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3D-printed concrete: applications, performance, and challenges

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Automatic construction systems have become the focus of the construction industry and research projects worldwide. Numerous technologies involving 3D printing (3DP) of concrete elements have been developed, and their application in construction projects has been growing. The 3DP in concrete construction is increasing due to its freedom in geometry, rapidness, formwork-less printing, low waste generation, eco-friendliness, cost-saving nature, and safety. Development of 3DP is not only limited to the earth but also gaining attention for building habitats in space. This study aims to present the technical, socio-economical, and environmental aspects related to 3DP of concrete structures for a systematic summation of the technology, guidelines, applications, challenges, and prospects of future research and market in the construction industry. This comprehensive review shows that challenges involved in 3D concrete printing should be analyzed further by researchers to enhance mechanical performance, durability, and sustainability and establish appropriate standard guidelines for printing structures.

Keywords: 3D printing; concrete; application; challenges; future market; future research direction

Highlights

- Reviewed recent progress and future opportunities of 3D-printed concrete structures.
- Opportunities of 3D concrete printing are increasing attractively.
- Reinforcing technology needs to be developed for 3D printing.
- Identified research gaps and directed future research on 3D printing of concrete.

1. Introduction

Additive manufacturing (AM) is a modern innovation, which has been developed and standardized to print any large and complex structure through a rapid prototyping system with good mechanical properties [1]. This technology can build three-dimensional (3D) objects by connecting layers of materials and can be applied to convert waste and by-products into new materials [2]. 3D printing (3DP) is an automated AM process of fabricating 3D objects from

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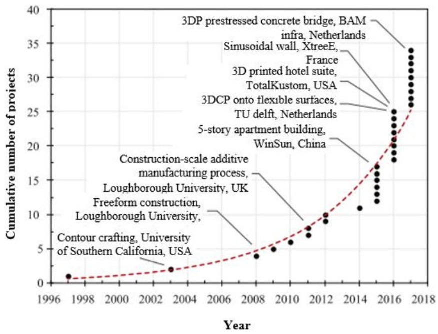


Figure 1. Development of large-scale 3DP for application in the construction sector [9].

computer-aided design models; the 3D models are divided into several 2D layers and deposited using suitable printers to construct the designed objects [3]. 3DP has achieved increased traction in different sectors, such as military, aerospace, and biomedicine and is currently regarded as a worthwhile manufacturing method in the construction sector [4,5].

Several technologies have been developed for 3DP, and fused deposition and powder bed fusion are the most commonly used methods in the construction sector [6–8]. The most revolutionary use of this technology in concrete construction began in 2014; before this time, inventions of different parts and technologies were still under development, and only a few projects were completed [9]. The development of increasing numbers of 3DP projects in the construction industry was presented by Buswell et al. [9] and is shown in Figure 1. This revolutionary development of printing projects is expected to increase rapidly because of the unique characteristics of 3DP. The AM technique is considered the most suitable method for construction because of its high recycling rate, and low waste production, and less materials consumption [2,10,11]. The cost sustainability of 3D-printed concrete (3DPC) structures is still under research. A study reported that the cost for printing a house with an area of approximately 200 m^2 is around \$4800, which is realistically more economical than the costs of traditionally constructed structures in China [12].

However, 3DP technology requires precise solutions for elements in conjunction with several parameters, such as project scale, selection of printing materials, and quality and strength of printed parts [1]. The printability and post-print behavior of elements depend on the properties of materials, printing method, time, temperature, and kinematics [13]. Moreover, the variation in the material composition of the applied techniques and the reinforcement system pose an obstacle [1]. Though there are trending improvement observed in mechanical properties of 3DPC in several researches, the anisotropic characteristics of it limits the prospective application of this technology to the printing of complex and large-scale structures under critical loading and environmental conditions [1,14]. Meanwhile, this automated construction technology eliminates the use of formwork, reduce labor requirement, minimizes the possible fatalities involved in manual operation, accelerates the construction process, and reduces the manual construction defects [4,15,16]. The most convenient feature of 3DP systems is the geometrical freedom in the structural plan and shape of members [10,17–19]. 3DP techniques allow assorted geometries, can be used to print hierarchical structures, and provide efficient materials for strong structures [20].

Several recent studies have investigated the potential of using 3DP in concrete components, but these studies are fragmented [1,4,14]. Although the previous researchers have reviewed the current progress of development of printing materials, printers and printing system [4,10,14,21], the reinforcing technology, structural performance, and challenges of 3DPC has not been extensively reviewed and updated with the current development. Some of the researchers captured several materials in their study to elaborate the application of AM [1,12]. An up-to-date critical review simultaneously representing the material selection, reinforcing technology, applications, performance and challenges, present market and future potential related to 3DP of concrete structures is therefore necessary to reveal the recent potential development. This study therefore aimed to review the application, performance, challenges, present and future market potential of the 3D-printed concrete in relation to construction systems. The details that should be considered in the selection of materials and methods are analyzed. The technical guidelines and approaches that are available and required when using 3DPC construction are also summarized. This review contributes to literature by gathering the overall aspects and critical issues related to 3DPC construction systems simultaneously. The outcome of this study will guide prospective researchers and end users regarding the application of 3DPC.

2. Manufacturing of 3DPC

2.1. Methods

The two main methods adopted in AM technology in the construction sector are extrusion-based layering (selective material deposition by extrusion) and powder-bed methods (selective binding) [6–8,22]. The extrusion-based layering have the resemblance with fused deposition modeling (FDM), where mixtures of selected materials are deposited layer by layer *via* an extrusion print head in accordance with a command given by computer-aided design tools to the crane, robot, or gantry of a 3D printer with six- or four-axis arms [4,7,10,23]. Most powder-based technologies are offsite methods that may be assembled on-site and are suitable for large and complex geometrical structural printing followed the method of stereolithography [24].

2.1.1. Extrusion-based layering

Contour crafting, concrete printing, and CONPrint3D are extrusion-based layering techniques, which can be applied in printing of concrete structures with cementitious materials, aggregates, and fiber reinforcements [4,15,17,25–27]. In general, concrete printing and contour crafting, which make up a similar technique called inkjet printing, and the materials mixture extruded through nozzles to produce vertical members [4,6,10,15,24,28,29].

Contour crafting is a gantry-based, fully onsite technology that was developed by Dr. Behrokh Khoshnevis from the University of Southern California [21,27,30]. This printing process is based on vertical extrusion of layers, where the layers can be strengthened using reinforcement ties manually [4,10]. A contour crafting machine has a wide printing zone with a $5\,\mathrm{m} \times 8\,\mathrm{m} \times 3\,\mathrm{m}$ work envelope [27]. This printing system offers good surface quality, rapid construction, and various materials [21]. Generally, concrete filaments that are 2–5 cm wide and 1–3 cm high are printed with this method [29].

Concrete printing was developed at Loughborough University, use a $4\,\mathrm{m} \times 1.6\,\mathrm{m} \times 1.5\,\mathrm{m}$ dimension printer developed by Apis Cor Company for an approximately $132\,\mathrm{m}^2$ wide printing zone [27]. High performance coarse-aggregate concrete and fiber reinforced concrete can be used in this method which resulting in a good mechanical performance of printed elements [10,31–33]. Up to 9.5 mm sized coarse aggregates and C30 concrete were reported to use in printing concrete mixture in the study of Rushing et al. [32,33]. Contour crafting and concrete printing techniques only limited to vertical extrusion and require initial formwork, therefore, complexity may arise depending on the geometry of structure to be printed along with the problem of hydrostatic pressure control and requires extra maintenance and operations [7]. Concrete onsite 3DP is also called CONPrint3D, which is the most appropriate technique of concrete printing developed in TU Dresden (Germany). In

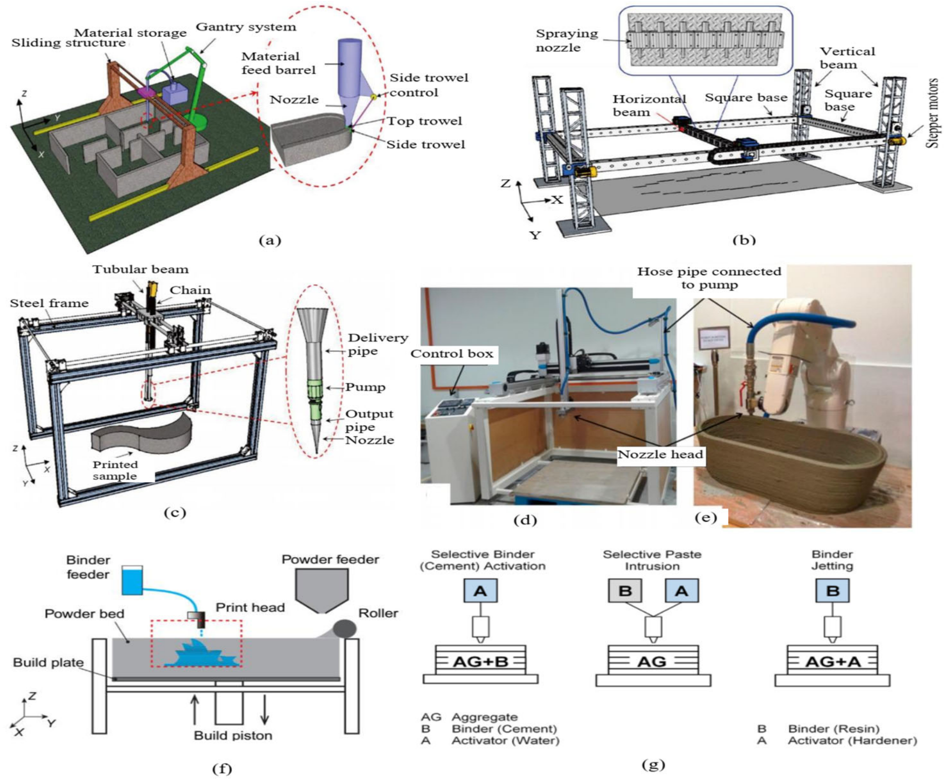


Figure 2. Typical printing system and components of printers: (a) contour crafting, (b) D shape, (c) concrete printing, (d) four-axis gantry, (e) six-axis robotic printer, (f, g) details of powder-bed method [11,21,30,39].

this method, the size of aggregates used in concrete can be larger than those used while adopting concrete printing and contour crafting method [10]. Typical arrangements for several concrete printing systems are shown in Figure 2.

2.1.2. *Powder-bed methods*

In particle-bed 3DP system, printing can perform directly by using cementitious materials or filling of the printed polymer-based formwork with conventional fresh concrete as well as extrusion-based technique [11]. The concept of selective deposition of cementitious composites was proposed by Dr. Pegna [34]. In this process, free-form construction of hollow element is done by placing a matrix layer of sand selectively covered by cement as a reactive agent, which is activated using water vapor. The particle-bed printing system can be explained by three techniques depending on the binder application technique as shown in Figure 2(g).

D-shape technique is a powder-bed method of printing, where granular powdered materials (sand-based) are deposited and bonded by cementitious materials layer by layer which was developed by Engineer Enrico Dini [8,15,21,35,36]. This process is fast and requires no external support even when printing overhanging parts [37]. All unbonded powder act as temporary support to the printed layers. The major challenge in this method is the removal of unbound powder and provision of reinforcing system [18].

Emerging object is another technique of powder-bed printing method, which was

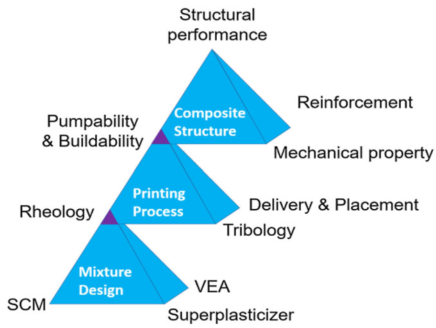


Figure 3. Multilevel design for 3DP material [14].

developed by Ronald and San Fratello [38]. In this method, a dry cement-bed was activated with the help of water and polymer. In all powder-bed method, a technique of drop-on-demand was applied for dropping binder solution on the bed of powder. Therefore, a non-continuous system was arisen, which need to control carefully.

2.2. *Material selection approach*

2.2.1. Extrusion-based cementitious printing materials

3DP materials should be thixotropic to ensure their pumpability, extrudability, and buildability within the allowed time [40–43]. Thixotropy is an indication of the ability to viscosity recovery and represents the rheology before and after extrusion. A multilevel material design approach observed in the study of Lu et al. [14], where the parameters relating to the material design to printed structures are interrelated as shown in Figure 3. Static and dynamic yield stress and viscosity which are known as rheological properties of cementitious mixtures depend largely on the water content, aggregate properties, gradation, mixing time, mixing system, and temperature [13,26,44]. Because these parameters are controlling the flocculation of particles and hydration reaction in mixture, consequently the rheology of the mixture [45]. The high yield stress and low plastic viscosity of mixture should be

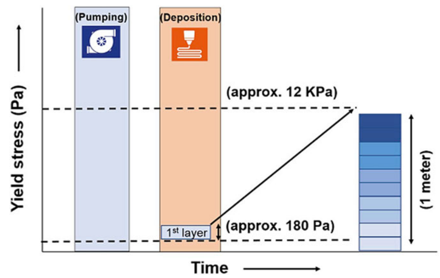


Figure 4. Typical variation in bottom layer yield strength with build height [45].

maintained as much as possible to ensure buildability and pumpability respectively, which generally depend on the technology used, pumping distance, size of nozzles, and compositions of mixtures [34,42,44]. The initial yield stress of an extruded layer depends on the density, gravity and extruded layer height, where the development of yield strength with time and successive layer deposition was shown in Figure 4 [45]. Initially, around 180–1000 Pa yield strength is required in extruded single layer for stability and the bottom layer should have approximately 12 kPa yield strength to support 1 m extruded layer upon it.

