Integration of 3D Concrete Printing in the construction industry: a short review

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Abstract. Over the past decade 3D printing technology has completely changed the face of manufacturing industry. However, the full potential of this paradigm-shifting technology has not been fully seen yet. When used in large scale, 3D printing can have many applications in the construction industry. The perceived benefits of such implementation primarily include the ease of construction, as formworks are not required, which can consequently lead to smaller construction times, greater flexibility for complex designs and potentially reduced waste. Upon discussing the main benefits, applications of 3D printed concrete structures are presented and the printing process is briefly reviewed. To allow for cost and time efficiency and sufficient printing quality, past research has focused on concrete's workability and mechanical properties. Reported data from recent experimental studies on 3D printed concrete materials are collated and results in terms of mix proportion design, compressive strength, speed rate are discussed. Finally, the potential of future applications is summarised.

Keywords: 3D printed concrete, applications, compressive strength, print speed

1. INTRODUCTION

Construction is progressing towards digitalization and automation, significant examples are the integration of CAD (Computer Aided Design) and BIM (Building Information Modelling) in the industry. 3D printing in construction could automate many of the building processes and potentially have a great impact in many fronts. One of the main benefits of the 3D printing process is that it can allow more freedom in design and more complex optimised designs to be formed. In traditional construction, construction time and waste are affected by the complexity of the structural formwork, whilst this becomes simpler and more efficient through the 3D printing process. The ease of buildability can then lead to reduction of the construction waste (up to 30–60%), the labour cost (up to 50–80%) and the construction time (up to 50–70%) [1].

On the other hand, among present limitations of 3D printing process in the construction sector are the challenges of integrating reinforcement in the printed structures, the lack of standardised regulations and design procedures as well as the potential high initial costs related to the initial development of digital models via specialised personnel. Despite the aforementioned challenges and with focus on the benefits of automation in the construction process, numerous applications have been realised over the last few years. Figure 1 presents examples of recent applications across the globe.

Structure	Country	Year	Reference
3D Printed Yvona House	France	2017	[2]
Military 3D Printed Concrete barracks	USA	2018	[3]
3D Printed House	Milan	2018	[4]
3D Printed Bus Hub	China	2018	[5]
3D Printed Concrete Bridge	China	2019	[6]
3D Printed Dubai Municipality	UAE	2019	[7]
3D Printed House	Czech Republic	2020	[8]
3D Printed Residential Building	Germany	2021	[9]
3D Printed House	Netherlands	2021	[10]

Figure 1. Examples of recent 3D concrete printed applications in the built environment (left); 3D printing facility (right).

In Europe, a 95 m² house with curved walls and corners was completed in 2017 in France using a patented 3D printing method called BatiPrint3, developed by researchers from the University of Nantes [2]. An industrial robot was used to build two layers of expansive foam serving as formwork for a third layer of concrete. Another 100 m² house topped with a roof terrace, made from recycled concrete and printed with a mobile robot was presented in Milan a year later [4]. In Czech Republic, an experimental 3D printed house was built within 22 hours with a lifetime period of 100 years, with the contractors claiming that they could save up to 50% of costs and 7 times of construction time compared to conventional passive houses [8]. Recently, a commercially available BOD2 construction printer was used in Germany, passing the strict German building code regulations and achieving the first 3D printed three-story residential building in Europe [10]. In Eindhoven, the Netherlands, a Dutch couple became in 2021 Europe's first inhabitants of a 3D-printed house, made from 24 concrete elements printed layer by layer. Further to houses, applications in China include a pedestrian bridge printed from composite materials, containing polyethylene fibre concrete, which successfully integrated digital design, cost efficiency, smart technology and architectural dynamism [6], but also the first 3D printed bus stations printed with renewable materials from construction waste [5]. In UAE, a two-storey administrative building was printed for the Dubai Municipality and only 3 workers and the machine were required to build the concrete walls of the whole building [7]. Among other projects in USA are concrete barracks printed in an army base in less than two days [3]. Finally, Figure 1 (right) shows a concrete printer facility used to build a two-storey house in Belgium by Kamp C. This was claimed to be the largest 3D concrete printer in Europe and the two-storey house was completed in just three weeks [11].

