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State-of-the-art of 3D printing technology of cementitious material—An emerging technique for construction

MA GuoWei[1,2*], WANG Li[3] & JU Yang[4]

[1] College of Architecture and Civil Engineering, Beijing University of Technology, Beijing 100124, China;
[2] School of Civil, Environmental and Mining Engineering, The University of Western Australia, Crawley, WA 6009, Australia;
[3] School of Mechanics and Civil Engineering, China University of Mining & Technology at Beijing, Beijing 100083, China;
[4] State Key Laboratory of Coal Resources and Safe Mining, China University of Mining & Technology at Beijing, Beijing 100083, China

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In recent few years, significant improvement has been made in developing largescale 3D printer to accommodate the need of industrial-scale 3D printing. Cementitious materials that are compatible with 3D printing promote rapid application of this innovative technique in the construction field with advantages of cost effective, high efficiency, design flexibility and environmental friendly. This paper firstly reviews existing 3D printing techniques that are currently being used in commercial 3D printers. It then summarizes three latest development of largescale 3D printing systems and identifies their relationships and limiting factors. Thereafter, critical factors that are used to evaluate the workability and printable performance of cementitious materials are specified. Easy-extrusive, easy-flowing, well-buildable, and proper setting time are significant for cementitious material to meet the critical requirements of a freeform construction process. Finally, main advantages, potential applications and the prospects of future research of 3D printing in construction technology are suggested. The objective of this work is to review current design methodologies and operational constraints of largescale 3D printing system and provide references for optimizing the performance of cementitious material and promote its responsible use with largescale 3D printing technology.

3D printing, cementitious material, construction automation

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1 Introduction

In recent years, 3D printing, also known as additive manufacturing (AM), is quickly gaining popularity in various applications. 3D printing is specifically defined by the American society for testing and materials (ASTM) as the fabrication of objects through the deposition of a material using a print head, nozzle, or another printer technology [1]. In the printing process, a digital 3D model is firstly created by dedicated software, or by the scanning of an existing object. Then, an algorithm cuts the digital model into 2D slices. Finally, a printer build the object slice by slice according to the digital prototypes [2,3]. This advanced technology realizes a rapid manufacturing of 3D objects of almost any shapes in a layer by layer manner and it can complete the fabricating process of a complex component with multiple materials and at cross-scales at a time. It has several key advantages in developing prototypes and mock-ups, including ease of duplicating products, cost-effective, time-efficient and privacy considerations [4,5]. Since the first 3D printer was invented by Charles Hull in 1986, 3D printing technique has been widely applied in the domains of industrial design, manufacturing, bioengineering, automotive engineering, aerospace engineering, food processing,

*Corresponding author (email: guowei.ma@uwa.edu.au)

architecture and buildings [6–9]. For example, the electrical discharge machining electrodes, electronic switch, architectural model, bone tissue engineering scaffolds, etc., can all be manufactured via a 3D printer [10,11]. In particular, 3D printing paves an innovative and efficient way to produce various complex structures in a surpassingly accurate process. Goyanes et al. [12] have fabricated individual tablets containing drug doses tailored to individual patients by means of fused-filament 3D printing (FF 3DP). The minimum feature can be realized was 0.1 mm. Ju et al. [13] has produced transparent aggregated geomaterials models through Polyjet printing with a relatively high feature resolution of 10–50 μm. Hsu et al. [14] have manufactured electrical discharge machining (EDM) electrodes through inkjet printing. The used material was gypsum powder and the printing accuracy was 0.1 mm. Zhang et al. [6] have 3D printed flexible circuits based on graphene using fused depositing modeling (FDM). The minimum feature can be realized was 1.75 mm. Based on the building manners, the printing processes can be mainly divided into several categories: extrusion deposition, light polymerization and powder bed based printing. The adopted printing materials can be liquid (photopolymer, photocurable acrylic resin, thermocurable epoxy, etc.), solid (thermoplastics, metal alloy, rubbers, etc.) and powders (plaster powder, metal powders, ceramic powders, etc.) [15,16]. Various commercialized 3D printers are available nowadays to produce almost any small scale structures [17,18].

From largescale perspective, buildings and structural components are also products that can be produced via 3D printing. It is of great feasibility to apply the 3D printing in the construction field. A few attempts have been conducted to explore the potential of 3D printing in the building and construction industry. The first attempt at cement-based AM was conducted in 1997 [19]. Concrete components were manufactured by depositing a thin layer of sand, followed by depositing a patterned layer of cement paste to selectively glue the sand together. Layers were compressed and then steam is applied to obtain rapid curing. But this work was not continued. Since 1998, professor Berokh Khoshnevis [20] at the University of Southern California (USA) developed a cementitious material AM process called “Contour Crafting”, which later become an effective method to print real-life houses. Contour crafting constructs concrete buildings through extruding cementitious concrete by a gantry-driven nozzle layer upon layer without using extra formworks. In 2007, an Italian engineer Enrico Dini [21] invented a largescale powder based 3D printer, named D-shape. It intended to create architectural artefacts using sand and an inorganic binder with 5–10 mm of the layer depth. The process is claimed to produce a material with similar properties to marble. In 2012, Novikov et al. from the Institute for Advanced Architecture of Catalonia (Spain), have built a robotic 3D printer, named ‘Stone Spray’ [22]. It creates architectural structures by gluing a mix of sand or soil together and with the help of a kind of eco-friendly binder. In 2013, Platt et al. [23] developed cellular fabrication technology (C-Fab), which can be applied in modern construction process more quickly and more affordably than other type largescale 3D printing process. C-Fab only used to create support structures for construction components. Insulating foam is firstly sprayed in the interior part of the support structure. Then concrete material is sprayed in the lateral parts, followed by adding external elements, like brick, stucco, etc. In 2014, Qingdao Unique Technology, a Chinese company, also exhibited their large 3D printer with a size of 12 m×12 m×12 m. By using a technology similar to fused deposition modeling (FDM), the printer extrudes a kind of half-melt glass reinforced plastic material layer upon layer on a base ground to construct the prototypes [24]. In 2015, the world’s advanced saving project (WASP) introduced a huge 3D printer, named BigDelta, which measures 12 m tall, 6 m wide and uses less than 100 W of power. BigDelta printed an adobe structure at the open-air construction site using eco-friendly material of clay, straw, dirt and water. An elevator was connected to the scaffolding of printer to deliver the relatively solid materials [25].

When the 3D printing comes into the construction field, the key issue of current 3D printing technology lies in the preparation of printable cementitious material. Recently, a few of printable materials have been explored for construction applications. Gibbons et al. [26] investigated the feasibility of using rapid-hardening Portland cement (RHPC) to produce structures by a powder-binding 3D printing system. They found that layered structures became less distinct and the fracture surface path was less influenced by the layers after water curing. Maier et al. [27] have demonstrated that calcium aluminate cements (CAC) is of high feasibility to be applied in 3D printing structures with favorable fresh and hardening properties. Xia and Sanjayan [28] developed a type of environmental friendly material, slag-based geopolymer, which was comprised of slag, silicate-based activator and fine sand. The proposed geopolymer has been proven to possess sufficient deposit ability to replace commercially available material in powder-based 3D printers, and shows good dimensional accuracy when utilized to print structures. The method developed in their study is readily scalable to produce large structural components. Khoshnevis et al. [29] proposed a kind of cementitious composite that is comprised of plaster and clay-like materials and could be smoothly extruded by contour crafting system, achieving a high surface-finish and highest geometric accuracy. However, this material has low stiffness at fresh stage and three percent shrinkage after extrusion and setting. Additionally, there are several alternative strategies for the design of extrudable cementitious material for 3D printing. Reactive powder concrete (RPC) is a kind of high strength and high performance concrete mixture. It is composed of very fine powders, such as cement, fine sand, quartz powder, fly ash and silica fume and high efficiency superplasticizer with no coarse aggregates [30,31]. Self-compacting concrete holds the basic principle that aggregate particles form a precise smooth grading with a maximum packing density and a considerable content of cement/cementitious paste with superplasticizer, which fill the voids between aggregates to produce favorable fluidity [32]. Sprayed concrete is another reference to the design of extrudable material. Optimized grading of aggregate, fine sand, high content cement and powdered additions make sprayed concrete easy-pumpable, easy-extrudable and with good adhesion and build-up thickness [33].