High-performance cement-based materials are inappropriate in rheological and stiffening properties, consequently are not thixotropic in nature [46]. Thixotropic materials should have 10–15 min of open time to provide sufficient extrudability and buildability; meanwhile, typical mixtures for concrete printing should have an open time of around 15–30 min [47]. Selection of open time varies with the scale of printing construction and printing speed, but need to control and specifies during mix design

Additionally, the special requirement of cement mixtures that should have zero slumps and a self-compacting ability are opposing but have to be present simultaneously for 3DP purposes [13,48,49]. A zero-slump concrete mix has high yield stress immediately after deposition; therefore, the layer does not deform

[13,18,42,49]. Study revealed that printable concrete mixture with slump value around 4–8 mm and slump flow between 150 mm and 190 mm give smooth surface after extrusion and shows good buildability [50]. However, the slump value can be optimized with other parameters such as viscosity and yield stress during materials design. In some cases, initially, a low yield strength and high viscous mixture need to maintain the high plasticity and good workability [31]. However, the possibility of cold joints formation could be increased when a freshly extruded layer has half (or less) of the yield stress of the underlying layer [18]. A high fraction of solid and strong interaction between particles may cause shear localized cracks in a fresh state. Additionally, to overcome the friction due to high rheological parameters a high pressure is needed for pumping and extrusion. However, excessive pressure can cause segregation and resulting loss in homogeneity in printing mixture [14]. This friction can reduce by adding small quantity of coarse materials; and consequently, good deposition and layer intermixing occur, thus reducing the jam and localized shear cracks problem [8]. Additionally, increasing the water–cement ratio exerts a positive impact on extrudability but reduces buildability [51]. Therefore, mixture with high yield strength and required flowability at the fresh state is needed for printing. On the other hand, rapid hardening mixtures are recommended for speedy construction [23]. Superplasticizers are added to release the water trapped inside voids and increase the rheological fluidity of the mix with increasing mechanical strength [21]. But, excessive amount of superplasticizers can show negative effect in buildability [51]. To maintain a proper open time while printing a large number of layers with several filament groups, 1% superplasticizer and 0.5% retarder were recommended primarily [52]. Additionally, the shape of aggregate can be an obstruction to flowability. Aggregates with smooth surface can move easily and increase the fluidity during extrusion. But it needs to be well graded, because the possibility of porosity and lower adhesion in smooth surface aggregate is high. However, an appropriate retarder may require to maintain the extrudability of a mix for long time. Retarder may consist of methylene-phosphonic acid, citric acid and formaldehyde [47]. Triethanolamine can be used for small dosages (up to 0.05%) as cement hydration retarder, can be useful to create a concrete mixture with setting time 20 min [53]. But, high dosages of triethanolamine can accelerate the cement setting. Addition of gypsum with cement can be helpful to control the setting of cement. But the hydration of gypsum with cement hydration has shown a complex behavior. In a previous research, with the replacement of 20%–60% cement by gypsum, the final setting time of the mixture decreased from 20 min to 16 min, and the temperature rose from around 27.72 °C to 31.49 °C; where for 100% gypsum content the final setting time was recorded 30 min [47]. Thus, appropriate retarder or accelerator with optimum content needs to select for perfect setting time of printing mixture.

Selection of materials optimum size depends on method and type of printing, printer types, and printing techniques. Materials used in concrete printing demonstrate high performance and are fiber-reinforced, coarse-aggregate concrete, which is considered superior to the mixture used in contour crafting in terms of strength [10,31]. Additionally, in contour crafting only fine-aggregate concrete or mortar can be used, but the mixture should have a high concentration of powdered materials, inorganic additives (silica fume, fly-ash), and viscosity-modifying admixtures [27]. The maximum size of materials depends on the printer nozzle's size and pumping capacity [49] and should be smaller than 1/10 of the diameter of printer nozzles, which is recommended by Ma et al. [21]. Previous research indicated that the size of the aggregates can go up to 2 mm for a nozzle diameter of 2 cm. The fine aggregate-to-cement and the fine aggregate-to-sand ratios were determined as 1.28 and 2, respectively after several trials [54]. In recent conventional coarse-aggregate concrete is also being used for 3DP, thus maximum size of materials for printing mixture is not limited beyond fine particles.

Cementitious materials that are generally used in 3DP are composed of 12%–16% OPC, 21%–26% silica fume, 25%–30% sand, 33%–35% fly ash, and 2%–4% water; otherwise specified [26,44]. For high-performance fiber-reinforced concrete printing, around 70% OPC, 20% fly ash, 10% silica fume, 3:2 sand/binder ratio, and 0.26 water/binder ratio are recommended [52,55,56]. Water-to-binder ratios in the range of 0.23–0.41 and binder-to-sand ratios in the range of 0.63–0.73 have been used in different studies. Meanwhile, printing materials with specific properties, such as lightweight, thermal insulation, and self-healing and self-sensing capacity, are expected to contribute to complex structures [30]. Silica fume can absorb a large amount of water; therefore, reducing the water content and improve the rheological properties of mixtures [26]. Additionally, micro-crystalline cellulose addition in cement-based printing materials can also enhance the plastic viscosity and yield strength of printing mortar. As reported in the study of Long et al. [57], after addition of 1% microcrystalline cellulose in cement mortar, the yield stress and viscosity of printing mixture get improved by 190% and 209%. There is no cracks observed while printing filament with this high performance mortar; thus shape retention capacity is also increased.

Geopolymers are formed from by-products (fly ash and slag); and are regarded as green cement and possess high mechanical properties, good durability and low carbon emission [10,48]. Though the thixotropic behavior of geopolymers is not as pronounced as that of OPC because of the absence of colloidal reaction between particles, which may be a challenge in using 3DP [55,58]. Another problem associated with geopolymer-based concrete is that hardening starts over time; this may disrupt pumpability and cause an extrusion problem in 3DP due to the discontinuity of flow [48]. Being a shear thinning material, geopolymer concrete loses its viscosity during pumping and cannot regain it immediately after printing. Thus, it cannot provide sufficient support to the upcoming layer printed on it. Preferably, after removal of external pressure, the original viscosity of printed concrete should recover immediately [58]. Reactors are needed to improve the rheology of the mixture. Attapulgite clay and slag [48] can accelerate the buildability of mixtures. The yield stress in geopolymers and OPC increases with time due to the interaction between particles and the chemical alteration of the binder. Inclusion of silica fume and fly ash enhances these properties [55]. Panda et al. [59] developed one-part geopolymer for 3DP by layer extrusion technique which consists of fly-ash and blast furnace slag in varying content with alkaline activator. The developed geopolymer binder can successfully use in extrusion printing system, and it can be regained its 70–80% original viscosity after 60 s of extrusion. However, no significant direct relationship exists among the yield stress, thixotropy, and viscosity properties of 3D printable materials [49]. Therefore, while applying geopolymer-based materials in extrusion layering technique more concern need to maintain the printability and stability of structures.

2.2.2. Powder-based printing material

In powder-bed technique, specially D-shape technology, an aggregate bed was prepared with very high resolution and the cementitious binder in liquid form has been deposited to activate and harden the layer [18]. The aggregate bed can be made of crushed stone, sand, gravel, crushed clay aggregates and ceramics [60]. In D-shape technology, recycled glass, fibers, wooden chips, pieced plastics, rubber, gypsum can be used as aggregate also. Additionally, approximately 0.2–4 mm sized materials are used in this method, and a minimum 5 mm thick layers can be printed [11,60]. Therefore, typically coarse aggregate cannot be used in this technique of concrete printing. Meanwhile, while preparing the aggregate bed for powder-based printing, additional processing is required. Particles greater than 20 μm size should be processed in a dry state, and particles finer than 5 μm can be placed in a dry or wet state in a powder deposition system [6]. In addition, recently a dry cement-powder bed was used to print a free-standing pavilion, which was developed by Rael et al. [61] at UC Berkeley. This dry cement-bed was activated by spraying water in layer by layer and harden over time. The major challenge is the penetration of slurry of binder through the compacted powder bed and maintains the rheology of the binder paste [11]. Though binder intrusion is difficult in this technique of printing, for higher water-cement ratio, higher penetration of binder and higher strength development noticed [11]. The yield strength in printing layer is dependent on the density and height of bed, acceleration due to gravity, and friction between particles. Therefore, all these points need to be optimized in powder-bed technique of printing to maintain the rheology and green strength of printing bed.

The limitations of cement-based printing materials while applying powder-based technique can overcome by using geopolymer-based materials [8], magnesium oxychloride cement (Sorel cement) and fiber-reinforced cement polymer [37]. Uses of slag-based geopolymer with fine sand, which is activated with a silicate-based activator, were proposed by Xia and Sanjayan [62]. This geopolymer has sufficient deposit ability and dimensional accuracy in powder-based printing systems and is scalable to print large structures. Slags contain high amount of silica and are amorphous and pozzolanic in nature, thus they are important for geopolymer; additionally, slag can enhance buildability of printable geopolymer mixture [48]. But the slag used in powder-based printing systems was recommended to be up to 50% of the total binder because the amount of slag beyond optimum level causes a very low green strength, which cannot resist the pressure in the de-powdering process [37,39].

If powder deposition techniques are applied to 3DP, then the agglomeration of fine powder during deposition should be considered because it creates a porous printed layer [62,63]. Additionally, powder density, penetration rate of binder droplet, and activation rate are the major influencing parameters for quality of powder-bed printed part. Gradation of particles in aggregate bed is also important to provide a required density for high compressive strength as well as sufficient permeable pores to penetration of sufficient binder [11]. However, the excessive amount of binder can be the reason for deformation and lowering the dimensional accuracy due to the necessity of longer hardening period. The green strength of the bed should be sufficient to carry the self-weight and ensure the shape stability after activation. For better strength addition of short fibers with particle-bed can be done along the probable high stress zone. However, the fibers must be compatible to the bed of aggregate and binder activator.

Geobeton Company has developed geocement, which consists of powdered geopolymer cement and a liquid geosilicate reagent [60]. This material has high resistance to frost, chemical, and fire attacks and high compressive strength due to the wide range of its setting time [60]. Post-processing is helpful to increase strength and reducing the anisotropy. Generally, recommended process is post-curing in alkaline activators, such as saturated anhydrous sodium metasilicate solution, at a specified temperature [62]. The optimum curing temperature is around 60 °C in 8 M NaOH solution, and this temperature accelerates geopolymerization and condensation, thereby increasing the compressive strength of the printed specimen by 30%–41% [64]. This result cannot be obtained in normal water curing. A special rock printing system is reported in the study of Zhang and Khoshnevis [65], where the system is relatively similar to powder-bed printing technique. In this system, the rock printer brings the concrete particle to the predefined position and binds them together with string, which means the strings acting as the binder in this system. Thus the problem of coarse-aggregate printing in particle-bed system can be solved, when the rock printing technology can apply in cementitious printable particle-bed by proper activator.

Performance of printed elements greatly depends on the selection of an appropriate material. Well-printed concrete generally has fewer voids that are greater than 0.2 mm in size compared with ordinary molded concrete [56]. However, poorly printed concrete has an excessive number of voids. Table 1 shows the suggestions for maintaining the typical properties of printable concrete mixtures to achieve maximum printability within a short period with high precision and mechanical strength. Extrudability and buildability are the critical fresh properties of printing concrete mixtures, and they have communal interactions with the workability and open time of such mixtures [52]. The special practices applied to address the problems that arise during the printing of non-homogenous cementitious materials are listed in Table 1. The typical requirements of additional components in printing mixtures, such as admixture, nanocomposites, and fibers, indicated in previous research are shown in Figure 5 [66]. To build the printed structural component, the requirements of additional reactants and agents should not be ignored.

2.2.3. *Parameters of concrete printing*

Printing parameters, such as printing speed, nozzle opening, standoff distance, temperature need to be controlled and pre-defined, because those are affecting the rheology and post-print behavior of printed concrete elements [4,32,71]. As observed from the review in Table 1, the open time and setting time should be optimized to control the rheology, extrudability, buildability, and shape stability of printing mixture; therefore, printing time gap also needs to be optimized because it relates to these properties. An increasing printing time gap from 15 to 30 min resulting in a reduction in bond strength and caused bond failure between layers [56], which gives similar concept as the conclusion from Wolfs et al. [72].

The adopted printing speed, nozzle opening size and time gap between printing layers are related to each other. Generally for printing purpose round and rectangular nozzles are being reported [34]. For rectangular nozzle of size 40 mm × 10 mm, around 30–35 mm/s speed was adopted in the study of Buswell et al. [9]. Another study reported around 50–66 mm/s nozzle travel speed for a circular nozzle of 9 mm diameter [73]. In recent conceivable printing, speed is around 150 mm/s up to 50 mm high layer, which is being adopted through CONPrint3D printing system [74]. Printing speed should be compatible to the materials properties as well as the size of structure to be printed. Additionally, the complexity of shape of printing layers also controls the time gap, which needs to be considered as well. Though time gap needs to be shortened as possible, for high-speed printing deformability of printed layers may also

Table 1. Typical measures required in printable concrete mixtures.