2. 3D PRINTING CONCRETE PROCESS

3D printing is the process of creating a physical object based on a computer-generated model by reposing certain material, unlike common manufacturing techniques where material is removed from a block of a certain material (i.e., milling). There are different types of 3D printing, but the most common and the one that can be used in construction is FDM (Fused Deposition Modelling). The process of FDM include different stages; first the desired object is modelled using CAD software and then the digital model is sliced into multiple digital layers using appropriate software, taking into account the specifications of the 3D printer [12]. The digital model containing the layers is uploaded on the printer, which then moves the extrusion head to specified coordinates, laying down the material layer by layer until the object is formed. The main steps of 3D printing are summarised in Figure 2.

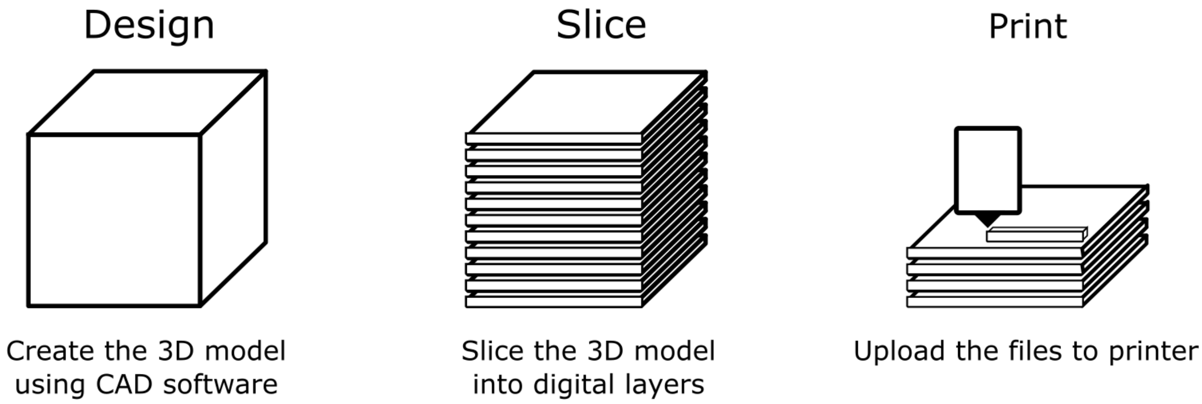

Figure 2. Main stages of 3D printing, based on FDM.

The 3D printing in construction, is based on the same principles as discussed, but it includes some unique features. First of all, there are three different types of 3D printers that can be used in such applications: gantry, crane or robotic. Gantry and crane printers are scalable, and therefore can be utilised for large projects, unlike the robotic ones that cannot scale up as easily. However, robotic printers can perform more complex tasks due to the more degrees of freedom than the other two types. The material used in 3D printing for construction is concrete, since it is one of the most commonly used materials in this industry. Therefore, in order to have the concrete ready, a mixer is essential and in order to feed the concrete from the mixer to the 3D printer a pump is needed. The end part of the printer head is the nozzle that should remain tangent to the tool path and develops the desired shape and size of the layer.

3. 3D PRINTED CONCRETE PROPERTIES BASED ON COLLATED DATA

3D printing of concrete elements includes a series of physical and process requirements that need to be satisfied in both the fresh and the hardened state. The printed material needs to be pumped appropriately, to be flowable enough, but at the same time to allow layer-by-layer printing immediately after extrusion. The print speed needs to ensure good bond strength between the layers without sacrificing cost efficiency. Hence, the selection of the raw materials and the mix influences the process parameters but also the mechanical strength in the hardened state. To this end, numerous experimental investigations have been carried out over the last years in order to optimise the mix proportion, but also to assess the mechanical performance of the printed samples.