Largescale 3D printing systems coupled with printable cementitious/cement-based materials paves a new way to produce construction projects. When 3D printing for cementitious materials comes into the field of civil engineering, it can enhance construction on several levels: it can shorten the development cycle of building real life scale construction projects by removing some time-consuming works in the conventional method [34]; it greatly reduces production costs incurred on the project by eliminating unnecessary waste, overlapping production and the requirement of labor [35,36]; it can also offer flexibility and freedom of architectural design and construction automation, and ensures higher safety in the construction process and performs a series of eco-friendly impact on the environments [37]. However, researches relating to 3D printing of cementitious material are still in their infancy. There still remain lots of limitations and barriers to overcome, such as fully understanding the mechanical design and operational principle of largescale 3D printing systems, compatibility optimizing of mix process, printable performance control and evaluation criteria of cementitious material, as well as the potential challenges and further developing directions, etc.

Wu et al. [38] and Perkins and Skitmore [39] have provided a comprehensive review of the state-of-the-art of 3D printing technology in the construction industry. Their works provide systematic understandings of the design and applications of largescale 3D printing in construction sector. The objective of our works is to review current design methodologies and operational constraints of largescale 3D printing system and provide references for optimizing the performance of cementitious material and promote its responsible use with largescale 3D printing technology. This paper is organized as follows. The first section of this paper gives an overview of the printing techniques available for commercialized 3D printers. The three largescale AM techniques, i.e. contour crafting, D-shape technology, and concrete printing, and their characteristics are described and discussed in detail. The paper then focuses on issues of design, preparation and requirements associated with manufacturing cementitious material appropriated to largescale printing techniques. The main benefits, potential applications and further developing direction of this advanced technique are presented. Finally, in the last section a few concluding remarks are drawn.

2 3D printing in manufacturing industry

Various 3D objects can be replicated by printers in a layer by layer process. 3D printing is a process in which various materials (liquid, powder, solid or sheet material) are successively solidified layer upon layer by extrusion, sintering, binding, polymerizing or other printing technology, and finally accumulating to form solid models. Each layer is equivalent to a cross section of the digital model and they fuse together to create the final shape [40,41]. Table 1 presents a summary of the commercialized AM technologies [42]. A large number of 3D printing techniques have been developed and commercialized in current market, such as selective laser sintering (SLS) [43], stereo lithography appearance (SLA) [44], and fused deposition modeling (FDM) [45]. SLS, SLA and FDM are three widely used techniques, which belong to powder bed typed, light-polymerization typed and extrusion typed AM technology, respectively [46,47].

Figure 1(a) shows the operating process of SLS. At first, one layer of powder is spread out over the bed area through a roller. Then specific areas are solidified by laser according to the designed model input to the computer. Once a layer is accomplished the platform falls down by a layer thickness and a new layer of powder is deposited over the previously sintered layer. These processes are repeated sequentially until the entire object is created. The SLS technique can be applied to manufacture 3D solids and structures utilizing various materials, such as metal alloy, gypsum, ceramic and glass [48–51]. ProX200 3D printer, produced by 3D Systems Ltd., is an example of commercialized devices employing SLS. It offers a relatively high resolution up to 100 μm×100 μm×20 μm, the molding-layer thickness ranges from 10–50 μm, and the space for printing is 140 mm×140 mm×100 mm [52]. SLA is the originally and widely used method for producing plastic objects. As shown in Figure 1(b), the liquid photopolymer material is stored in a container. A platform is firstly immersed to a depth equivalent to the thickness of one layer, and then UV light beam is utilized to selectively polymerize the liquid photopolymer. Then the platform is lowered down by a layer thickness, the solidified layer of polymer is simultaneously dispensed and the laser beam scans across the surface and harden it again. The 3D object is therefore created by sequentially polymerizing the polymer layer by layer [53,54]. Objet Connex500 3D printer, produced by Stratasys Ltd., is an example of commercialized devices employing SLA. It offers a relatively high resolution up to 600×600×1600 dpi with a dot accuracy of 10–50 μm, the molding-layer thickness ranges from 16–30 μm, and the space for printing

Table 1 Summery of commercialized AM technologies

Type	Technologies	Materials
Extrusion	Fused deposition modeling (FDM)	Thermoplastics, eutectic metals, edible materials, rubbers, modeling clay, plasticine, metal clay
	Robocasting or Direct Ink Writing (DIW)	Ceramic materials, metal alloy, cermet, metal matrix composite, ceramic matrix composite
	Composite Filament Fabrication (CFF)	Nylon, nylon with short carbon fiber reinforcement in the form Carbon, Kevlar, Glass
Light polymerized	Stereolithography (SLA)	Photopolymer, resin
	Digital Light Processing (DLP)	Photopolymer, resin
Powder bed	Powder bed and inkjet head 3D printing (3DP)	metal alloy, powdered polymers, plaster
	Electron-beam melting (EBM)	Almost any metal alloy
	Selective laser melting (SLM)	Titanium alloys, cobalt chrome alloys, stainless steel, aluminum
	Selective heat sintering (SHS)	Thermoplastic powder
	Selective laser sintering (SLS)	Thermoplastics, metal powders, ceramic powders, glass
	Direct metal laser sintering (DMLS)	Almost any metal alloy
Laminated	Laminated object manufacturing (LOM)	Paper, metal foil, plastic film
Powder fed	Directed Energy Deposition	Almost any metal alloy
Wire	Electron beam freeform fabrication (EBF^3)	Almost any metal alloy