Parameters	Description	Improvement techniques	Ref.
Flowability	• Directly related to workability of mix • Required to maintain continuous pumping of mixture	• Addition of Actigel and bentonite clay • Addition of superplasticizers around 0.2%–2% • Hydration inhibitor • Addition of an air-entraining agent	[14,20,49,51,52]
Extrudability	• Related to particle size, workability, open time, and setting time of mix • Required to maintain continuous extrusion of printing layers	• Addition of sodium carboxymethyl cellulose (CMC) • Applying the principle of self-compacting concrete • Applying the principle of sprayed concrete	[52,67]
Buildability	• Related to setting time, printing gap, green strength and intra-layer bonding capacity of mix • Ensures the bond strength between extruded layers without deformation	• Increasing the number of adjacent filament layers • Addition of superplasticizers reduces the water demand • Attapulgite nano-clay • Viscosity modifying agent • Low gypsum content in cement	[21,52,66]
Open time	• It is a function of setting time and workability • Indicator to viscosity and yield stress • Need to long enough to ensure sufficient extrudability without negatively affecting the buildability	• Addition of superplasticizers • Addition of a retarder/accelerator when necessary • Inclusion of synthesized polymer of sulfur and black carbon • Addition of sodium tetraborate	[4,21,34,52]
Setting time	• Related to binder properties, mix proportion and additives • Need to adjust with time for printing gap by the help of admixtures • Need to large enough to allow the sufficient extrudability, and have to optimum for developing enough green strength to support upcoming fresh layers	• Addition of blast furnace slag • Polyamide, aluminide, titanium sintered together • Addition of gypsum and lithium hydroxide • Increased dispersion time	[21,47]
Shape stability	• Directly related to open time, buildability and intra-layer bond strength • Ensures the structural appearance and performance after completion of printing and hardening of the whole part	• Addition of silica fume and nano-clay • Addition of short fibers • Curing in an appropriate medium • Attapulgite nano-clay • Viscosity modifying agent	[37,58,66–70]

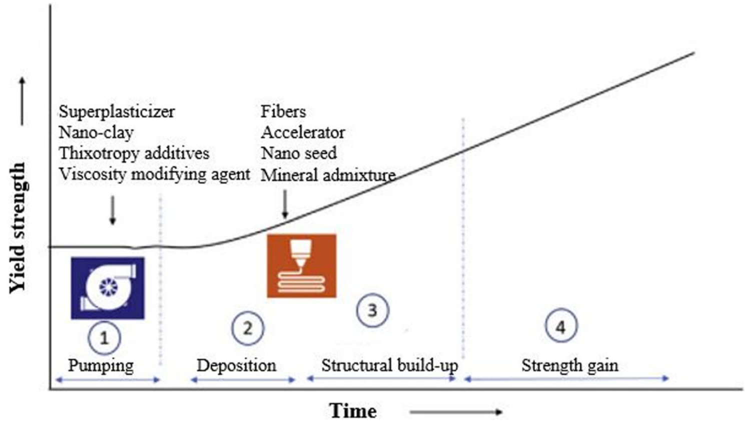


Figure 5. Typical admixture requirement in various stages of 3DPC mixtures [66,69].

occur, which need to handle carefully. After experiment on the printing quality with four distinct nozzle sizes (10–25 mm), Xu et al. [75], recommended around 50–60 mm/s speed for nozzle travel and they also observed best printing quality with 15 mm nozzle opening. For the higher nozzle opening, higher rate of material extrusion occurs, but the surface quality of printed specimen get worsens. On contrary, the number of layers can be lessened by using bigger nozzle diameter, which consequently will minimize the problem of low bond strength between layers, but buildability of thicker layer needs to be ensured. Additionally, for round shape nozzle, the possibility of porosity and void formation along the interface is much higher compared to other shapes [56].

In general, for a higher static yield stress printing mixture, a lower standoff distance is resulting in excellent bond strength between successive extruded layers [71]. As observed from the study of Panda et al. [71], the cementitious printing mixture without nano-clay showed no any significant variation in bond strength when standoff distance varied between 15 mm and 20 mm. But for a similar study, the printing mixture with nano-clay showed 33% improved bond strength between successive layers, when standoff distance reduced from 15 mm to 20 mm. reduction of micro-porosity and increased yield stress of the mixture occurred due to addition of nano-clay and consequently better bonding observed for lower standoff distance. The standoff distance is dependent on the nozzle opening size and printing speed. Thus it is recommended to keep lower than the nozzle opening size [71].

Printing quality and mechanical performance of printed elements also depend on the printing environment. At high temperature, printed elements immediately undergo drying, which causes a lower intermixing between successive printed layers and reduction in bond strength. Bond strength depends on the surface moisture and thus a significant dosage of superplasticizer recommended for high intermixing and less porous interface formation [8,76,77]. According to the environmental condition and printing material, additional dosage of superplasticizers or additives must be used.

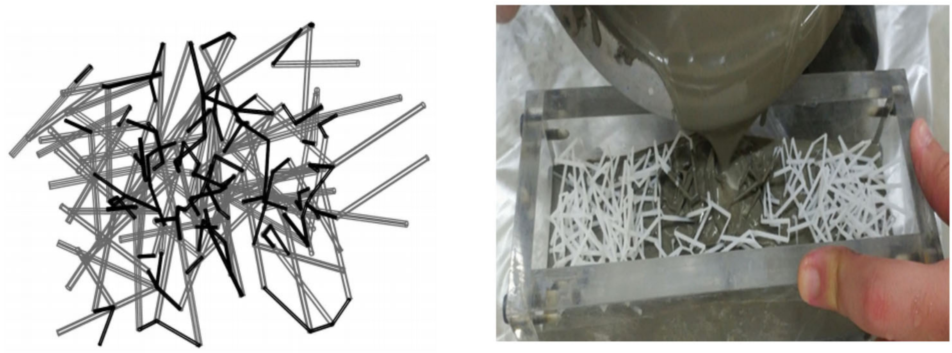
Building rate can be set out according to the vertical stress of printed element and the critical failure stress of the element for a specified build height. The vertical stress is dependent on the building rate, height and density of printed layer at specified time. Critical failure stress is correspondence of the static yield stress and geometrical factors. For an adoptable building rate, the critical stress will be more than the vertical stress, which means the structure will be stable [31]. For complex plan, while printing with a specific building rate, optimal tool path need to be predefined to overcome the unnecessary overlapping and delays. A collision-free tool path optimization solution was described in the study of Zhang and Khoshnevis [65] for contour crafting technique of concrete printing with two nozzles. The objectives of the tool path design are to optimize the path and time of printing without any collision of nozzles. Additionally, the problem of complexity and large-scale structure printing can be solved by using multiple nozzles and by using multiple printers simultaneously. In both cases, standard tool path design needs to be carried in respect of printing materials characteristics and building parameters. All these parameters are related to the method and materials for printing. According to the plan, size and shape of printing element, the method and parameters for printing can be assumed.

2.3. Reinforcing technology

2.3.1. Fiber-reinforced concrete printing

The use of fiber reinforcement to provide increased ductility, tensile strength, deflection resistance, and fracture energy to printed concrete elements is gaining attention [67,78,79]. Different types of fibers are used in 3DPC construction; examples of these fibers are polyethylene microfibers [17], polypropylene fibers [67], polyvinyl alcohol fibers [80], carbon, glass, and basalt fibers [20], and steel fibers [78,79]. Fibers exert crack-bridging effects within printed concrete under load, and this effect delays crack development, reduces crack width, and consequently enhances performance. The addition of fibers considerably alters the rheological properties of the fresh mixture. Addition of fibers generally causes high water demand in cementitious mixture, thus resulting in low viscosity, which can create the problem of pumpability and extrudability. Therefore, the content of fibers in the mixture should be controlled. To reduce the possibility of plastic shrinkage, fibers are used in printing concrete up to the recommended value of 1.2 kg/m^3 [56]. In consideration of printability and other physical contents, 1%–1.5% fibers by volume were recommended by previous research [17]. Meanwhile, the addition of excessive fibers may clog the extrusion nozzle and prevent smooth printing [20], thus need to provide additional workability, either by addition of superplasticizers or proper fiber treatment. Before using polymeric fibers in a 3DPC mix, they should be heat treated in order to result in good fiber dispersion and bonding with cementitious paste [20]. For carbon fibers, heat treatment should be done around 400 °C temperature, whereas for basalt and glass fibers, 500 °C should be used for thermal treatment [20]. Additionally, the possibility of micro-cracks is increasing in printed concrete elements with the increasing fiber volume. However, the high tensile strain capacity causes high strain energy as well as tensile cracks in mold casted and printed fiber reinforced concrete [81]. Therefore, optimum content of fiber addition should be maintained.

The random orientation of fibers in mixtures results in a high strength of the printed layer. The direction of fiber alignment that is parallel to the extrusion direction produces the best tensile performance but the worst compressive strength [67,80]. Therefore, the preferable direction of fiber alignment is parallel to the loading direction. To control the high degree of fiber alignment, the nozzle diameter should be smaller than the average length of the fiber [20]. Additionally, fibers show effectiveness by pull-out and not by yielding like mild steel bars; therefore, a directly parallel fiber alignment along the principal tensile stress plane is inefficient [79]. On this basis, further investigations of fiber



(a) (b)

Figure 6. (a) Randomly distributed fibers and (b) extrusion of concrete mix on printed fibers [82,83].

alignments are required for clarification and guidance.

Modeling on the fiber reinforcement alignment adjusted with the 3DP system was performed in previous research [82,83]. The authors [82,83] reported that in order to model the fiber orientation, the fiber length, boundary condition, directional angles, self-sustaining supporting condition, and spacing of fibers need to be inputted. Then, 3D modeling of the fiber distribution can be performed, as shown in Figure 6.

However, the danger of the formation of cold joints increases with fiber addition [29]. Fiber addition increases the strength of printed layers separately, not integrated the successive deposited layers and neither integrates the interfaces. Thus, special attention needs to incorporate these issues. However, special 3D textile reinforcement between concrete layers produces a nail between layers acting through the 2D coarse mesh of the textile, which can increase the bond strength.

The major challenge of fiber addition in concrete printing is controlling the direction of fibers, possibility of blockage and reduction in pumpability and extrudability. This review study recommended short synthetic and flexible fibers addition can be advantageous. Additionally, natural flexible fibers are also effective with respect to strength improvement of concrete. For example, plastics, hemp fibers, cotton fibers, wool can be used to investigate the effectiveness and performance in terms of printability and stability.

2.3.2. *Application of bar reinforcement*

Reinforcing bars can be inserted manually during printing and post-tensioned after printing the concrete structures. However, placing reinforcement in an onsite direct printing system is not feasible with printers. Therefore, the printing of hollow structures can be done to place the reinforcing bars inside the hollow spaces between printed concrete layers, which will finally be bonded by the infill concrete [18]. Typical bar reinforcement systems in the 3DPC system are shown in Figure 7(a–g). An approach of mesh molding, which has been developed at ETH Zurich, additively prints the steel reinforcement; then, the concrete is manually added to the steel reinforcement cage [84]. However, the process requires a special tool path and building plan design and can delay the printing.

Another wire extruding system was described by Lim et al. [58] (Figure 7(c)). This system involves a direct extruder, which requires torque to push the wire reinforcement in the extrusion nozzles.

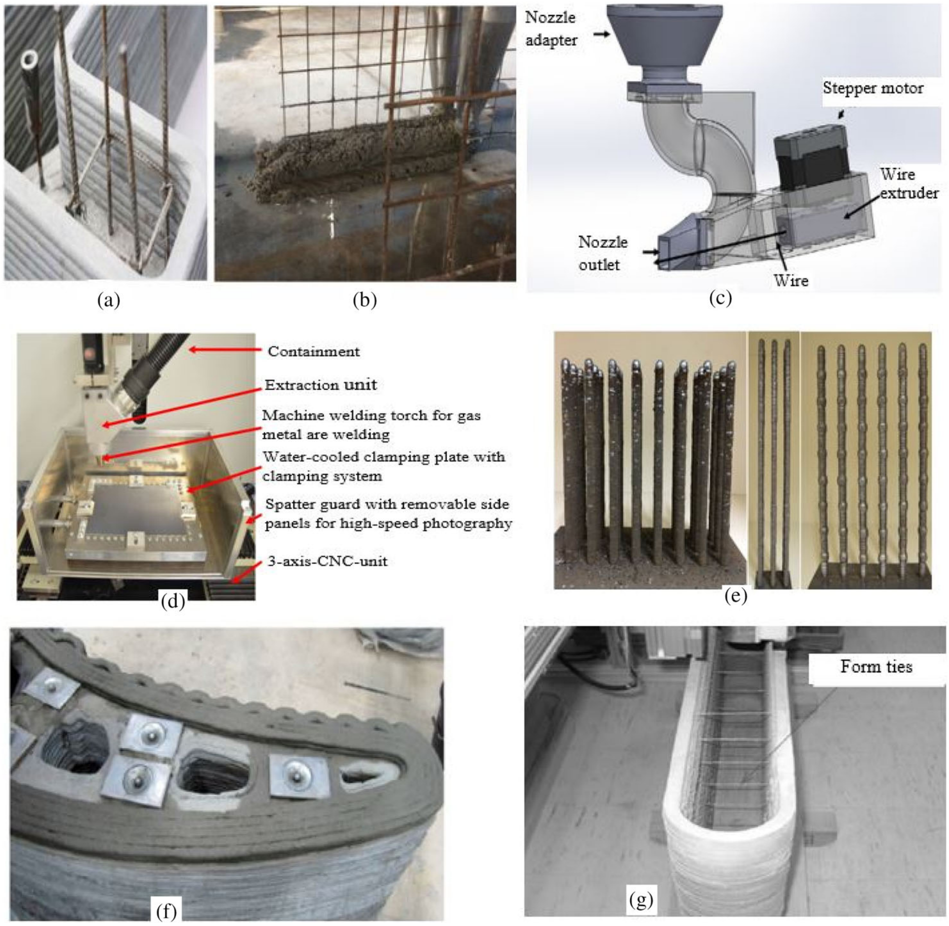


Figure 7. (a) Vertical steel reinforcement in contour crafting technology (WinSun), (b) forked nozzle laying (Hua Shang Tengda Ltd.), (c) cable insertion printing nozzle, (d) production of reinforcements, (e) printed reinforcing bars, (f) anchor-type reinforcing system, and (g) tie system [14,29,58].