Almost a decade ago, Le et al. [13] examined high-performance fibre-reinforced fine aggregate concrete extruded through a 9 mm nozzle and experimentally evaluated the effect of the mix design and admixtures on the mechanical properties. The optimum mix was found to have sand/binder ratio equal to 3:2 and water/binder (W/B) ratio equal to 0.26 together with a superplasticiser and retarder. They also built a large-scale component to assess the feasibility of 3D printed concrete structures. Aiming to maximise the compressive strength (i.e., by minimizing the water/binder ratio), whilst at the same time allowing for appropriate water content to ensure concrete's buildability, Malaeb et al. [14] reported an experimental study on 3D concrete samples. They studied the effect of the mix ratio on extrudability, flowability, buildability, compressive strength, and open time. It was recommended that a minimum W/B of 0.39 and a minimum nozzle of 20 mm would be needed to allow extrudability and prevent segregation. In [15], an experimental programme was carried out to investigate the mechanical properties of 3D printed concrete reinforced with carbon, glass and basalt fibres. The flexural strength of the tested samples was in the range of 10-30 MPa, depending on reinforcement fibre type and print path, whereas density and porosity tests were also performed. Further to mechanical properties, authors in [16] examined the rheological behaviour (torque at different applied rotation and shear stress vs shear rate) of the samples in order to optimise the mix. With respect to the mechanical properties, it was proved that they are influenced by the printing direction and additional printing parameters (such as shape and nozzle orifice and complexity of the printed structure). The importance of the design and geometry on the nozzle mouth and its effect on the interface bond between concrete layers is analysed in [17]. This study was part of real-life application bridge in the Netherlands which, due to the lack of standard codes, was based on the concept "design by testing". Following a comprehensive rheological analysis to optimise the buildability, Weng et al. [18] studied both small-scale samples for materials characterisation, but also successfully produced from the same cementitious material a larger scale hollow column with a height of 800 mm. Experimental results of compressive and flexural strength of fine-grained printed concrete are also reported in [19] and are comparatively analysed with casted ones from the same mix, demonstrating promising material for large-scale implementation. The mechanical properties of printed concrete were also experimentally examined by [20], demonstrating once again the dependence of the mechanical performance by bonding behaviour between the printed interlayers. It was also examined the possibility of applying metal lath reinforcement to enhance the tensile behaviour.

Table 1 summarises the basic parameters of indicative collated research studies on 3D printed concrete samples [13-20], including information for the prepared mix, the implemented nozzle diameter, the sample size and the type of testing performed at each study. Figure 3 summarises the 28 days compressive strength from the collated data, along with the print speeds.

Table 1. Basic parameters of collated data on 3D printed concrete samples.

Authors	**Information for the (optmimum) mix**	**Nozzle**	**Sample size**	**Tests**
(Le et al., 2012) [13]	<u>*High-performance fibre-reinforced fine-aggregate Concrete:*</u> 3:2 sand/binder ratio plus 1.2 kg/m^3 of 12/0.18 mm length/diameter fibres with W/B: 0.26 together with a superplasticiser and retarder of 1 and 0.5% by weight of binder.	9 mm	100 mm cubes	Extrudability, Workability, Open Time, Buildability, Compressive Strength
(Malaeb et al., 2015) [14]	<u>*Cement Concrete:*</u> 125 g of cement, 80 g sand, and 160 g fine aggregates with W/B: 0.39 and1 mL accelerator and 0.625 mL retarder	20 mm	50 mm cubes	Flowability, Extrudability, Buildability, Open Time, Compressive Strength
(Hambach et al., 2017) [15]	<u>*Fibre-reinforced Portland cement paste*</u> W/B: 0.3 with 0.3 % by weight of hydration inhibitor	2 mm	18 mm cube 60×12×6 mm prisms	Compressive Strength, Flexural Strength, Density, Porosity
(Paul et al., 2018) [16]	<u>*Cementitious materials:*</u> Optimised mix ratios based on slump test	8 mm (mortar) 10×20 mm (geopolymer)	50 mm cubes 160×40×40 prisms	Compressive Strength, Flexural Strength, Workability, Rheological Behaviour
(Saleta et al., 2018) [17]	<u>*Cementitious materials*</u>	30 mm (for the scaled test)	40 mm cubes	Compressive Strength, Direct tensile test, Creep/shrinkage test
(Weng et al., 2018) [18]	OPC: Sand: Water: Fly Ash: Silica Fume:	30×15 mm (for the prisms)	50 mm cubes 350×300×30 prisms	Compressive Strength, Flexural Strength,