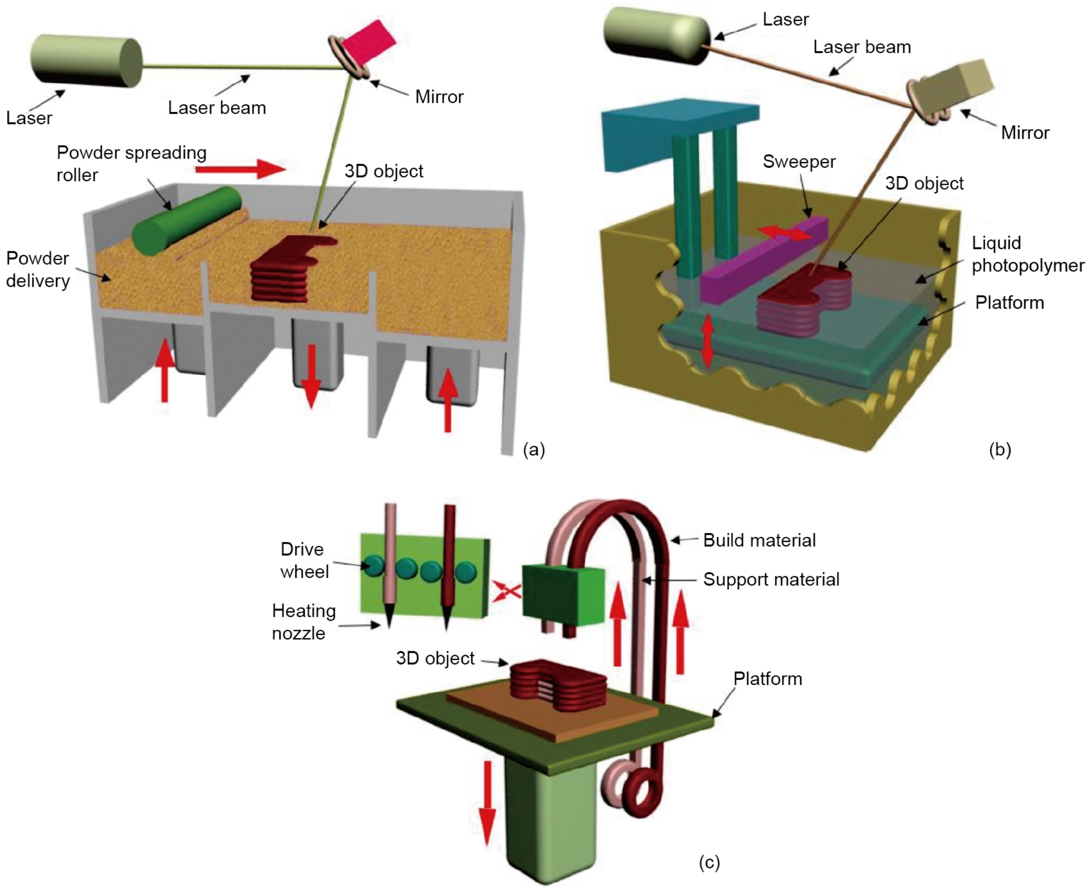

Figure 1 (Color online) Illustration of the operating process of (a) SLS, (b) SLA and (c) FDM.

is 500 mm×400 mm×200 mm [55]. Figure 1(c) illustrates the operating process of FDM. Different with SLS and SLA, FDM is an extrusion process to fabricate physical prototypes. Materials used in FDM process are initially in the form of filament. They will be melted and turn to liquid state when passing through the heated nozzles. The melted material is deposited according to the profile of model's cross sections. Once cooled down, the material is solidified and sticks to the previously extruded structures. 3D models are also built in a continuously layered manner. After completion of one layer, the nozzle moves up ward along the *z* direction or the table lowers in *z* direction, and then the next layer is printed [56,57]. Duplicator 4/4× 3D printer, produced by Wanhao Ltd., is an example of commercialized devices employing FDM. Its maximum printing size is 225 mm×145 mm×150 mm with a nozzle diameter of 0.4 mm [58]. Other than the above cited technologies, the Polyjet technique, a variant of SLA, is also a type of 3D printing process. It provides a new approach to prepare complex photoelastic models, which can experimentally characterize the stress field by the isochromatic fringe orders, based on the birefringence property of transparent photoelastic materials. It has been successfully applied to physically visualize and transparentize the stress field of heterogeneous materials and solve some scientific problems in rock engineering and civil engineering [13,55,59].

3 3D printing in construction field

In recent years, the development of largescale AM has been developed to accommodate the need of architecture and construction. Different in the deposition process and building manner, current printing procedures targeted at architecture and construction mainly include the following three types that could offer construction automation.

3.1 D-shape

D-shape is a large 3D printer that selectively binds sand with magnesium-based binder in order to create stone-like objects. Similar to the SLS printing process, sand powder material is spread out to a desired thickness, and then the print head equipped with a set of spreading nozzles deposits a binding liquid to selectively bind the sand together according to the digital prototypes. Meanwhile, the remaining sand serves to support the structure. This is done in a layer-by-layer manner. Once completed, the printed part can be taken out of unconsolidated material and remaining powder can be reused in another fabrication process [60].

Figure 2 depicts the schematic view of the D-shape technology. The core of the D-shape printer is the printer head installed with hundreds of spraying nozzles. The printer head is connected to the square base by a horizontal beam, which can freely move along *X* axis. And the square base moves upwards (*z*-axis) along vertical beams through four stepper motors. During printing process, spraying nozzles selectively sprays a binding liquid on predefined areas of the sand layer. Once a layer has been printed, a horizontal beam also act as powder material spreader prior to subsequent layer manufaction [61].

D-shape has been proven to be very effective in printing very largescale structures. A 1.6 m high freeform sculpture and a whole house build in one single printing process depicted in Figure 3 are created by D-shape. A research project funded by the European Space Agency (ESA) has been suc-

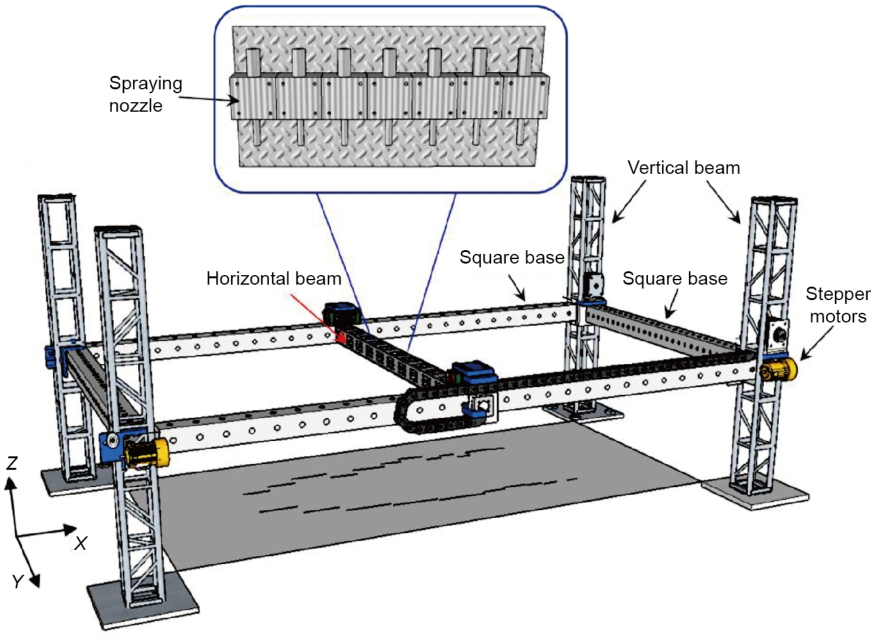

Figure 2 (Color online) Schematic view of the D-shape printer.

(a) (b) (c)

Figure 3 (Color online) Largescale structures manufactured via D-shape technology. (a) 1.6 m high sculpture; (b) a complete house printed in one single process; (c) landscape house design based on a Mobius strip.

cessful in printing full scale components for the lunar bases with a simulated moon dust via D-shape, however how the printer will work in the environment on the moon has also been subject to tests [61]. It is claimed that D-shape will allow military to construct infrastructure such as bunkers, hospitals and bases, much faster than it would take with more traditional methods [62]. Enrico Dini and a collaborator Vittadello intended to print out many different structural blocks using the D-shape technique. The material was a mixture of sand, salt and an inorganic binding agent. The blocks were assembled by machines to create a futuristic looking structure [63]. D-shape with respect to the other techniques proved to be very effective in printing very large scale objects. For instance, it allowed to build in one single printing process a whole house [64].

(1) Case 1

An urban temple project for the city hall of Pontedera (Pisa) [60], as illustrated in Figure 3(a).