However, slippage of a steel wire from the original position is major concern. The extrusion of wire can cause additional pressure to the freshly printed layers, which can affect buildability and shape stability. However, steel wire or cable insertion with fiber reinforcing geopolymer matrix can improve the tensile capacity of printed elements by 290%, as reported in [58]. The cable insertion system provides confinement in each layer of printed element by forming coil-like configuration. However, it limits in the direction of printing layers, and cannot be effectively applied across the interface or vertical to the section. Meanwhile, for the post-tensioning system, straight voids should be kept within the structures for the insertion of post-tensioning tendons, which may cause an obstruction to freedom in the geometrical form [30].

Reinforcement can be printed directly through printer. The concept of reinforced concrete printing involves a printing device connected to a rotating spool, which can feed the reinforcement into the printing head and then integrate the concrete-reinforcement filament released from the nozzle [85]. A novel approach of printing steel reinforcement was proposed in the

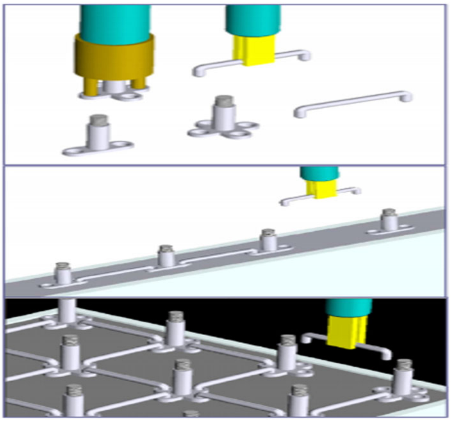


Figure 8. Modular reinforcement system [28].

study [29] on the basis of the gas–metal–arc welding process with a conventional three-axis CNC system, as shown in Figure 7(d). Dimensional accuracy, geometry, viscosity, and surface tension are affected negatively by the excessive heat generated from the rapid printing of layers. Additionally, the authors reported high yielding and strain capacity of the printed steel reinforcement and good bonding with printed concrete, but it has around 20% less strength than conventional steel reinforcement. A typical printed steel reinforcement is shown in Figure 7(e). But, printing steel reinforcement and concrete simultaneously is not feasible because of the high temperature generated from steel printing, which needs to cool down in order to print with concrete [29]. However, the joint and arrangement of reinforcement need to investigate significantly, as the current knowledge of printing reinforcement is not sufficient.

Several special anchor-type reinforcing systems and tie bars can also be used between the printed hollow layers of the concrete wall (Figure 7(f,g)). Robotic modular entrenching of steel mesh reinforcement into each layer can be done through robotic feeding system [28] (Figure 8). This mesh reinforcing system can be effectively applied simultaneously with concrete printing to reinforce the interface of printed layers. The provision of extensive lapping in mesh reinforcement in interlayer direction significantly improves the bond strength and the flexural capacity can be increased up to 290% [86]. However, the main challenges in this method are continuity of printing in different directions with various shapes and provision of joints between printed elements.

3. Application in construction

Although 3DPC construction is still developing, attractive structures have already been constructed using this technology. The process involved in the onsite printing of a full-scale building can be described in two steps, namely, onsite printing of formwork layers using the printing mortar and addition of reinforcement using another automatic device [28]. The offsite manufactured components of a building can be assembled on the site [87]. In accordance with any selected printing technique, different approaches can be adopted to print and construct a large structure. As described by Duballet et al. [87], horizontally printed layers on the floor can be moved in a vertical position to create a flat wall (Figure 9). Duballet et al. [87] also described a printed beam with an additional reinforcing assembly. Adopting similar technique the company BAM Infra printed concrete bridge components, where the hollow units were printed in horizontal plan and finally assembled in structures. Although the method of printing varies with different manufacturers, the principles of final assembly of structures are similar.

Buildings and bridges are the two top civil engineering construction sectors, where the government and industry are paying significant attention. The 3DP technology has great potential to manufacture architectural building and bridge components. For this reason, this study reviewed recent developments and identified potential challenges of using 3DP technology in building and bridge construction.

(a) Flat wall (Democrite Project, 2015) (b) Beam (WASP, 2015) (c) Hollow bridge unit, (BAM Infra, 2017)

Figure 9. Printed components of structures [87]

(a) Andy Rudenko's garden (2014) (b) Lewis Grand Hotel, Philippines (2015) (c) Five-story apartment building, China (2015)

(d) Two-story building, China (2016) (e) Office building, UAE (2016) (f) Gaia house, Massa Lombarda (2018)

Figure 10. Remarkable 3DPC building structures in the world [40,67,90].

3.1. 3D-printed building structures

Building sectors are moving to efficient construction technology [88]. In 2014, the first 3D-printed house in Europe was constructed by Dutch architects [89]. Several excellent structures have been printed in recent years, as shown in Figure 10. Andy Rudenko's garden was constructed by using contour crafting technology in 2014, with sand and cement was used to print the structure, and modeling was performed with the RepRap 3DP open-source project [40] (Figure 10(a)). Several multistoried buildings, as shown in Figure 10(b–d), have also been printed successfully. The world's first 3D-printed five-storied building in China was printed by WinSun Company in 2015 in an area of 1100 m^2 (Figure 10(c)) [67]. The wall of this building was printed hollow for thermal insulation, with a zig-zag pattern inside to provide reinforcement. Only 17 days were required to print and 48 h of construction were needed for a 250 m^2 office building in Dubai in 2016, which was printed using a special mixture of cement paste with fiber-reinforced gypsum (Figure 10(e)). In addition, disaster shelter houses in different areas are being printed for a service life of around 4–6 years with minimum cost and effort. The low-cost materials produced from waste products derived from natural sources are noticeable in 3DPC structures, as shown in the Gaia house (Figure 10(f)). Furthermore, 3DP technology is being planned for use in space by the European Space Agency and NASA. All of these significant applications explore the current development of 3DP technology in concrete construction.

3.2. *3D-printed bridge structures*

Although printed building structures highlight the development of the system, the printing of bridge structures is not comparable in number. A large-scale bridge for traffic movement requires consideration of loading conditions and design complexity, which explains the small number of printed bridge structures. Most printed bridge structures are for pedestrians, as shown in Figure 11. A 12 m long and 1.75 m wide pedestrian bridge printed in Spain using D-shape technology and constructed by Acciona Company (Figure 11(a)). Fused concrete powder and polypropylene reinforcement were used to build the bridge [5]. A concrete bridge for cyclists was constructed by the BAM Infra using prefabricated concrete blocks (Figure 11(b)). Several exclusive 3DPC structures were built in 2019, and examples include a 26.3 m long and 3.6 m wide 3DPC pedestrian bridge in Shanghai and a concrete bridge in California printed in 14 h by the US Marine [91] (Figure 11(c,d)).

Specially printed concrete structures with specific and significant matters are listed in Table 2. The recent trend of using 3DP technology in concrete construction is noticeable because these structures have an excellent appearance, are characterized by an easy and fast construction period, and are economic. Difficulties that may arise in the arrangement, printing, and assembly of the entire structure could overcome with advanced technologies, which are researchers trying to develop. 3DPC structures, such as heavy high-rise buildings, small single-unit homes, and pedestrian bridges with small to large spans, are amazing in terms of architectural and structural performance.

4. Performance of 3DPC elements

4.1. *Performance under loading conditions*

3DPC structural components possess anisotropic properties [30,80]. According to literature [49,94], the strength of a printed concrete element depends on the loading direction because of the anisotropic behavior; high compressive and flexural strengths exist in the direction perpendicular to the layer of deposition. Marchment et al. [8] observed around 3%–16% higher flexural strength and 15%–48% higher compressive strength are observed in the perpendicular direction compared with the values in the lateral direction depending on the delay time, as shown in Figure 12.

(a) Pedestrian bridge, Spain (2016)
(b) Cyclist bridge, Netherlands (2017)
(c) Pedestrian bridge, US (2019)
(d) Pedestrian bridge, China (2019)

Figure 11. Outstanding 3DPC bridge structures in the world [33,91,92].

However, mechanical performance of 3DPC elements depends on applied materials and printing technology. Using the extrusion-based technique generally results in higher strength compared with that of the powder bed system. The powder bed of OPC and calcium aluminum silicate cement mixture activated by an aqueous solution of lithium carbonate as the binder achieves around 8 MPa compressive strength with 50% porosity [36]. In general average compressive strength of the printed specimens by applying selective cement activation technique was around 5.3–16.4 MPa [11]. Feng et al. [94] tested 50 mm specimens printed by applying powder-bed technique, where a mixture of plaster, vinyl polymer, and carbohydrate was used as aggregate bed and a binder solution of humectant and water was used. They obtained around 11.6–16.8 MPa compressive strength after 6 months of curing. Their results revealed as the size of the printed layer increases, defects also increase, and strength consequently decreases. Curing with a controlled temperature and properly selected activator solution enhances the strength of the printed elements [37].

Adopting extrusion layering technique, Asprone et al. [41] printed and tested the flexural strength of a 3D-printed fiber-reinforced concrete beam. The concrete mix used to print the beam consisted of a maximum of 4 mm aggregates with a 0.39 water–cement ratio and 0.5% polypropylene fibers. They obtained a 14 mm slump value for this concrete mix, and the average compression strength of the printed cylinder was in the range of 34–42 MPa. In addition, the compressive strength of the 3DPC specimens at 20 min was around 1 MPa and could increase to around 50 MPa after 28 days [47]. A printing

Table 2. Special 3DPC structures in the world.

3D-printed construction	Applied method	Reinforcing system	Construction duration	Specialty	Critical point	Ref.
Lewis Grand Hotel, Don Juico Avenue, Philippines (2015)	Extrusion-based	Manual insertion of rebar between printed layers	100 h	Saves 60% cost	Need to install the rebar, plumbing, and wiring hardware manually	[33]
Office building, Dubai, UAE (2016)	Extrusion-based (gantry)	Fiber-reinforced plastic and glass-fiber reinforced gypsum	17 days to print and 2 days to assemble	Saves 50% cost	A 6 m high, 36 m long, and 12 m wide printer was used	[90]
Two-storey building, China (2016)	Contour crafting	Traditional mild steel frame	45 days	Can withstand an earthquake as strong as 8 on the Richter scale	20 tons of C30-grade concrete used	[33]
Gaia house, Massa Lombarda (2018)	Extrusion-based	Cavity between zigzag-printed layers of the wall was filled with rice husk	10 days	A mixture of natural mud, rice husk, and chopped rice straw was used as a construction material	The materials were biodegradable, and timber supports were needed to carry the roof	[93]
Cyclist bridge, Netherlands (2017)	Extrusion-based prefabricated elements	Pre-stressed system	3 months	Can bear a weight of up to 40 lorries	800 layers of pre-stressed unit designed and printed for constructing the bridge	[33]
Pedestrian bridge, Shanghai (2019)	Extrusion-based	Polyethene fiber reinforced	450 h	Saves 33%	44 hollow concrete units and 64 handrail units were used to assemble the bridge	[91]

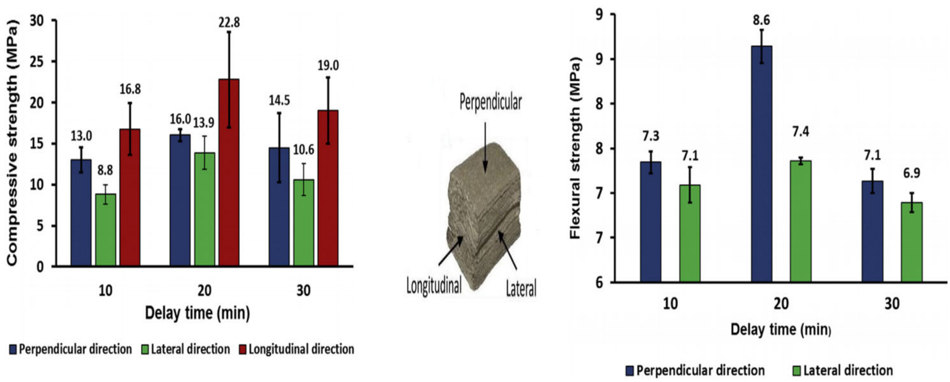


Figure 12. Variation in mechanical strength with delay time along different testing directions [8].

mixture with small-sized aggregates shows good compressive and tensile strength. As reported in literature [95], 104% increased compressive strength was obtained in concrete with 2.36 mm aggregates compared to 12.5 mm aggregates. Additionally, a 70 MPa printing concrete mix was developed by Papachristoforou et al. [96] by using a mixture of natural sand and limestone instead of conventional sand. The flexural strength of fiber-reinforced 3DPC beam elements is about 10–30 MPa, which is dependent on the fiber types, alignment, and loading path [20]. However, several researchers obtained around 11%–15% increased strength in the printed element compared with casted specimens [49]. However, printed coupons can reach up to 3% tensile strain, which is approximately 300 times that of conventionally casted concrete specimens [14]. A high performance concrete printing mix was developed by Lim et al. [97], where 10 MPa flexural strength of printed elements was considered as a lower limit for mix design. Additionally, this high performance self-reinforced concrete can reach up to strain level 8% [81]. The possibility of tensile cracks due to increased tensile strain energy is needed to be considered for high strength printing materials design. Therefore, overall strength depends on the material property, mixing proportion, additives, and technology used. According to research, the achievable compressive strength of printed concrete specimens may vary between 100 and 110 MPa when the concrete printing technique is applied [12]. The typical composition of materials for printing concrete construction and the observed mechanical properties from the respective studies are listed in Table 3.