	Superplastizier= 1:0.5:0.3:1:0.1:1.3 (g/L) (weight proportion of cement content)			Rheological characterization,
(Nerella et al., 2019) [19]	*Fine-grained concrete*		40 mm cubes 160×30×30 prisms	Compressive Strength, Flexural Strength
(Joh et al., 2020) [20]	*Concrete (binder: cement, fly ash, silica fume)* Water/Binder ratio: 0.29 with 8.27 kg/m^3 of high-performance water-reducing agent and 1.65 kg/m^3 of viscosity Agent	40 mm	40 mm cubes, 160×40×40 prisms	Compressive Strength, Flexural Strength, Splitting Tensile Strength

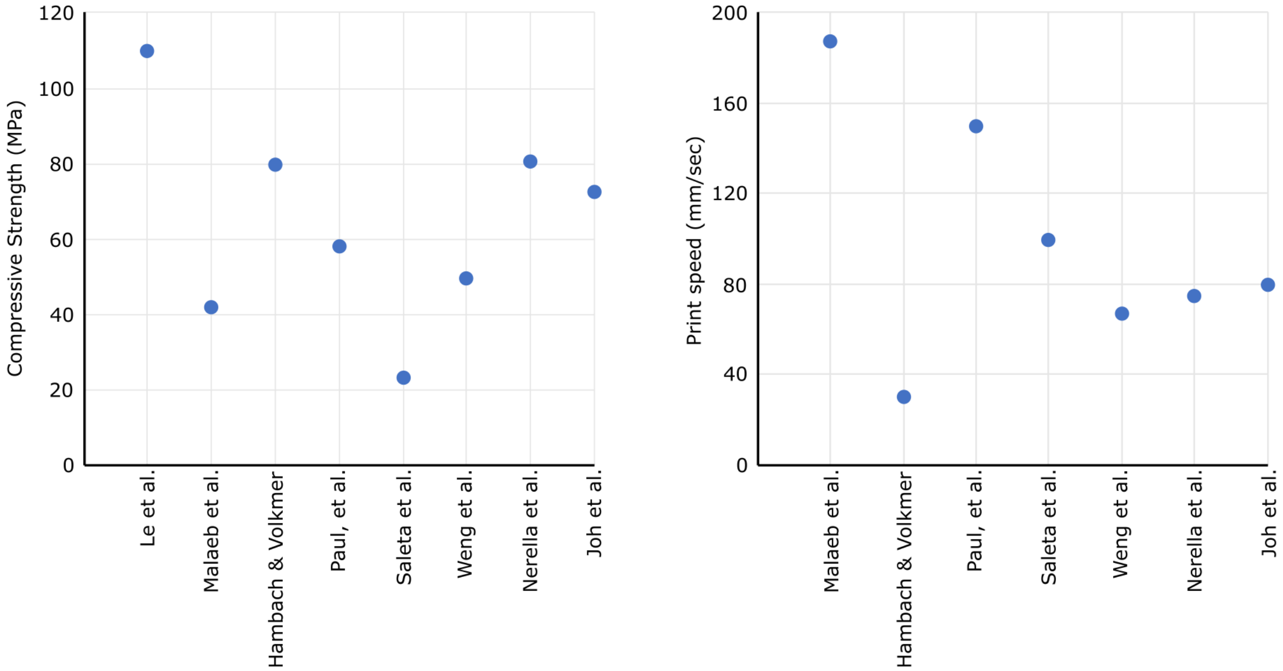

Figure 3: Maximum compressive strength at 28 days of 3D printed concrete (left); Print speed of 3D printed concrete based on collated data (right).