Year: 2008;

Designer: Andrea Morgante;

Size: 3 m×3 m×3 m;

Material: inorganic binder, sand/mineral dust;

Production process: powder-based;

Product: one-piece structure.

(2) Case 2

One single process printed house [61], as illustrated in Figure 3(b).

Year: 2010;

Designer: Marco Ferreri;

Production process: powder-based;

Product: one-piece structure;

Time consumption: 3 weeks;

(3) Case 3

Landscape house design based on a Mobius strip [65], as illustrated in Figure 3(c).

Year: estimated to be built in 2017;

Designer: Janjaap Ruijssenaars;

Area: 1100 m^2;

Material: a bio-plastic made out of 80% vegetable oil, concrete paste;

Production process: powder-based;

Product: hollow components.

3.2 Contour crafting

Contour crafting (CC) is a mega-scale automatic construction process that controlled by computer to exploit the superior surface forming capability of troweling to create smooth and accurate planar and freeform surfaces. Contour crafting offers better surface quality, higher build speed, and wider range of optional materials [20,35,66]. CC can reliably print out very large objects with dimensions of several meters, which is contributed by equipping with a multi-axis robotic arm. Contour crafting has been developed to effectively address the issue of high-speed automated construction [67,68].

The schematic plot in Figure 4 depicts the construction process based on contour crafting printing. A gantry system can carry the printing nozzle move along X axis and Z axis and two parallel sliding structures carry the nozzle moving along Y axis. The CC process combines an extrusion and a filling process as illustrated in the exaggerated area in Figure 4. Two trowels are installed on the printing nozzle to create smooth and accurate object surfaces. The external edges are built firstly as the printing nozzle moves according to the pre-set path. Thereafter, another type of cementitious material is poured to fill the internal volume formed by the outer edges [28]. Using materials with rapid curing properties and low shrinkage characteristics, the structural components can be built up rapidly with consecutively deposited layers.

Bosscher et al. [69] proposed a mobile contour crafting platform driven by a translational cable-suspended robot. Their CC system enable significant improvements in better portability, lower cost and build larger structures over other type of CC systems. Zhang and Khoshnevis [68] has provided a systematic solution for enhancing the overall efficiency of contour crafting systems, including optimal machine operation plan for single nozzle CC system and collision-free operation plans for multiple nozzle CC system. Contour crafting has been successfully applied in in-site application. Existing example is from Rudenko's garden [70], where he managed to build a castle. Material used in a printer was a mix of cement and sand. Whole building was printed on a single run, except of towers, that were printed separately and assembled to the building. In 2014, WinSun, a company in China, built ten houses in Shanghai using a gigantic 3D printer (150 m×10 m×6.6 m) within 24 h. Each building (200 m^2 floor area) was entirely created by high-grade cement and glass fiber. After that, they built the highest 3D printed building, a five-story apartment and the world's first 3D printed villa [71]. Figure 5 gives several examples of full scale builds from contour crafting printing.

(1) Case 1

Concrete wall [35], as illustrated in Figure 5(a).

Year: 2006;

Designer: Behrokh Khoshnevis;

Size: 1.52 m×0.61 m;

Material: cement paste;

Product: rebar reinforced;

Production process: outer wall is firstly extruded, then the inner part is placed.

(2) Case 2

Hollow walls with corrugated internal structure [60], as illustrated in Figure 5(b).

Year: 2013;

Designer: Behrokh Khoshnevis;

Material: concrete;

Production process: extrusion;

(3) Case 3

Castle printed *in-situ* [70], as illustrated in Figure 5(c).

Year: 2014;

Designer: Andrey Rudenko;

Material: concrete;

Area: 15 m^2;

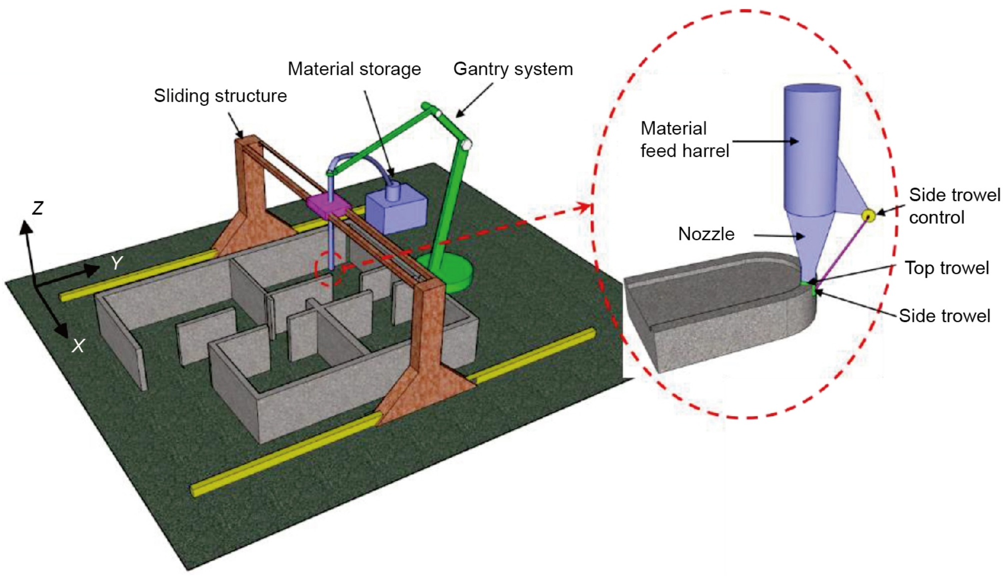

Figure 4 (Color online) Construction of building using contour crafting printing.

Figure 5 (Color online) Examples of full scale builds from contour crafting printing. (a) Concrete wall with a height of 60 cm; (b) hollow walls with corrugated internal structure; (c) castle printed *in-situ*; (d) five-story apartment built by WinSun; (e) clay and straw wall, over 2 m and still growing.

Product: components assembling;

Production process: extrusion.

(4) Case 4

3D printed five-story apartment [71], as illustrated in Figure 5(d).

Year: 2015;

Company involved: WinSun, China;

Floor area: 1100 m^2;

Material: combination of cement, glass fiber and construction waste;

Production process: extrusion.

(5) Case 5

First adobe building [25], as illustrated in Figure 5(e).

Year: 2016;

Designer: WASP project;

Material: clay, straw, water;

Current size: 2.7 m in height, 5 m in diameter, 135 layers;

Weight: 40 t;

Printing speed: 20 min/layer;

Production process: extrusion.

3.3 Concrete printing

Concrete printing is another largescale construction process. Concrete printing is similar to the contour crafting to a certain extent, since the print head used for the extrusion of cement mortar is also mounted on an overhead crane. Printing nozzle moves along a pre-programmed path and continually extrudes concrete materials. Compared with contour crafting, 3D concrete printing is also based on the extrusion of cement mortar, but this method has a smaller resolution of deposition, results in better controlling of complex geometries [60]. Concrete printing has the potential to produce highly customized building components [72,73].