Printed wall and beam sections with and without reinforcements were tested under blast loading conditions by Burroughs et al. [98]. Singly reinforced section with 9.5 mm rebar, basalt bar, and mesh reinforcements were used separately for specimen preparation, where the reinforcing bars and meshes were inserted manually. The authors observed that the blast damage in the printed specimen was more prominent than that in the casted specimens (Figure 13). The observation also revealed that the printed concrete materials spalled from the reinforcements because of poor bond strength between the concrete and reinforcements. They concluded that optimization of the printing mixture and overall printing system can improve the performance of printed concrete specimens under blast pressure [98]. Minimal information is available about the performance of 3DPC structures under heavy loading conditions. Available results indicate that printed concrete structures can efficiently carry loads if the

Table 3. Typically observed mechanical properties of 3DPC.

Material/compositions									
Sand	Binder	Reinforcements	Water/binder	Additives	Density (kg/m^3)	Compressive strength (MPa)	Flexural strength (MPa)	Bond strength between successive layers (MPa)	Ref.
<2 mm (sand :binder = 0.6:0.4)	Cement CEM I 52.5 (70%) + fly ash conforming to BS EN 450 (20%) + undensified silica fume (10%)	{1.2 kg/m^3} polypropylene micro fibers of 0.18 mm diameter and 12 mm length	0.26	1% superplasticizer and 0.5% retarder	2350	75–102	6–17	0.7–2.3	[52,56]
<4.75 mm (sand :binder = 0.6:0.4)	Cement CEM I 52.5 (61.5%) + silica fume (21%)	{1% by volume} carbon fibers of 7 µm diameter and 3 mm length	0.4	0.3% water reducing agent	1927	30–91	10–30	–	[20]
<465µm (sand :binder = 0.6:0.4)	Geopolymer Class F fly ash with 46.7% activator	{0.25%–1% by volume} polypropylene fibers with 11.2 µm diameter and 6 mm length	0.467	0.4% (CMC)	–	13–36	6.1–7.8	1.7–3.1	[67]

(a) (b)

Figure 13. Post-blast faces of (a) casted wall and (b) printed wall [98].

Figure 14. Local capillary suction at the interfaces between layers of printed concrete [102].

proportion and methodology of printing are selected properly.

4.2. Critical exposure conditions

Printing materials are sensitive in critical exposure conditions. Rapid structuration of printed layers and risk of drying shrinkage in hot climate could lead to degradation in mechanical strength and durability [56,99]. However, printed structures need protection from adverse environmental conditions, such as ultraviolet radiation, water and chemical exposure, and high temperatures. Post-treatment using epoxy hardeners and protection against ultraviolet radiation are needed [60]. Glass powder can be added in printing concrete mixture to increase the packing density, consequently to reduce the porosity of printed elements and improve the durability against chemical and water absorption [100]. Ethylene-vinyl acetate modified cementitious mixture possesses high resistance to water and chemical absorption and penetration, thus it can be applied in 3DP to enhance durability [101]. However, this additive may cause negative effect in mechanical strength. Weak intra-layer bonding zone can provide path for intense capillary suction of aqueous liquid into the structure may result in strength deterioration [102]. Figure 14 shows local capillary suction at the interface between printed layers and cracks

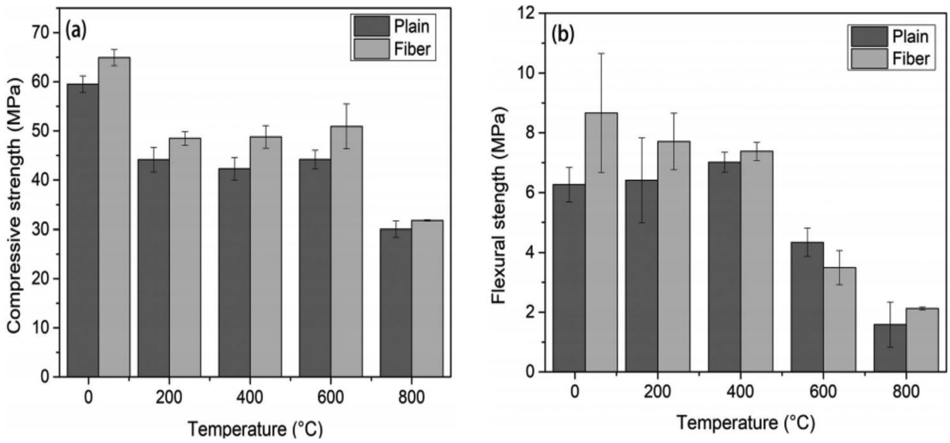


Figure 15. Residual strength in printed concrete specimens after exposure to elevated temperatures [103].

[102], where the main path of suction was the cold joint, which was formed due to high printing time interval.

Vulnerability to fire and elevated temperatures is very high for printed concrete elements due to the finer size of materials in 3DP mixture. A previous study proved that PVA fiber-reinforced printing concrete is more effective than plain concrete in terms of residual strength after exposure to high temperatures of up to 800 °C [103]. The author reported that the residual modulus of elasticity in the fiber-reinforced concrete printed specimens was 5.3%, whereas plain concrete had 4.8%. The variation in the compressive and flexural strengths of the printed parts was noticeable, as shown in Figure 15. Around 49% residual compressive strength was observed by the author in the printed fiber-reinforced concrete specimens, which is very near that of the plain one, after exposure to 800 °C for 60 min following ISO 834 [103].

The performance and durability of 3DPC structures exposed to freeze–thaw cycles, cyclic moisturization, chemical exposure, water, and elevated temperatures must be carefully investigated. A 3DP mixture is derived from very fine materials compared with conventional casted concrete, and the possibility of voids occurring in the printing layers is very high. Therefore, water and chemical absorption will also be higher than those in conventionally casted elements. In order to minimize the porosity of printed specimen nano-clay, silica fume, viscosity modifying agents were recommended [77]. Thus while selecting aggregates for design of 3DP mixture, it must be well graded and with high packing density. Structures that are printed using a mixture of different polymers with cementitious materials need further care when exposed to high temperatures and chemicals.

5. Sustainability of 3D-printed structures

Application of AM techniques reduce the 70% raw material requirement and waste production and bring economic and environmental satisfaction in construction [5,11,21]. This technology can reduce 30%–60% of construction waste, 50%–70% of the time requirement, and 40%–80% of the labor cost [23,51,104]. The flow diagram in Figure 16 shows the sustainability of 3D construction technology in terms of reduced labor requirement, absence of formwork requirement, and decreased waste production. WinSun Company claimed that they have printed and sold over 100 houses at a reasonable

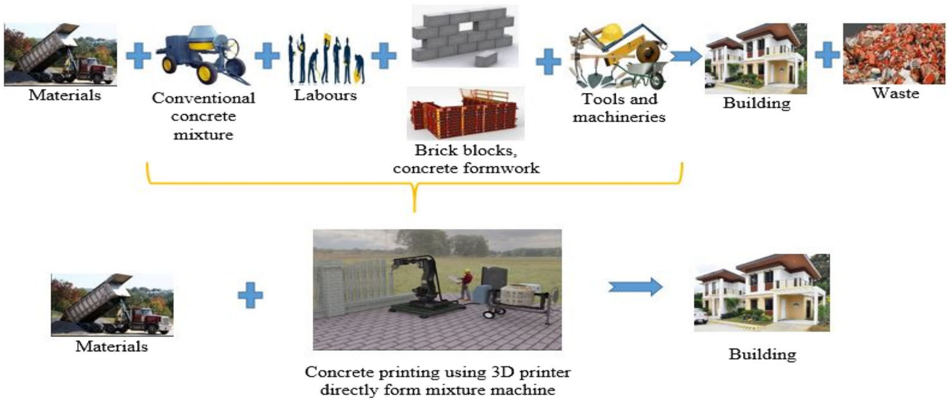


Figure 16. Conventional construction and 3DP system.

cost of $30,000 each [5]. In China, a company printed relatively cheap houses at a cost of around $4,800 per unit within 24 h [1]. The advantage of the 3DP system is the formwork-less method, which saves money, labor, and time; around 35%–60% [8,15,30,48,49] of the total concrete construction cost and 50%–75% of the construction time [4,31] are consumed by formwork and molding preparation, and the figures vary widely in different countries.

As an automated system, 3DP reliably reduces the heavy work of laborers and the possibility of accidents and enhances safety in construction [8,18,105]. The reduced noise production, low waste spread, and time-saving increase the social reliability of 3D-printed structure construction systems. Moreover, the poor performance and productivity issues found in most conventional construction systems arise from heavy work by laborers; this problem is acute even in developed countries, such as the UK, USA, Singapore, and Hong Kong [12]. The automation in construction technology can alleviate this problem. The 3DP system is powered by electric energy, a much-reduced emission takes place during whole construction, which provides environmental safety. According to literature, around 80% of the world's total waste is generated from construction [10]. Post-construction waste is dangerous to the environment and requires space and labor for disposal, which can be minimized reliably by the controlled use of the material in an automated system of 3DP [15,48,89]. In addition, the machinery used in 3DP must be eco-friendly such that recycling and replacement of older printed parts can be performed without any environmental risk [89]. By contrast, AM technology consumes energy and causes environmental footprints, which may impose negative effects on the environment.

A study [89] on the feasibility of 3DP technology in construction industries was conducted based on environmental satisfaction, material greenness, social policies, public acceptance, and machinery involvement The study showed nearly 60% sustainability of 3DPC construction in Australia [89]. This result is a good sign of feasibility because the sustainability of the 3DP system in construction industries remains under investigation; significant research and observations are needed to introduce proper guidelines and standards.

6. Challenges involved in 3DPC structures

6.1. *Low bond strength between successive layers*

The properties of printing materials and the printing process influence the bonding

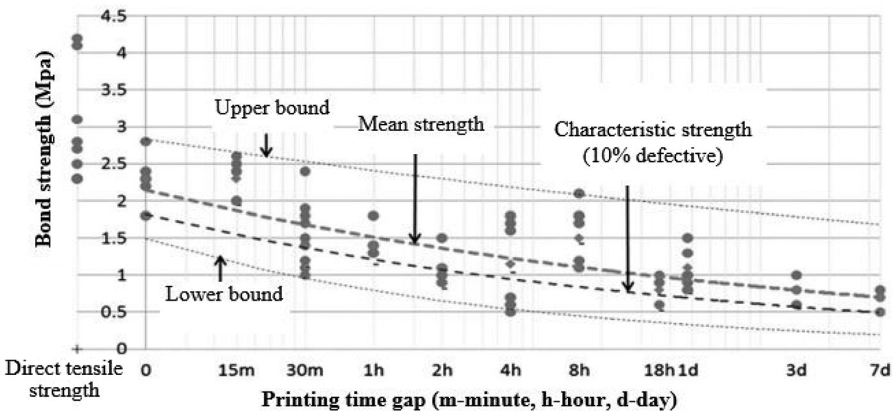


Figure 17. Typical variation in tensile bond strength with a printing time gap [56].

between two successive printed layers [95]. The porosity trapped between successive printed layers possesses a challenge, resulting in inferior interfacial bond quality and decreased mechanical performance [1]. Speedy structuration, which is a result of a non-reversible chemical reaction during hydration, causes a weak bond between particles, and could cause degradation in shear strength [42]. The yield stress of OPC also increases with time, which creates a problem when the rate of structuration is too speedy compared with the delay time between successive printed layers [99]. Additionally, a short mixture setting time gives rise to the possibility of producing cold joints at the layer interface, resulting in reduced homogenous structures and low bond strength [95]. The structuration rate within 0.2–0.75 Pa/s is suitable for maintaining the stability of the mixture and addressing the problem of sensitivity to stoppages and delays between printing [106].

Meanwhile, the bond strength between layers inversely depends on the printing time gap; the bottom layer needs sufficient time to gain strength and carry the upper layer [24,42]. Le et al. [56] found a variation in tensile bond strength between successive layers of printing with different time gaps, as shown in Figure 17. Their results revealed that printed specimens with a printing time gap of over 15 min failed along with the interface between printed layers, and material failure was observed in the specimens with a time gap of less than 15 min. Around 53% lower bond strength was observed between successive printed layers for specimens with a printing gap time of 30 min. The minimum recommended value of tensile bond strength between successive layers is 0.8 MPa [56], which must be ensured by adjusting the time gap and rheological properties of printing materials.

