsourced, “ICON & New Story 3D Printed House in Austin, Texas USA.” [Online]. Available: https://3dsourced.com/guides/3d-printed-house-

2/#4_ICON

[5]. S. Sarah, “Robotic 3D Printed Yhnova House Officially Inaugurated, Tenants to Move In Soon,” 3DR holdings. Accessed: Jun. 24, 2022. [Online]. Available: https://3dprint.com/207936/3d-printed-yhnova-house-done/

[6]. A. Frearson, “Chinese company 3D prints 10 buildings in a day using construction waste.” [Online]. Available: https://www.dezeen.com/2014/04/24/chinese-company-3d-prints-buildings-construction-waste/

[7]. T. L. Pham, D. T. Trinh, T. H. T. Nguyen, T. Q. Do, and P. A. Nguyen, “Study on flexural behaviour of printed concrete wide beams using polypropylene fibres,” *Minist. Sci. Technol. Vietnam*, vol. 65, no. 4, pp. 48–53, 2023, doi: 10.31276/vjste.65(4).48-53.

[8]. L. Grozdanic, “Giant robots are building a futuristic house in Switzerland.” [Online]. Available: https://inhabitat.com/giant-robots-and-3d-printers-are-building-a-futuristic-house-in-switzerland/

[9]. Cobod, “Cobod Products.” [Online]. Available: https://cobod.com/

[10]. B. Zhu, J. Pan, B. Nematollahi, Z. Zhou, Y. Zhang, and J. Sanjayan, “Development of 3D printable engineered cementitious composites with ultra-high tensile ductility for digital construction,” *Mater. Des.*, vol. 181, p. 108088, 2019, doi: 10.1016/j.matdes.2019.108088.

[11]. Y. Weng, M. Li, M. J. Tan, and S. Qian, “Design 3D printing cementitious materials via Fuller Thompson theory and Marson-Percy model,” *Constr. Build. Mater.*, vol. 163, pp. 600–610, 2018, doi: 10.1016/j.conbuildmat.2017.12.112.

[12]. K. Manikandan, K. Wi, X. Zhang, K. Wang, and H. Qin, “Characterizing cement mixtures for concrete 3D printing,” *Manuf. Lett.*, vol. 24, pp. 33–37, 2020, doi: 10.1016/j.mfglet.2020.03.002.

[13]. A. Kazemian, X. Yuan, E. Cochran, and B. Khoshnevis, “Cementitious materials for construction-scale 3D printing: Laboratory testing of fresh printing mixture,” *Constr. Build. Mater.*, vol. 145, pp. 639–647, Aug. 2017, doi: 10.1016/j.conbuildmat.2017.04.015.

[14]. F. Hamidi and F. Aslani, “Additive manufacturing of cementitious composites : Materials , methods , potentials , and challenges,” *Constr. Build. Mater.*, vol. 218, pp. 582–609, 2019, doi: 10.1016/j.conbuildmat.2019.05.140.

[15]. B. Lu *et al.*, “A systematical review of 3D printable cementitious materials,” *Constr. Build. Mater.*, vol. 207, pp. 477–490, 2019, doi: 10.1016/j.conbuildmat.2019.02.144.

[16]. Y. Wei, D. Tay, Y. Qian, and M. J. Tan, “Printability region for 3D concrete printing using slump and slump flow test,” *Compos. Part B*, vol. 174, no. May, p. 106968, 2019, doi: 10.1016/j.compositesb.2019.106968.

[17]. A. V. Rahul, M. Santhanam, H. Meena, and Z. Ghani, “3D printable concrete: Mixture design and test methods,” *Cem. Concr. Compos.*, vol. 97, no. March 2018, pp. 13–23, 2019, doi: 10.1016/j.cemconcomp.2018.12.014.

[18]. Z. Liu, M. Li, Y. Weng, T. N. Wong, and M. J. Tan, “Mixture Design Approach to optimize the rheological properties of the material used in 3D cementitious material printing,” *Constr. Build. Mater.*, vol. 198, pp. 245–255, 2019, doi: 10.1016/j.conbuildmat.2018.11.252.

[19]. C. Zhang, Z. Hou, C. Chen, Y. Zhang, V. Mechtcherine, and Z. Sun, “Design of 3D printable concrete based on the relationship between flowability of cement paste and optimum aggregate content,” *Cem. Concr. Compos.*, vol. 104, no. September, p. 103406, 2019, doi: 10.1016/j.cemconcomp.2019.103406.

[20]. N. Roussel, “Rheological requirements for printable concretes,” *Cem. Concr. Res.*, vol. 112, pp. 76–85, Oct. 2018, doi: 10.1016/j.cemconres.2018.04.005.

[21]. A. Essop, “Polish researchers explore automation for 3D printed building,” 3Drintingindustry.com. Accessed: Jun. 24, 2022. [Online]. Available: https://3dprintingindustry.com/news/polish-researchers-explore-automation-for-3d-printed-building-170796/

[22]. S. Muley, T. Nandgude, and S. Poddar, “Extrusion–spheronization a promising pelletization technique: In-depth review,” *Asian J. Pharm. Sci.*, vol. 11, no. 6, pp. 684–699, Dec. 2016, doi: 10.1016/j.ajps.2016.08.001.

[23]. S. Hou, Z. Duan, J. Xiao, and J. Ye, “A review of 3D printed concrete: Performance requirements, testing measurements and mix design,” *Constr. Build. Mater.*, no. xxxx, p. 121745, 2020, doi: 10.1016/j.conbuildmat.2020.121745.

[24]. H. Cui, Y. Li, X. Cao, M. Huang, W. Tang, and Z. Li, “Experimental Study of 3D Concrete Printing Configurations Based on the Buildability Evaluation,” *Appl. Sci.*, vol. 12, no. 6, p. 2939, Mar. 2022, doi: 10.3390/app12062939.