Figure 6 illustrates the operation process of concrete printing. Printing head installed in a tubular steel beam can freely move in *X*, *Y* and *Z* directions. Fresh concrete is firstly deli-

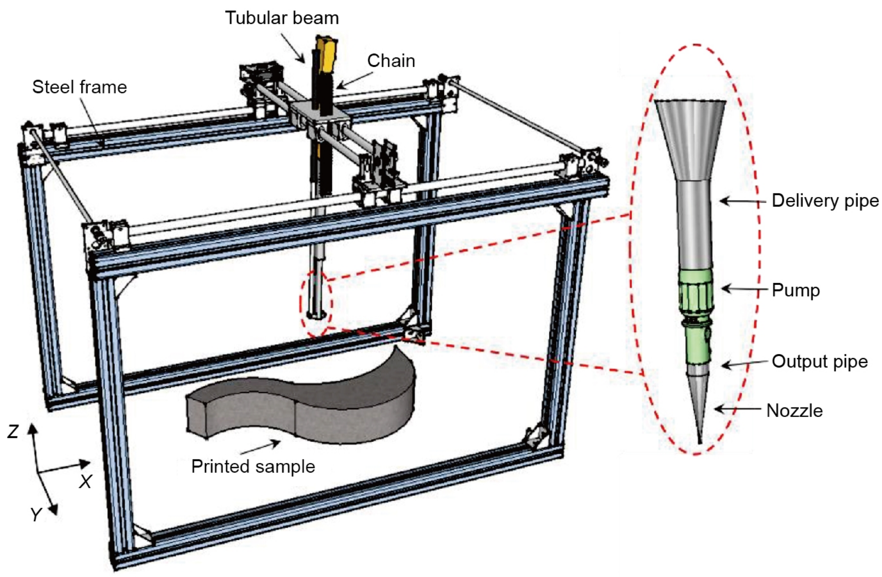

Figure 6 (Color online) Schematic of concrete printing, magnified region is the concrete deposition system.

vered to a pump through the delivery pipe. Then concrete material is delivered smoothly to the printing nozzle with the help of the pump. Finally, concrete filaments are extruded out from the nozzle to continually trace out the cross section of structural components.

Similar to FDM, 3D concrete printing deposits concrete mixture through a nozzle to build structural components without the use of formwork and subsequent vibration. Engineer Alex Le Roux from Baylor University [74] designed and built a concrete 3D printer, which could print an entire 8×5×7 foot structure within 24 h with cement composite. The print speed was 0.3 feet/s. A research team at Eindhoven University of Technology (TU/e) in the Netherlands has just unveiled their massive concrete 3D printer to the public. The printer is made up of a four axis gantry robot and features a print bed of 9.0 m×4.5 m×3 m. It also has its own mixing pump, with the entire printer controlled by a numeric controller [75]. Lim et al. [72] at Loughborough University (UK) has developed a novel Concrete Printing system within a 5.4 m×4.4 m×5.4 m steel frame. A named Wonder Bench shown in Figure 7(a) is manufactured by concrete printing, which consists of 128 layers with an average printing speed of 20 min/layer. Lim et al. [76] applied a non-conventional way of additive manufacturing, curved-layered printing, curved layered fused deposition modelling (CLFDM), to large-scale construction process. A doubly-curved 4-part sandwich panel printed by means of CLFDM is illustrated in Figure 7(c). Gosselin et al. [77] developed a new largescale concrete printing process, where ultra-high performance concrete is deposited through an extrusion print head mounted on a six-axis robotic arm.

(1) Case 1

Wonder Bench [60], as illustrated in Figure 7(a).

Year: 2015;

Size: 2 m×0.9 m×0.8 m, 128 layers;

Printing speed: 20 min/layer;

Estimated weight: around 1.1 t;

Product: internal structure including functional voids and reinforcement.

(2) Case 2

Acoustic damping wall element [77], as illustrated in Figure 7(b).

Year: 2016;

Designer: C. Gosselin (France);

Material: concrete;

Size: 650 mm×650 mm×300 mm;

Time consumption: 2 h;

Printing speed: 4.6 min/layer;

(3) Case 3

Printed doubly-curved 4-part sandwich panel [76], as illustrated in Figure 7(c).

Year: 2011;

Designer: Sungwoo Lim (UK);

Material: concrete;

Size: 1.5 m×1.5 m×0.1 m;

Curing conditions: consistent high humidity (90%–100%), wet hessian, plastic sheeting covers;

Exhibited at the Building Centre Exhibition, London.

3.4 Characteristics of largescale 3D printing

Existing practices related to largescale 3D printing process and that have the potential for real-life construction are described in above sections, namely contour crafting, D-shape and concrete printing. These three largescale manufacturing processes are similar in that they build components in an automotive and layer-by-layer manner, however, each process keeps its own distinct features, resulting in different advantages when applied in engineering situations. Table 2 presents

Figure 7 (Color online) 3D components manufactured by concrete printing. (a) Wonder bench (2 m×0.9 m×0.8 m); (b) acoustic damping wall element; (c) curved-layered construction component.

Table 2 Similarities and differences of largescale AM process in construction

	Contour crafting	D-shape	Concrete printing
Process	Extrusion based	Selective binding	Extrusion based
Support	Vertical: no Horizontal: lintel	Unused powder	A second material
Material	Cementitious material	Sand	High performance concrete
Printing resolution	Low (15 mm)	High (0.15 mm)	Low (9–20 mm)
Layer thickness	13 mm	4–6 mm	5–25 mm
Print head	1 nozzle	Hundreds of nozzles	1 nozzle
Nozzle diameter	15 mm	0.15 mm	9–20 mm
Printing speed	Fast	Slow	Slow
Printing dimension	Mega-scale	Limited by frame (6 m×6 m×6 m)	Limited by frame

a summary in respect to the characteristics of each largescale additive manufacturing process.

In terms of printing scale, contour crafting is a promising approach to realize real-life construction contributed by its multi-axis robotic arm. Compared with contour crafting, the manufacturing dimension of the other two processes is greatly restrained by their deposition method and in particular the mechanical frame. In terms of printing speed, the contour crafting and concrete printing process are currently fixed with a single and large-diameter nozzle, resulting in a high layer build up speed. Contour crafting and concrete printing process, while being quite fast, are limited to low printing resolution and large layer thickness. D-shape possesses higher printing resolution (i.e. the smallest detail that can be built) which precisely profit from the small-diameter nozzles. Hence it is a dilemma to acquire favorable printing speed and resolution. Increasing printing precision will inevitably extend the printing time and require more layers to print. In terms of deposition path, contour crafting reduces operating time between layers by outlining a whole layer with two passes of the printing head. This process specialized in manufacture wall-like components and structures. D-shape print the entire cross-section by only a single traverse. Concrete printing also utilizes a single deposition nozzle, however, unlike D-shape, it has to traverse the entire build area by lots of cycles. In terms of manufacturing over-hanging areas, contour crafting process needs a lintel to bridge the gap right above the windows, otherwise adopting self-supporting layers to form small curvature structures. It is beyond the capability of contour crafting to print an entire building including window and roof all at once. However, the powder bed method D-shape is a good solution to this problem, which uses the unconsolidated powder surrounding the unfinished objects to support the whole structure through the constructing process. It allows the entire building being printed within a single process once the dimension of the printer is larger than the house.

Each of the three above cited techniques exploit slightly different construction methods, processes and materials. Each method keeps its own advantages and limitations for wide applications. It is therefore expected that future studies should be conducted on developing composite functional 3D printers that equipped with two or more printing heads and material transportation paths and expand the applicability of 3D printing in the construction industry.

4 Design methodologies of cementitious material for 3D printing

Given that the above cited largescale 3D printing system are compatible with gantry system which is transportable or can be set up on site, a combination of the largescale 3D printing technique with high strength and high performance cementitious materials could result in a higher quality 3D printing system for construction. In order to ensure the mixture with good workability and printable performance for applying in a largescale 3D printer, the cementitious material must be designed to coordinate with the design of the 3D printer, including its material storage system, delivery system, depositing system, printing system and control system [78]. Figure 8 shows a general requirement in the mixing design of cementitious mixture for construction-scale 3D printing. In principle, the cementitious material shall be easy-extrusive, easy-flowing, well-buildable, and with good mechanical strength and proper setting time in order to reach a continuous paste from the printing nozzle and to ensure a rapid modelling of freeform construction.