Bond strength also degrades with the free surface moisture on the existing layer [8,76]. The most favorable condition found in research is saturated surface dry conditions, where excessive moisture content can degrade the bond strength [23]. The thixotropic behavior as well as initial stiffness of the mixture also opposes the bond strength between layers [8,42]. Meanwhile, water should have present to ensure sufficient intermixing between layers, and long terms hydration reaction [107]. Additionally, wider contact area between successive layers resulting in more bond strength. Thus significant malleability and intermixing between layers need to be increased through additional provisions. However, anisotropic conditions in straight

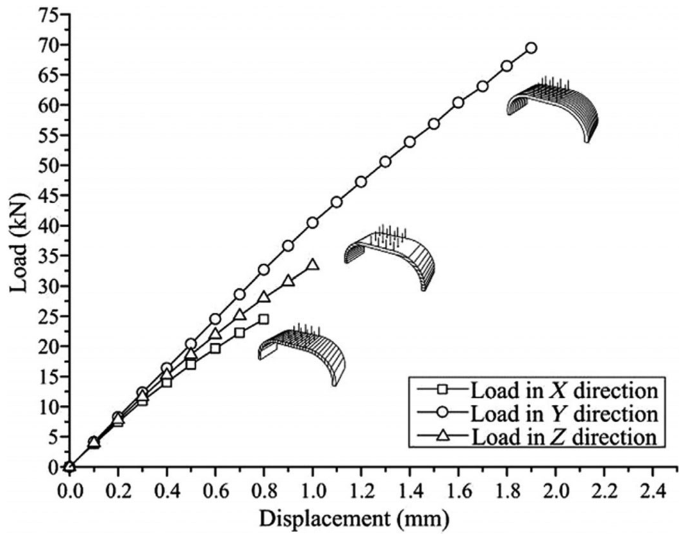


Figure 18. Typical load–deflection curve of a printed structure with a load applied in varying directions [109].

printing layers can be minimized by curved layer printing systems up to a certain limit [73,108]. Increasing the thickness of printed layers with increasing the time delay between successive layers results in less porous and higher interlayer-bonded printed elements [1]. In the study of Hosseini et al. [76], a sulfur-black carbon–sand mortar was used as a binder in the intra-layer of successive printed layers; 99% sulfur was added to 1% black carbon to prepare the binder with heat treatment. Applying a layer of this mortar between two successive printing layers like masonry work, 100% tensile cohesion improvement occurs [76,107].

6.2. Anisotropic behavior

Printed concrete elements demonstrate anisotropic behavior under loading conditions. As discussed in Section 4.1, the significant variation in tension and compression testing results on printed elements are due to variation in the loading direction. A noticeable variation is observed in the microstructure of the material inside each layer and at the boundaries between layers because of the layer-by-layer printing process [1]. As observed in previous research [8], the maximum compression carrying capacity of a printed concrete specimen is along the perpendicular direction of printing, as shown in Figure 12. The authors also reported that the lowest strength is found when the loading direction is lateral to the printing direction. Therefore, the anisotropic behavior of printed concrete varies with different printed layers, loading directions, and printing processes. To develop the maximum stress criteria of a 3D-printed structure, a study was conducted on a 100 mm thick printed arch under dead and surface loads, as shown in Figure 18 [109]. The load–deflection curve of an arch structure obtained from the numerical analysis (Figure 18) confirms that the printing direction significantly affects the ultimate load-carrying capacity and deflection of the structure. Printed concrete structures have characteristic anisotropic mechanical behavior because the tension induced between the printed layers of structural elements results in reduced ultimate strength under loading [14]. The internal voids and cold jointed zone along the interface of successive layers are the crucial reasons that induce anisotropy in printed elements [110].

Furthermore, the addition of fibers causes increased anisotropy in printed concrete specimens. Anisotropy varies significantly depending on the printing method. As observed in the extrusion-based technique, the anisotropic behavior of concrete elements is much more pronounced than that of the powder bed technique. Anisotropy also varies depending on the measured strength of specimens; anisotropic coefficients of 0.25, 0.46, 0.63, and 0.68 were observed in previous research [110] that evaluated compressive, tensile, bending, and shearing strengths, respectively. No significant modeling between parameters related to the anisotropy of printed concrete and no suggestions to optimize this behavior were provided. Therefore, the anisotropic behavior of 3DPC elements needs further investigation to establish a proper correlation among the parameters.

6.3. Complications in formwork-less printing

Large areas are open in air during 3DP because of the formwork-less construction system, which leads to the risk of cracking due to excessive drying shrinkage [56]. The non-uniform shrinkage of two successive layers reduces tensile bond strength [23]. Drying shrinkage is accelerated by several chemical admixtures that are generally used in printing concrete mixtures for hydration acceleration or retardation [47]. Printing materials consist of very fine particles, which have high water demand due to the large surface area and consequently lead to high autogenous and drying shrinkage [4]. Alkali addition accelerates the hydration in the binder and produces a large amount of portlandite, which can reduce drying shrinkage by up to four times [111]. The addition of around 20% gypsum with 5% silica fume in cement for printing mixtures shows no expansion or shrinkage according to previous research [21].

Meanwhile, deformations may arise during the printing of successive layers of concrete because the plastic deformations of printed layers cause radial deformation of the entire shape. Printing mixture should have sufficient green strength and capability to resist extrusion pressure [49]. Wolfs et al. [13] obtained 14%–21% radial deviation from the mean level when they printed a cylindrical shape of 40 successive printed layers. Traditional finishing of chemical or physical post-processing systems, such as sintering of the printed surface, may be required because the layer-by-layer printing system produces a ribbed pattern that is not smooth [89,108]. Surface quality greatly depends on the nozzle shape, and a square orifice is preferred for good surface finishing [4]. The vertical components of the structure to be printed can be printed in the horizontal plan and rotated into the vertical plan, which results in a surplus amount of systematic complexity in a conventional cast-in-situ system. Though rapid hardening binder and D-shape technology can adopt for printing overhanging elements [19], large-scale structures still need additional supporting arrangements to be printed. As reported in previous research, printability of complex wall can be increased by filling self-compacting concrete into a polymer foam formwork applying 3DP technology [112]. Several elements in building structures must be connected before being subjected to load. The connections, joints, and interfaces between the elements, such as roof, lintels, door and window frames, electrical and plumbing conduits, and connections with foundations, may negatively influence the continuity and simplicity of printing.

6.4. High cost of printing

In general, 3DP technology requires special and expensive machinery operation, which consumes more energy and cost than the conventional method. As the complexity and size of printing structure increases, the requirement of costlier machinery and arrangement along with supporting tools also increases [74]. Moreover, to operate machineries, skilled and experts are needed, which consequently charges more. For example, industrial AM fusion technology requires metal powders and high-energy beams that consume more electrical energy than ordinary methods [113]. Consequently, the cost of the process increases noticeably. Moreover, 3D concrete printing technology, when applied to large structures, requires large mass production, which is time-consuming and expensive [1]; it could be optimized after the improvement of machines and technologies applied in the design. The crucial issue is the selection of all parameters that may cause difficulties or faults during and after printing technology applications. The labor due to pre-processing file preparation, machinery arrangement and post-processing cleaning, removal of supports or adjoining additional materials, and surface treatments cannot ignore [5]. Several positive aspects were obtained from [109], which discovered that D-shape technology requires half the cost of the conventional construction system. Another study [12] highlighted significant case studies and revealed that most of the cases of 3DP technology save money. Additionally, this system ensures quality and precision, which cannot be measured in monetary terms. Table 2 shows that currently printed structures achieve around 33%–60% cost saving compared with structures built using the conventional construction method. Conventional flat wall construction is cheaper than the irregular shaped one, but shape is not relevant to cost in 3DP technology [104].

Reduced demand for materials, time, energy, and increased environmental benefit can be possible by optimizing the design space, which can lead to reduced construction costs [108]. Optimization must be performed without compromising strength and quality by adopting the redistribution of materials within the spaces and maintaining all boundary constraints. The Russian company Apis Cor built a 38.11 m^2 house at a cost of approximately $10,150 and claimed that this cost is incredibly lower than that of constructing a home using the conventional method [114]. Around 60% of the cost was required for construction, and the rest was spent for wiring, doors, windows, and finishing. WASP Company printed 30 m^2 house with wall thickness of 40 cm, which requires a material cost of only 900 Euro [93]. Additionally, using cheaper and locally available supporting tools as replacing the costlier heavy machinery can be a solution. As the CONPrint3D using a 3D printer by upgrading such local machines as a mobile concrete pump [74]. Consequently a 25% cost savings and 4–6 times shorter construction time being reported. Therefore, the cost of printing can be optimized depending on the technology, materials, and location of the structure.

6.5. *Lack of standards*

Specifications and standards remain lacking because 3DP technology, especially in concrete construction, is relatively new. Challenges also remain in the selection of materials. Additionally, design and construction guidelines are not sufficient. The selection of the shape and size of printed elements still depends on the available printer's properties and the material properties due to the lack of specifications [89]. ASTM Committee F42 and ISO/TC 261 members are working on developing particular standards for AM [4], but guidelines and standards for 3DP of concrete materials and printed structures are seriously lacking. The standard exploration by ACI Committee 564 [115] is expected to innovate the 3DP technology of concrete structures. Current standards for the selection of materials, preprocessing, printing time, process, and allowable printed layers should be specified to enhance the application sustainability. Guidelines for testing printing materials and printed specimens under different loading and boundary conditions along with varying exposure conditions must be generalized by a specified code. Similar to conventional reinforced concrete structural components, each structural element must be printed while maintaining the guidelines for selecting size, shape, and mechanical properties in the design. The reinforcement system in 3DPC structures must also be standardized.

The major challenges involved in 3DP of concrete materials and printed structures are summarized in Table 4 together with the general techniques needed to optimize the risk associated with quality and strength. After studying the research on 3DPC structures, the major challenges described in Section 6 can be addressed by implementing measures involving the addition or deduction of specific additives. All risks cannot be fully eliminated, but optimization can significantly improve the performance and sustainability of 3DPC structures.

7. Future opportunities

7.1. Future market

Although 3DP technology is well accepted as a digital and innovative technology, it remains a vision in local daily construction. This technology has just entered developed industries and will require some time for local adoption, and consequently, influencing the market [89]. The main reason for this situation is the complex technology involved. A study analyzed the viability of 3D-printed construction technology, and the authors obtained a 58.33% viability level in the Australian market [89]. Although studies on the 3DP construction market are few, several of them revealed that the expected increment rate of the global 3DP material market value is 20% per year, which was US$165 million in 2013 [12]. Forbes [117] estimates that the worldwide market value of 3DP will reach around $32.78 billion by 2023, with an expected annual growth rate of 25.76% from 2018. By 2025, 25% of buildings in UAE and in 2019, around 2% of new structures are expecting to be constructed using 3DP technology [118]. Rapid urbanization and economic and architectural feasibility account for a large share of the 3DP market in the building sector.

The application of this technology not limited to structures for shelter in earth, but also this technology takes the challenge to built-up habitants for used on the moon, Mars or other planet and any position in space using the available local resources from these sites. In the competition called by NASA in 2019 for taking the challenges of modeling virtual Martian habitats, the team of SEArch and Apis Cor, Zopherus and Mars Incubator have participated [119]. These taken challenges of building habitats in space are a sign of extensive revolution of 3DP system. Though the sustainability and service quality must need to analyze extensively, before started to construction and live in those habitats.

Therefore, the future opportunities of 3DPC structures are not only limited to earth, but also it can be extended to different planets. This innovation will make construction easier in planet like Mars, moon, and others; meanwhile, the dream of living in the space will come true earlier. In addition, the contribution of 3DP system in construction industries will increase tremendously.

7.2. Future research directions

The application of 3DPC construction is in its infancy even in several developed countries. The lack of standards and guidelines prevents local construction companies from adopting this technology. This study identifies and examines the potential areas

Table 4. Summary of challenges and techniques to overcome such challenges.

Challenges	Techniques for optimization	Ref.
Low bond strength between successive layers	• Apply traditional methods of surface preparation, such as sandblasting and scrabbling • Decrease nozzle stand-off distance • Shorten printing time • Addition of fibers, adhesives/epoxy, synthesized polymer of sulfur and black carbon • Adjust surface moisture	[4,14,23,76]
	• Use adhesives, such as epoxy polymers, in the bond interface when necessary • Print a rough surface similar to a frog mark in bricks to interlock with the new layer	Suggestions by the authors
Deformation and appearance complexity from a formwork-less system	• Create dome-shaped structures where possible • Apply traditional finishing	[89,108]
	• Eliminate protective coating by using an additive • Change the printer nozzle shape as needed	Suggestions by the authors
Drying shrinkage and plastic deformations	• Decrease the water/cement ratio • Increase the sand/cement ratio • Add fiber reinforcements • Add gypsum, fly ash, and calcium sulfoaluminate cement	[21,47,56,111,116]
High cost	• Optimize the design space by the allocation of materials and topological study • Incorporation of local instruments and tools instead	[74,108]
	• Use locally available materials and by-products • Establish proper guidelines and standards needed to eliminate trial and error losses • Develop high-strength printing concrete mixture with reduced amount of raw materials	Suggestions by the authors

of application and the performance of 3DPC structures, which requires further investigation.