Note that the highest recorded value of the compressive strength was for fibre reinforced concrete, while based on the mix, a range of strengths (42 MPa-110 MPa) have been achieved, as with conventional concrete. The experimental print speed also varied over a range of 30-188 mm/sec, which is another parameter that needs careful consideration, as it affects the efficiency of 3D printing as a construction method.

It is apparent from all the different studies presented, that there are many parameters that can influence the 3D concrete printing. Namely these are the flow rate, print speed, nozzle shape and size and most importantly the concrete mix. As it is seen in Table 1, concrete mix used in 3D printing is not the conventional concrete widely used in construction applications. Figure 4 presents a schematic comparison of the 3D printable concrete with conventional concrete. Furthermore, researchers are using different ingredients in concrete (binders, aggregates, chemical admixtures, reinforcement materials) to investigate their impact on the major properties, such as rheology, setting time, pumpability, extrudability and buildability [21].

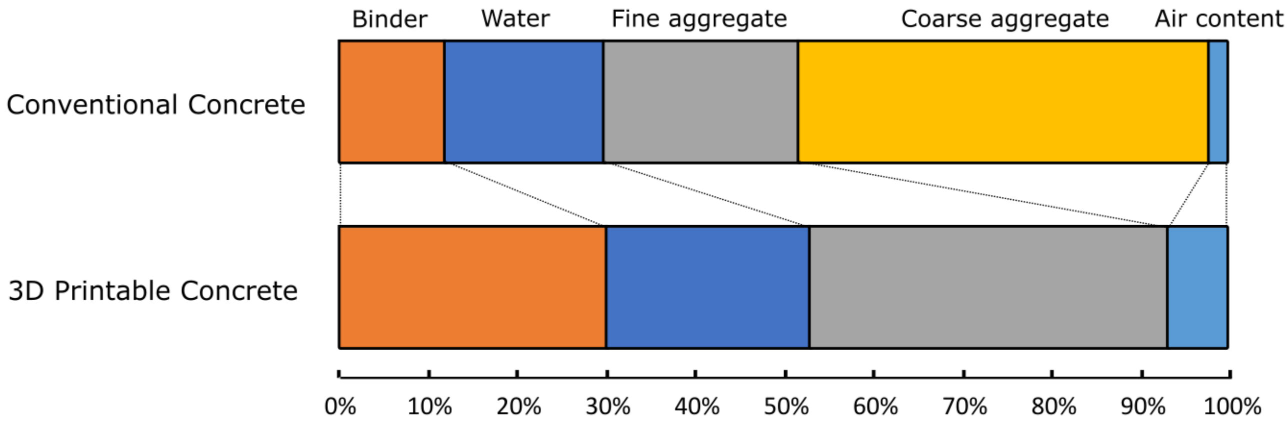

Figure 4. Comparison of volume of materials used in conventional concrete and in 3D printable concrete (adapted from Rehman and Kim, 2021 [21]).

4. SUMMARY

The present paper presented an overview of applications, processes and experimental studies performed for 3D printed concrete structures. To allow for cost efficiency and sufficient printing quality, past research has focused on concrete's workability and mechanical properties, which were mainly optimised via trial-and-error methods. A series of large-scale pilot projects have already been completed across the globe, saving construction time and waste, compared to conventional construction techniques. To achieve a standardised 3D printing process for concrete, more research in different fields (e.g., reinforcement techniques, design codification, material and geometry optimisation) is required. As of now, 3D printing appears a promising construction method, that further to the benefits related to cost and material savings, it can be applied for affordable housing in low-income countries, or even for building in Lunar or Mars utilising in-situ material.

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