4.1 Extrudability control

The cementitious materials for 3D printing need to have an acceptable degree of extrudability, which related to the capacity of material to continuously pass through the small pipes and nozzles at the printing head. Extrudability control of cementitious material for 3D printing shall lie in a smooth grading of materials. Alternative raw materials should have rounded shape and fine particles. Compared to angular aggregates, employing round shape aggregates would enable a better control of extrudability and decrease blocking potential for a given water to powder ratio. Generally, basic principle of grading design for printing material is to use a considerable volume of cementitious paste to fill the voids formed between smooth graded aggregate particles. This is to a large extent similar to the preparation method of self-compacting concrete [79,80].

A certain amount of trials have been carried out to explore the optimal extrudability control for cementitious materials. Malaeb et al. [37] found that the most suitable mixture was composed of a fine aggregate to a cement ratio of 1.28 and a fine aggregate to sand ratio of 2.0. And the maximum size of an aggregate is set as 1/10 of the diameter of the printing nozzle. Le et al. [81] selected sand with a maximum size of 2 mm to manufacture concrete paste used for a small nozzle with a diameter of 9 mm, which provides a high printing resolution. The optimum mixture of a high-performance printing concrete was found to have a 3:2 sand-binder ratio with the latter comprising 70% cement, 20% fly ash and 10% silica fume. Perrot et al. [82] prepared a kind of cement paste used for 3D printing extrusion techniques, which containing 50%

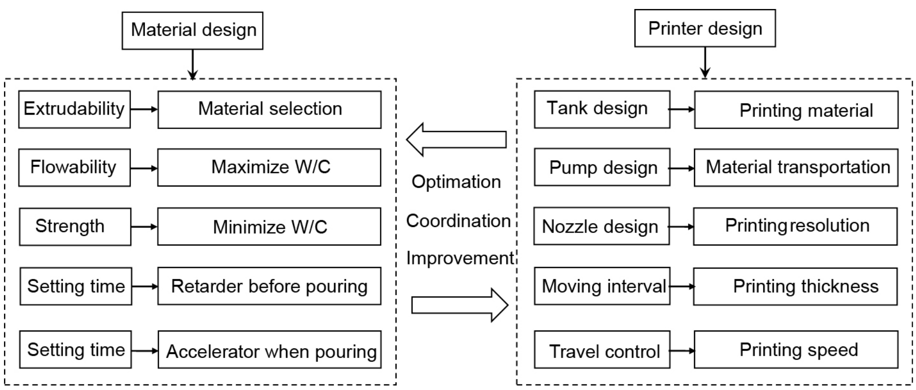

Figure 8 General requirements in the mix design of cementitious mixture for construction-scale 3D printing.

cement, 25% limestone filler and 25% kaolin. The average particle sizes of these three powders are 10, 9 and 15 μm.

4.2 Flowability control

Flowability of printing paste is also a key parameter to evaluate the printable performance of cementitious paste. Flowability controlling makes sure that the paste can be easy-pumpable in the delivery system and easy-depositable in the deposition system. There are two commonly used approaches to improve the flowability of cement mixtures. It is obvious that the most important parameter affecting the flowability of cement paste is the water to binding material ratio. However, a higher water content could lead to large pore or void content, reduce the mechanical strength to a large extent [83]. In most cases, a superplasticizer is preferred to improve the flowability of cement paste while maintaining comparable or higher mechanical strength to increasing water content. The addition of a superplasticizer would disperse the flocculated cement particles, thereby releasing some of the water trapped inside the voids to increase the rheology fluidity of the paste [84,85]. Malaeb et al. [37] tested the flowability of 3D printing concrete materials that contained four mass ratios of superplasticizer by means of slump flow test. The flowability rates of concrete materials with 0.14%, 0.28%, 0.3%, and 0.35% of superplasticizer was 1.1, 1.15, 1.2 and 1.4 cm/s, respectively. Le et al. [81] demonstrated that concrete mixture with a water binder ratio of 0.26 and a superplasticizer binder ratio of 0.01 can be printed through a 9 mm diameter nozzle with consistent filaments to build up to 61 layers in one session.

The particle grading of concrete paste is another main factor that governs its rheology and fluidity in the fresh state. Generally, a wider particle size distribution would contribute to a higher packing density and yield a better flowability [86,87]. Therefore, it is recommended to adjust the powder content and the coarse aggregate content to approach a highest packing density. Through proper mix proportioning, fine mineral admixtures, such as fly ash, blast furnace slag and silica fume, would fill the voids formed between larger cement particles, play a lubricant effect to prevent cement particle from forming into blocks, and delays the hydration of cement, thereby displacing the water in the voids and enhancing the flowability of the paste [88]. However, excess content of fine powders may increase the viscosity of the paste, leading to an adverse effect [89]. Park et al. [90] concluded that, for the plastic viscosity, the sample with high wt% of both blast furnace slag and silica fume shows about 0.5 Pa s, not so high value compared with 1.2 Pa s of the sample only 15% silica fume. Ferraris et al. [91] found that the maximum viscosity 0.06 Pa s of cement paste was reached at a mean particle diameter of about 11 mm, and maximum yield stress 30 Pa was reached at a mean particle diameter of 5.7 mm. Overall, the flowability of cementitious material is influenced by several inter-related factors. Comprehensive consideration is needed to achieve the optimal fluidity.

4.3 Buildability control

Buildability is another critical parameter to evaluate the printable performance of cementitious material, which refers to the ability of material to retain its extruded shape under self-weight and pressure from upper layers. Buildability can be considered as the early stage stiffness. The extruded cementitious paste must have sufficient buildability to enable it being lay down accurately, keep the form right after deposition, be hard enough to bear the weight of further layers without collapsing and yet still be suitable to provide a good bond between layers. In regular concrete material, aggregate constitutes a bulk of volumes, therefore providing favorable dimensional stability. In the case of printing cementitious paste, similarly, favorable buildability is achievable at relatively higher content of fine aggregate and sand. From another perspective, chemical additives could offer positive contributions to the increase of buildability. Incorporate a small doses of viscosity modifying agent (VMA) can reduce bleeding and improve the stability of the concrete mortars. The VMA also brings down the powder requirement and still maintains the required stability. Lachemi et al. [92] demonstrated that the apparent viscosity of paste with 0.075% of viscosity modifying agent (VMA) was more than four times higher than that of 0.025% of VMA when the shear rate is at 10 s^{-1}. The yield stress was decreased from 18 Pa to 4 Pa with the increase of dosages of VMA from 0.025% to 0.075%. Sonebi et al. [93] found that when VMA was fixed at 0.06%, plastic viscosity value decreased form 2.18 Pa s to 1.6 Pa s with the increase of dosages of superplasticizer from 0.6% to 1.1%. Early strength agent could promote the hydration and rapidly shorten the setting time of cement. Lin et al. [94] investigated the influence of three types of early strength agent, lithium carbonate, lithium hydroxide, sulfates, on the strength of cement-based printing material. Test results show that a ratio of 0.05% lithium hydroxide can shorten setting time to 9 min and cement mixed with lithium hydroxide indicates the highest improvement of 2-h strength than the other two.