- Low bond strength and anisotropic behavior of 3DPC elements are the major challenges to apply 3DP technology in conventional concrete [1,110]. Similar to conventional concrete, a specific ratio of ingredients in printing concrete materials is required to establish a specific grade of strength given the anisotropic characteristics of printed elements. However, structural design should have compatible methodology with the anisotropy of printed elements. The incorporation of fibers to improve bond ability and the development of design guidelines to meet the performance requirements of printed concrete need to be investigated further.

- An effective joining system of printed components and the method of reducing drying shrinkage need to be investigated further, where both complications are being generated due to the nature of formwork-less printing system [47]. Currently, the manual techniques of assembling the off-site printed elements are being used to reduce this issue, while the full automation system may reduce the high cost of printing.
- Proper design and construction as per standard design guidelines require less labor and cost as well as provide superior performance. The design standard for each type of printing materials and printing technology need to be established as the current specifications are somewhat arbitrary [89]. In addition, the reinforcement installation systems and relevant guidelines are insufficient while the demand for 3DP technology is increasing. Printing system needs to be developed for large-scale building structures with composite materials. Furthermore, the self-reinforced system can be an innovative solution for 3DPC elements on the basis of high-strain capacity engineered cementitious composites, which need to be properly investigated [81]. Ultra-high performance concrete mixed with high volume fibers can be applied in large structures, which is proposed as a solution for printing complex and thin structures with sufficient strength [120]. However, the rheology and printing performance of these types of concrete has to be investigated deeply.

Proper investigations and significant information will pave a way for better selection of materials and methods for 3DP. Thus more investigations on full-scale 3DPC elements and case studies on large printed structures are needed to be done. However, printed structures could undergo severe loading conditions, thus impact, fatigue, dynamic behavior of 3DPC elements should have considered. Creep and long-term deflection behavior of 3DPC is not very satisfactory due to the finer size of aggregates [4], which are need to be properly analyzed. Additionally, durability of 3DPC structures with variation in exposure conditions, such as water, acidic or alkaline medium, elevated temperature, fire, ultraviolet radiation, and freeze–thaw cycles, must be considered when evaluating the performance and durability of printed structures.

8. Conclusions

3DP is gaining popularity, because this system unquestionably provides high precision, is applicable to a wide choice of materials, allows freedom in planning and designing complex structures, and has low waste production record. An extensive review of the current implementation of the technology in different places and the materials used for 3DP of concrete structures was conducted. Despite the extensive benefits, significant challenges are involved in the adoption of 3DP in concrete structure construction. The foremost challenges associated with the materials and methods of 3DPC were also discussed. On the basis of the observations from this review and current practices, the following conclusions were obtained.

- FDM is one of the most commonly applied technologies in 3DP of concrete structures because of its low cost, simplicity, and high-speed processing. Simplified onsite printing methods, such as contour crafting, concrete printing, and CONPrint3D, were developed using this technology. D-shape technology based on the powder bed technique can be applied in construction industries. The selection of methods depends on the materials and structures to be printed.

- The composition of materials for concrete printing is a challenging feature in 3DP technology because the quality of printed elements greatly depends on the properties of printable mixtures. The fresh and rheological properties of concrete mixtures depend on the proportions, sizes, and properties of ingredients. The printing characteristics of the mixture must be controlled against open time, delay time, and setting time to provide sufficient flowability, printability, and buildability.
- Reinforcement techniques are still under consideration for 3DP technology. The fiber reinforcement system is easier than other types because it can be applied in conjunction with concrete printing, and the bar reinforcement and post-tensioned system show improved performance in terms of strength.
- The improvement in the mechanical properties of printing concrete mixtures must be analyzed based on composition, printing technology, and loading conditions. In most cases, the mechanical properties of printable mixtures with sufficient compositions are reliable and comparable to those of mold-casted concrete.
- The major challenges involved in the 3DP of concrete structures under critical exposures are also discussed in this work. Measures to address the risks are provided. The lack of standards controls the present market of the 3DPC system because of the high construction cost. The expected market values predicted by different agencies are high, but the development of specific standards can increase the global adoption of this technology.

After studying crucial studies on 3DP of concrete structures, a clear concept that arises is that this technology can offer incredible prospects and potential for the concrete construction industry if the associated challenges are minimized.

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References

[1] Ngo TD, Kashani A, Imbalzano G, et al. Additive manufacturing (3D printing): a review of materials, methods, applications and challenges. Compos Part B Eng. 2018;143:172–196.
[2] Ford S, Despeisse M. Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. J Clean Prod. 2016;137:1573–1587.
[3] Bogue R. 3D printing: the dawn of a new era in manufacturing? Assem Autom. 2013;33:307–311.
[4] Paul SC, van Zijl G, Tan MJ, et al. A review of 3D concrete printing systems and materials properties: current status and future research prospects. Rapid Prototyp J. 2018;24:784–798.
[5] Buchanan C, Gardner L. Metal 3D printing in construction: a review of methods, research, applications, opportunities and challenges. Eng Struct. 2019;180:332–348.
[6] Al-Qutaifi S, Nazari A, Bagheri A. Mechanical properties of layered geopolymer structures applicable in concrete 3D-printing. Constr Build Mater. 2018;176:690–699.
[7] Gosselin C, Duballet R, Roux P, et al. Large-scale 3D printing of ultra-high performance concrete – a new processing route for architects and builders. Mater Des. 2016;100:102–109.
[8] Marchment T, Sanjayan JG, Nematollahi B, et al. Interlayer strength of 3D printed concrete: influencing factors and method of enhancing. In: Sanjayan JG, Nazari A, Nematollahi B, editors. 3D concrete printing technology. 1st ed. Vol. 12. Amsterdam: Elsevier; 2019. p. 241–264.
[9] Buswell RA, Leal de Silva WR, Jones SZ, et al. 3D printing using concrete extrusion: a roadmap for research. Cem Concr Res. 2018;112:37–49.
[10] Nematollahi B, Xia M, Sanjayan J. Current progress of 3D concrete printing technologies. Paper presented at: 34th International Symposium on Automation and Robotics in Construction; 2017 Jun 28–Jul 1; Taipei, Taiwan. p. 260–267.
[11] Lowke D, Dini E, Perrot A, et al. Particle-bed 3D printing in concrete construction – possibilities and challenges. Cem Concr Res. 2018;112:50–65.
[12] Wu P, Wang J, Wang X. A critical review of the use of 3-D printing in the construction industry. Autom Constr. 2016;68:21–31.
[13] Wolfs RJM, Bos FP, Salet T. Early age mechanical behaviour of 3D printed concrete: numerical modelling and experimental testing. Cem Concr Res. 2018;106:103–116.
[14] Lu B, Weng Y, Li M, et al. A systematical review of 3D printable cementitious materials. Constr Build Mater. 2019;207:477–490.
[15] Biernacki JJ, Bullard JW, Sant G, et al. Cements in the 21st century: challenges, perspectives, and opportunities. J Am Ceram Soc. 2017;100:2746–2773.
[16] Sakin M, Kiroglu YC. 3D printing of buildings: construction of the sustainable houses of the future by BIM. Energy Procedia. 2017;134:702–711.
[17] Ogura H, Nerella VN, Mechtcherine V. Developing and testing of strain-hardening cement-based composites (SHCC) in the context of 3D-printing. Materials. 2018;11:1375.
[18] Wangler T, Lloret E, Reiter L, et al. Digital concrete: opportunities and challenges. RILEM Tech Lett. 2016;1:67.
[19] Panda B, Tay YWD, Paul SC, et al. Current challenges and future potential of 3D concrete printing. Materialwiss Werkstofftech. 2018;49:666–673.
[20] Hambach M, Rutzen M, Volkmer D. Properties of 3D-printed fiber-reinforced Portland cement paste. Cem Concr Compos. 2017;79:62–70.
[21] Ma G, Wang L, Ju Y. State-of-the-art of 3D printing technology of cementitious material – an emerging technique for construction. Sci China Technol Sci. 2018;61:475–495.
[22] Bos F, Wolfs R, Ahmed Z, et al. Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing. Virtual Phys Prototyp. 2016;11:209–225.

[23] Panda B, Paul SC, Mohamed NAN, et al. Measurement of tensile bond strength of 3D printed geopolymer mortar. Measurement. 2018;113: 108–116.
[24] Sanjayan JG, Nematollahi B, Xia M, et al. Effect of surface moisture on inter-layer strength of 3D printed concrete. Constr Build Mater. 2018;172: 468–475.
[25] Kreiger MA, MacAllister BA, Wilhoit JM, et al. The current state of 3D printing for use in construction. Paper presented at: Proceedings of the 2015 Conference on Autonomous and Robotic Construction of Infrastructure; 2015 Jun 2–3; Iowa State University, Ames, IA. p. 149–158.
[26] Liu Z, Li M, Weng Y, et al. Mixture design approach to optimize the rheological properties of the material used in 3D cementitious material printing. Constr Build Mater. 2019;198: 245–255.
[27] Kazemian A, Yuan X, Cochran E, et al. Cementitious materials for construction-scale 3D printing: laboratory testing of fresh printing mixture. Constr Build Mater. 2017;145: 639–647.
[28] Khoshnevis B. Automated construction by contour crafting – related robotics and information technologies. Autom Constr. 2004;13:5–19.
[29] Mechtcherine V, Grafe J, Nerella VN, et al. 3D-printed steel reinforcement for digital concrete construction – manufacture, mechanical properties and bond behaviour. Constr Build Mater. 2018;179:125–137.
[30] Tay YWD, Panda B, Paul SC, et al. 3D printing trends in building and construction industry: a review. Virtual Phys Prototyp. 2017;12:261–276.
[31] Zhang J, Wang J, Dong S, et al. A review of the current progress and application of 3D printed concrete. Compos Part A Appl Sci Manuf. 2019; 125:105533.
[32] Rushing TS, Stynoski PB, Barna LA, et al. Investigation of concrete mixtures for additive construction. In: Jay G. Sanjayan, Ali Nazari, Behzad Nematollahi, editors. 3D concrete printing technology. UK: Elsevier; 2019. p. 137–160.
[33] 3DPrint.com: the voice of 3D printing/ additive manufacturing; n.d. Available from: https://3dprint.com
[34] Hamidi F, Aslani F. Additive manufacturing of cementitious composites: materials, methods, potentials, and challenges. Constr Build Mater. 2019; 218:582–609.
[35] Cesaretti G, Dini E, De Kestelier X, et al. Building components for an outpost on the Lunar soil by means of a novel 3D printing technology. Acta Astronaut. 2014;93:430–450.
[36] Shakor P, Sanjayan J, Nazari A, et al. Modified 3D printed powder to cement-based material and mechanical properties of cement scaffold used in 3D printing. Constr Build Mater. 2017; 138:398–409.
[37] Xia M, Nematollahi B, Sanjayan J. Printability, accuracy and strength of geopolymer made using powder-based 3D printing for construction applications. Autom Constr. 2019;101: 179–189.
[38] Ronald R, San Fratello V. Developing concrete polymer building components for 3D printing. Paper presented at: Proceedings of the ACADIA 31st Annual Conference of the Association for Computer Aided Design in Architecture; 2011 Oct 13–16; Banff, BA, Canada.
[39] Xia M, Nematollahi B, Sanjayan JG. Development of powder-based 3D concrete printing using geopolymers. In: Jay G. Sanjayan, Ali Nazari, Behzad Nematollahi, editors. 3D concrete printing technology. UK: Butterworth-Heinemann. 2019. p. 223–240.
[40] Hager I, Golonka A, Putanowicz R. 3D printing of buildings and building components as the future of sustainable construction? Procedia Eng. 2016; 151:292–299.
[41] Asprone D, Auricchio F, Menna C, et al. 3D printing of reinforced concrete elements: technology and design approach. Constr Build Mater. 2018; 165:218–231.
[42] Roussel N. Rheological requirements for printable concretes. Cem Concr Res. 2018;112:76–85.
[43] Zhang Y, Zhang Y, She W, et al. Rheological and harden properties of the high-thixotropy 3D printing concrete. Constr Build Mater. 2019;201: 278–285.