4.4 Setting time control

As mentioned earlier, printing material requires a long setting time to maintain a consistent flow rate for good extrudability, where appropriate retarders are needed to control the setting time. Retarders can be absorbed on the surface of cement particles to form an insoluble layer, which delays the hydration of cement. Lin et al. [94] tested the effect of six common retarders on the setting time of extrudable printing material. Among them, the optimal retarder for the cement-based paste was sodium tetraborate, the mix ratio of which from 0.1% to 0.3% could increase the jelling time from

28 min to 109 min, and the final setting time from 49 min to 148 min. Sodium gluconate and tartaric acid also performed favorable retarding effect.

However, printable material still requires a short setting time to promote the material acquire enough early strength right after being deposited out from nozzles. Setting accelerators are a class of admixtures commonly used for concrete to produce an immediate set. Accelerating admixtures comprise chemicals that promote the speed of cement hydration, thereby shortening the setting time and improving the speed of early stiffness development. Paglia et al. [95] investigated the setting behavior of cementitious mixture mixed with different type of accelerators. Results indicated that the setting time of concrete with 4.5% mass dosage of alkaline accelerators approximately was about 57% of that with 8.0% mass dosage of alkaline-free accelerators. The study results of Maltese et al. [96] showed a dosage of alkali-free accelerator from 2% to 7% by cement mass reduce the setting time of cement paste from 360 min to 150 min.

4.5 Mechanical property control

Lim et al. [60] developed a high performance cementitious mixture for concrete printing. It comprises 54% sand, 36% reactive cementitious compounds and 10% water by mass. The water/binder ratio is approximate to 0.28. The compressive strengths of extruded and deposited paste are between 80% and 100% of the standard cast specimen. While the flexural strength of extruded samples are close to the standard cast specimen. Feng et al. [97] studied the mechanical behavior of 3D printed structures using cementitious powder. The average compressive strength of printed cubic specimens ranges from 7.23 MPa to 16.8 MPa, not suitable for structural members. Gosselin et al. [77] presented a novel premix of high performance printing concrete paste, which is composed of 30 wt%–40 wt% Portland cement, 40 wt%–50 wt% crystalline silica, 10 wt% silica fume and 10 wt% limestone filler. Flexural strength of printed samples ranges from 11.7 MPa to 16.9 MPa. It would be desirable to employ fibers to strengthen the printed structures. Nerella et al. [98] developed a potentially replaceable material for concrete 3D printing using 31.1% brick, 22.3% limestone, 18.2% aerated concrete, 3.7% lightweight concrete. Printed specimen has a 21-d compressive strength of 80.6 MPa, 9.85% higher than that being casted. Shao et al. [99] demonstrated that extruded fiber composite was better in strength, stiffness, fiber distribution and orientation, compared with the casted products. Christ et al. [100] added 1% short PAN fibers with maximum length of 1 cm to a matrix of cellulose-modified gypsum powder. Test results of printed samples demonstrated a 180% increase of bending strength and up to 10 times higher fracture strength compared to non-reinforced samples. Although flexural strength can be further increased to more than 400% with higher content and longer length of fibers, the composite was not printable. Feng et al. [97] presents innovative composite structures that are composed of 3D printed elements reinforced with FRP materials. The maximum compressive strength of 3D printed samples wrapped with FRP sheets was 31.5 MPa, which is 1792.0% higher than the unreinforced samples. Nerella et al. [101] proposed a composition of a high-performance printable mortar. The compressive strength of saw-cut specimens in perpendicular and parallel directions to the layer-interface-plane were 80.6 and 83.5 MPa, respectively. The flexural strength were 5.9 and 5.8 MPa, respectively. All the measured values were higher than traditionally casted specimens. Malaeb et al. [37] tested the compressive strength of 3D printed cubes. The concrete material for 3D printing was comprised of cement, sand and fine aggregate. The strength for samples were in the range of 41.5 to 55.4 MPa. Le et al. [81] proposed a high performance printing concrete, which contained 1.2 kg/m^3 micro polypropylene fibers. The 1-d, 7-d and 28-d compressive strength of this material was 20, 80 and 110 MPa, respectively.

4.6 Shrinkage control

Shrinkage is an important concern that associates with the printing performance of cementitious material since it affects the dimensional accuracy and stability of printed structures. As discussed above, cementitious material for 3D printing requires high water content to ensure good flowability and extrudability. As a result of this special requirement, excess water is added beyond the volume necessary for hydration. The excess water evaporates from the cement, leading to a high drying shrinkage deformation during setting and hardening process of the composite [102]. Moreover, 3D printed components always have larger area of surfaces directly exposed to ambient conditions than conventionally casted structures using mould or formworks. This case would promote the evaporation of free water [103].

There are several alternative methods of preventing shrinkage. Decrease of water to cement ratio (W/C) and increase of the sand to cement ratio (S/C) are both feasible solutions to shrinkage control. For a given age, a low value of W/C can reduce the drying shrinkage strain. The more the fine aggregate, the less the shrinkage deformation of the composite [104]. Shrinkage reducing admixture (SRA) is also employed to reduce shrinkage by lowering the surface tension induced by water evaporation. Shrinkage under drying condition decreases by over 80% by a combined use of fly ash and calcium sulfoaluminate cement [105]. Additionally, fibers could control the shrinkage crack to an acceptable level. Experimental test results indicate that crack area decreased by 36.0% in the mix with structural nano-synthetic fiber (0.26 vol%) compared with concrete without any mixing fibers [102].

4.7 Optimization for mixture proportion

The mix design of cementitious materials of 3D printing needs to meet the above mentioned requirements of the fresh and hardened materials. A flowchart describing the preparation procedure of cementitious mixture design for construction-scale 3D printing is shown in Figure 9. Extrudability must be favorable to ensure the mixture can be smoothly deposited from narrow nozzles by selecting grading raw materials with maximum particle size of about one tenth of nozzle diameter. Adjusting water to binder ratio (W/B) to make the mixture produces an efficient flowability so that material can be fluently transported in the delivery system. The material behavior at fresh stage controls the quality of the printing process. After raw materials and water to binder ratio are fixed, it is possible to optimize and coordinate the buildability, setting time, strength and shrinkage control using additives including pozzolanic particles, superplasticizer, retarder, accelerator and fibers, etc.

However, there are two key dilemmas in the mix process in respect to the flowability, buildability and mechanical strength. The first one is regarding to the water to binder ratio. To be delivered smoothly cementitious paste need a relatively high water quantity. At the same time to acquire good buildability (i.e. ability to maintain extruded shape) to and exhibit high strength, cementitious paste must have a low water binder ratio. Another dilemma results from the setting time. On one hand, good flowability requires a relatively long setting time to maintain a consistent flow rate and prevent from blocking in the transportation system. On the other hand, good buildability needs a short of setting time to enable the material harden quickly to obtain stiffness to support the weight of subsequent layers. To master these contradictions, superplasticizer is expected to balance the water binder ratio and retarder and accelerator are helpful to