[44] Weng Y, Li M, Tan MJ, et al. Design 3D printing cementitious materials via Fuller Thompson theory and Marson-Percy model. Constr Build Mater. 2018;163:600–610.
[45] Panda B, Unluer C, Tan MJ. Extrusion and rheology characterization of geopolymer nanocomposites used in 3D printing. Compos Part B Eng. 2019;176:107290.
[46] De Schutter G, Lesage K, Mechtcherine V, et al. Vision of 3D printing with concrete – technical, economic and environmental potentials. Cem Concr Res. 2018;112:25–36.
[47] Vaitkevičius V, Šerelis E, Kerševičius V. Effect of ultra-sonic activation on early hydration process in 3D concrete printing technology. Constr Build Mater. 2018;169:354–363.
[48] Panda B, Tan MJ. Experimental study on mix proportion and fresh properties of fly ash based geopolymer for 3D concrete printing. Ceram Int. 2018;44:10258–10265.
[49] Paul SC, Tay YWD, Panda B, et al. Fresh and hardened properties of 3D printable cementitious materials for building and construction. Arch Civil Mech Eng. 2018;18:311–319.
[50] Tay YWD, Qian Y, Tan MJ. Printability region for 3D concrete printing using slump and slump flow test. Compos Part B Eng. 2019;174:106968.
[51] Malaeb Z, Al Sakka F, Hamzeh F. 3D concrete printing: machine design, mix proportioning, and mix comparison between difference machine setups. In: Sanjayan JG, Nazari A, Nematollahi B, editors. 3D concrete printing technology. 1st ed. Vol. 6. Amsterdam: Elsevier; 2019. p. 115–136.
[52] Le TT, Austin SA, Lim S, et al. Mix design and fresh properties for high-performance printing concrete. Mater Struct. 2012;45:1221–1232.
[53] Han J, Wang K, Shi J, et al. Mechanism of triethanolamine on Portland cement hydration process and microstructure characteristics. Constr Build Mater. 2015;93:457–462.
[54] Malaeb Z, Hachem H, Tourbah A, et al. 3D concrete printing: machine and mix design. Int J Civil Eng Technol. 2015;6:14–22.
[55] Panda B, Unluer C, Tan MJ. Investigation of the rheology and strength of geopolymer mixtures for extrusion-based 3D printing. Cem Concr Compos. 2018;94:307–314.
[56] Le TT, Austin SA, Lim S, et al. Hardened properties of high-performance printing concrete. Cem Concr Res. 2012;42:558–566.
[57] Long W-J, Tao J-L, Lin C, et al. Rheology and buildability of sustainable cement-based composites containing micro-crystalline cellulose for 3D-printing. J Clean Prod. 2019;239:118054.
[58] Lim JH, Panda B, Pham Q-C. Improving flexural characteristics of 3D printed geopolymer composites with in-process steel cable reinforcement. Constr Build Mater. 2018;178:32–41.
[59] Panda B, Singh GB, Unluer C, et al. Synthesis and characterization of one-part geopolymers for extrusion based 3D concrete printing. J Clean Prod. 2019;220:610–619.
[60] Pacewicz K, Sobotka A, Gołek Ł. Characteristic of materials for the 3D printed building constructions by additive printing. MATEC Web Conf. 2018;222:01013.
[61] Rael R. 3D printing powder compositions and methods of use. US 9,388,078 B2, 2016.
[62] Xia M, Sanjayan J. Method of formulating geopolymer for 3D printing for construction applications. Mater Des. 2016;110:382–390.
[63] Utela BR, Storti D, Anderson RL, et al. Development process for custom three-dimensional printing (3DP) material systems. J Manuf Sci Eng. 2010;132:011008.
[64] Xia M, Sanjayan JG. Methods of enhancing strength of geopolymer produced from powder-based 3D printing process. Mater Lett. 2018;227:281–283.
[65] Zhang J, Khoshnevis B. Optimal machine operation planning for construction by contour crafting. Autom Constr. 2013;29:50–67.
[66] Panda B, Ruan S, Unluer C, et al. Improving the 3D printability of high volume fly ash mixtures via the use of nano attapulgite clay. Compos Part B Eng. 2019;165:75–83.
[67] Nematollahi B, Vijay P, Sanjayan J, et al. Effect of polypropylene fibre addition on properties of geopolymers

made by 3D printing for digital construction. Materials. 2018;11:2352.
[68] Kazemian A, Yuan X, Meier R, et al. Performance-based testing of Portland cement concrete for construction-scale 3D printing. In: Sanjayan JG, Nazari A, Nematollahi B, editors. 3D concrete printing technology. 2nd ed. Amsterdam: Butterworth-Heinemann, Elsevier; 2019. p. 13–35.
[69] Panda B, Lim JH, Tan MJ. Mechanical properties and deformation behaviour of early age concrete in the context of digital construction. Compos Part B Eng. 2019;165:563–571.
[70] Chen Y, Chaves Figueiredo S, Yalçinkaya Ç, et al. The effect of viscosity-modifying admixture on the extrudability of limestone and calcined clay-based cementitious material for extrusion-based 3D concrete printing. Materials. 2019;12:1374.
[71] Panda B, Noor Mohamed NA, Paul SC, et al. The effect of material fresh properties and process parameters on buildability and interlayer adhesion of 3D printed concrete. Materials. 2019; 12:2149.
[72] Wolfs RJM, Bos FP, Salet T. Hardened properties of 3D printed concrete: the influence of process parameters on interlayer adhesion. Cem Concr Res. 2019;119:132–140.
[73] Lim S, Buswell RA, Valentine PJ, et al. Modelling curved-layered printing paths for fabricating large-scale construction components. Addit Manuf. 2016;12:216–230.
[74] Mechtcherine V, Nerella VN, Will F, et al. Large-scale digital concrete construction – CONPrint3D concept for on-site, monolithic 3D-printing. Autom Constr. 2019;107:102933.
[75] Xu J, Ding L, Cai L, et al. Volume-forming 3D concrete printing using a variable-size square nozzle. Autom Constr. 2019;104:95–106.
[76] Hosseini E, Zakertabrizi M, Korayem AH, et al. A novel method to enhance the interlayer bonding of 3D printing concrete: an experimental and computational investigation. Cem Concr Compos. 2019;99:112–119.
[77] Rahul AV, Santhanam M, Meena H, et al. Mechanical characterization of 3D printable concrete. Constr Build Mater. 2019;227:116710.
[78] Bos F, Ahmed Z, Jutinov E, et al. Experimental exploration of metal cable as reinforcement in 3D printed concrete. Materials. 2017;10:1314.
[79] Bos FP, Bosco E, Salet T. Ductility of 3D printed concrete reinforced with short straight steel fibers. Virtual Phys Prototyp. 2019;14:160–174.
[80] Yu J, Leung C. Impact of 3D printing direction on mechanical performance of strain-hardening cementitious composite (SHCC). In: Wangler T, Flatt R, editors. First RILEM International Conference on Concrete and Digital Fabrication – Digital Concrete 2018 (DC 2018). RILEM Book Series. Vol. 19. Cham: Springer; 2019. p. 255–265.
[81] Zhu B, Pan J, Nematollahi B, et al. Development of 3D printable engineered cementitious composites with ultra-high tensile ductility for digital construction. Mater Des. 2019;181: 108088.
[82] Nam YJ, Park J, Woon Yoon SH, et al. 3D printing of fibers and reinforcements for cementitious composites to maximize the fracture-resisting performance of FRCCs. Proceedings of the 9th International Conference on Fracture Mechanics of Concrete and Concrete Structures (IA-FraMCoS); 2016.
[83] Nam YJ, Hwang YK, Park JW, et al. Fiber-reinforced cementitious composite design with controlled distribution and orientation of fibers using three-dimensional printing technology. In: Jay G. Sanjayan, Ali Nazari, Behzad Nematollahi, editors. 3D concrete printing technology. UK: Elsevier; 2019. p. 59–72.
[84] Hack N, Lauer WV. Mesh-mould: robotically fabricated spatial meshes as reinforced concrete formwork. Archit Des. 2014;84:44–53.
[85] Bos FP, Ahmed ZY, Wolfs RJM, et al. 3D printing concrete with reinforcement. In: Luković M, Hordijk DA, editors. High tech concrete: where technology and engineering meet, Proceedings of the 2017 Fib Symposium; Jun 12–14; Maastricht, The Netherlands. Cham: Springer; 2018. p. 2484–2493.
[86] Marchment T, Sanjayan J. Mesh reinforcing method for 3D concrete printing. Autom Constr. 2020;109:102992.

[87] Duballet R, Baverel O, Dirrenberger J. Classification of building systems for concrete 3D printing. Autom Constr. 2017;83:247–258.
[88] Ferdous W, Bai Y, Ngo TD, et al. New advancements, challenges and opportunities of multi-storey modular buildings – a state-of-the-art review. Eng Struct. 2019;183:883–893.
[89] Avrutis D, Nazari A, Sanjayan JG. Industrial adoption of 3D concrete printing in the Australian market. In: Jay G. Sanjayan, Ali Nazari, Behzad Nematollahi, editors. 3D concrete printing technology. UK: Elsevier; 2019. p. 389–409.
[90] WINSUN. The world's first 3D-printed office building is in Dubai; n.d. Available from: http://www.winsun3d.com
[91] Weiguo X. The world's largest concrete 3D printed pedestrian bridge, Tsinghua University; 2019. Available from: https://news.tsinghua.edu.cn
[92] Ceroni F, Pecce M. Evaluation of bond strength in concrete elements externally reinforced with CFRP sheets and anchoring devices. J Compos Constr. 2010;14:521–530.
[93] Alberto Chiusoli. The first 3D printed house with earth – Gaia, WASP Company; 2018. Available from: http://www.3dwasp.com
[94] Feng P, Meng X, Chen J-F, et al. Mechanical properties of structures 3D printed with cementitious powders. Constr Build Mater. 2015;93:486–497.
[95] Zareiyan B, Khoshnevis B. Interlayer adhesion and strength of structures in contour crafting – effects of aggregate size, extrusion rate, and layer thickness. Autom Constr. 2017;81:112–121.
[96] Papachristoforou M, Mitsopoulos V, Stefanidou M. Evaluation of workability parameters in 3D printing concrete. Procedia Struct Integr. 2018;10:155–162.
[97] Lim S, Buswell RA, Le TT, et al. Development of a viable concrete printing process. Proceedings of 28th International Symposium on Automation and Robotics in Construction; 2011 Jun 29–Jul 2; Seoul, South Korea. p. 665–670.
[98] Burroughs JF, Johnson CF, Al-Chaar GK, et al. Automated construction with concrete: response of wall and beam sections to blast loads. Structures Congress 2018 – Blast, Impact Loading, and Response; 2018 Apr 19–21; Fort Worth, TX. Reston, VA: American Society of Civil Engineers; 2018. p. 412–424.
[99] Panda B, Noor Mohamed NA, Tay YWD, et al. Bond strength in 3D printed geopolymer mortar. Cham: Springer; 2019. p. 200–206.
[100] Ting GHA, Tay YWD, Qian Y, et al. Utilization of recycled glass for 3D concrete printing: rheological and mechanical properties. J Mater Cycles Waste Manag. 2019;21:994–1003.
[101] Yeon K-S, Kim KK, Yeon J, et al. Compressive and flexural strengths of EVA-modified mortars for 3D additive construction. Materials. 2019;12:2600.
[102] Schröfl C, Nerella VN, Mechtcherine V. Capillary water intake by 3D-printed concrete visualised and quantified by neutron radiography. In: Wangler T, Flatt R, editors. First RILEM International Conference on Concrete and Digital Fabrication – Digital Concrete 2018 (DC 2018). RILEM Book Series. Vol. 19. Cham: Springer; 2019. p. 217–224.
[103] Weng Y, Li M, Liu Z, et al. Printability and fire performance of a developed 3D printable fibre reinforced cementitious composites under elevated temperatures. Virtual Phys Prototyp. 2019;14:284–292.
[104] Yang H, Chung JKH, Chen Y, et al. The cost calculation method of construction 3D printing aligned with internet of things. EURASIP J Wirel Commun Netw. 2018;2018:147.
[105] Sanjayan JG, Nematollahi B. 3D concrete printing for construction applications. In: Sanjayan JG, Nazari A, Nematollahi B, editors. 3D concrete printing technology. Vol. 1. Amsterdam: Elsevier; 2019. p. 1–11.
[106] Assaad JJ. Correlating thixotropy of self-consolidating concrete to stability, formwork pressure, and multilayer casting. J Mater Civil Eng. 2016;28:04016107.
[107] Marchment T, Sanjayan J, Xia M. Method of enhancing interlayer bond strength in construction scale 3D printing with mortar by effective bond area amplification. Mater Des. 2019;169:107684.

[108] Oropallo W, Piegl LA. Ten challenges in 3D printing. Eng Comput. 2016;32: 135–148.
[109] Feng P, Meng X, Chen J-F, et al. Mechanical properties of structures 3D-printed with cementitious powders. In: Jay G. Sanjayan, Ali Nazari, Behzad Nematollahi, editors. 3D concrete printing technology. UK: Elsevier; 2019. p. 181–209.
[110] Ma G, Li Z, Wang L, et al. Mechanical anisotropy of aligned fiber reinforced composite for extrusion-based 3D printing. Constr Build Mater. 2019;202:770–783.
[111] Yuan X, Chen W, Lu Z, et al. Shrinkage compensation of alkali-activated slag concrete and microstructural analysis. Constr Build Mater. 2014;66: 422–428.
[112] Furet B, Poullain P, Garnier S. 3D printing for construction based on a complex wall of polymer-foam and concrete. Addit Manuf. 2019;28:58–64.
[113] Rejeski D, Zhao F, Huang Y. Research needs and recommendations on environmental implications of additive manufacturing. Addit Manuf. 2018;19: 21–28.
[114] Apis Cor|3D Printed Homes|United States; n.d. Available from: https://www.apis-cor.com/
[115] American Concrete Institute. 3-D printing with cementitious materials. 2019.
[116] Zhang J, Gong C, Guo Z, et al. Engineered cementitious composite with characteristic of low drying shrinkage. Cem Concr Res. 2009;39: 303–312.
[117] Jennings R. Forbes Company, China lays groundwork for Asian, world lead in 3D printing; 2018. Available from: https://www.forbes.com
[118] Government of Dubai, Dubai Future Foundation, Making Dubai the worlds 3D printing hub; 2019. Available from: www.dubaifuture.gov.ae
[119] NASA announces $1,00,000 winners of virtual 3D-printed mars habitats|Space; n.d. Available from: https://www.space.com/3d-printed-mars-habitats-nasa-prizes.html
[120] Khayat KH, Meng W, Vallurupalli K, et al. Rheological properties of ultra-high-performance concrete– an overview. Cem Concr Res. 2019;124: 105828.