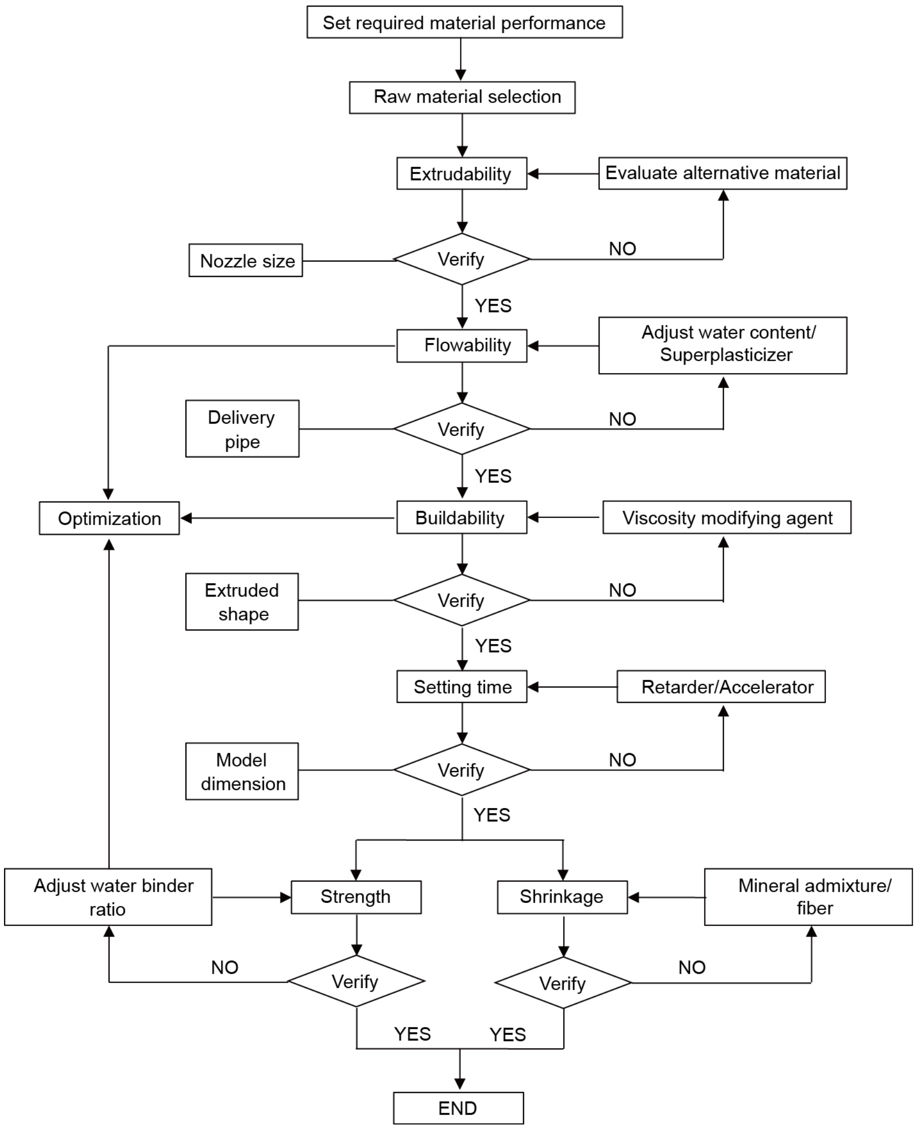

Figure 9 Preparation procedure for cementitious mixture design for construction-scale 3D printing.

control the setting time of cementitious paste in their fresh and hardened state.

5 Advantages, applications and challenges for using 3D printing cementitious materials

5.1 Advantages of 3D printing of cementitious material

Various automation control technologies can be applied in 3D printing techniques, such as 3D scanning in the digital model acquisition process [106], data file generation and process, wireless spatial location technology, computer numerical control technique and mechanical control technique involved in the printing process [107], 6-axis robotic arm, swarm robots and automatic climbing and mobile technology applied in the material transportation process and structural components assembly process [108]. These automation control technologies contribute to numerous benefits for developing cementitious-material 3D printing in real life construction and most important ones could be resumed as:

5.1.1 Design flexibility

The layer manufacturing manner of 3D printing opens new possibilities for shaping materials, and formwork-free structures could be easily realized by this mean. This technique allows great freedom in the architectural design and provides flexibility in building civil engineering structures with various architectural geometries that are difficult or even not possible to build up using current manual construction practice [66]. It gives almost unlimited possibilities for architects and builders to handle the geometric complex constructions with ease. 3D printing process has certain limitations, but the design freedom and freeform construction it offers are unparalleled, which are the main interests for 3D printing applied to largescale construction, rather than the speed nor material [109].

5.1.2 Social impact

Current on-site construction activities will inevitably produce various harmful emissions and generate a significant amount of wasted formworks and solid materials that are hard to be reused [110]. The environmental and social impact of 3D printing is noteworthy. A 3D printer is an electric-powered machine without any emissions. Because of its accurate construction process, 3D concrete printing could result in near zero material waste. Additionally, noises produced in the building process will be dramatically reduced. The conventional construction is a labor intensive process and a process with lots of safety issue. On average, there are 52 workers in 1000 were injured in the construction process in Australia, and 40 in 1000 in the USA [111]. Automatic printing process greatly reduces the labor requirement. Life cycle analysis (LCA) results indicate that the cumulative energy demand of manufacturing products by means of 3D printing can be reduced by 41%–64%, and concomitant emission reductions and minimized environmental impacts [112]. Based on the life cycle theory, one industry usually goes through four stages: start-up stage, growth stage, mature stage and degenerating stage. 3D printing in manufacturing sector has been developed for approximately 30 years in China, and it gradually turns into the second growth stage [113]. However, the 3D printing in construction industry is still in the start-up stage. Progressive innovation and development are required for construction-related 3D printing to bring the environmental advantages and social benefits into full play.

5.1.3 Cost benefit

3D printing process offers construction automation. Hence, it will drive down the cost of existing methods from the following three aspects. In terms of time cost, 3D printing can significantly speed up the construction process. Reportedly, the building process takes a quarter of the time required to build an equivalent structure with traditional means [109,114]. In terms of material cost, the mount of raw materials required to fabricate objects can be well estimated before printing process begins and material can be accurately deposited to the right place during the printing process, resulting in decreasing material consumption and eliminating unnecessary material waste [115,116]. In terms of manpower cost, the highly automated process of 3D printing can significantly reduce the labor requirement in the construction process. From another aspect, automated system can reduce the material waste and unnecessary work through lessening the impact of human error in the building process. Camille et al. [117] presented a cost comparison for construction a wall from 40 MPa concrete between using traditional method and 3D printing, as given in Table 3. Apparently, using 3D printing to build concrete components can cut almost all the cost of labor and formwork requirement. Cost of formworks, according to rough statistics, may take up 35%–60% of the overall costs of concrete structures [118]. Total cost of concrete wall by 3D printing is approximate a quarter of that by traditional construction method just based on the presented data.

Figure 10 presents the breakeven relationship between conventional and additive manufacturing process. In conventional manufacturing, the cost for each incremental unit of production decreases with the total number of manufactured objects, while cost per unit increases as complexity increases. Contrarily, the cost of 3D printing mostly remains uniform for each unit production, little effected by the total number and complexity. Therefore, current 3D printing shows superiority in low-to-medium-sized production and relative complex structures. However, in years to come, improvements in adoption rate and throughput of 3D printing will further, 3D printing manufacturing costs will gradually decline [3,119]. Economies of scale would be achieved by such technology

Table 3 Cost estimates for construction a wall from 40 MPa concrete using traditional method and 3D printing

	Traditional method			3D printing		
	Cost	Amount	Price	Cost	Amount	Price
Supply of concrete	\$200/m^3	150 m^3	\$30000	\$250/m^3	150 m^3	\$37500
Pumping	\$20/m^3	150 m^3	\$3000	\$20/m^3	150 m^3	\$3000
Labor	\$20/m^3	150 m^3	\$3000	–	–	–
Formwork	\$100/m^2	1500 m^2	\$150000	–	–	–
Total			\$186000			\$40500

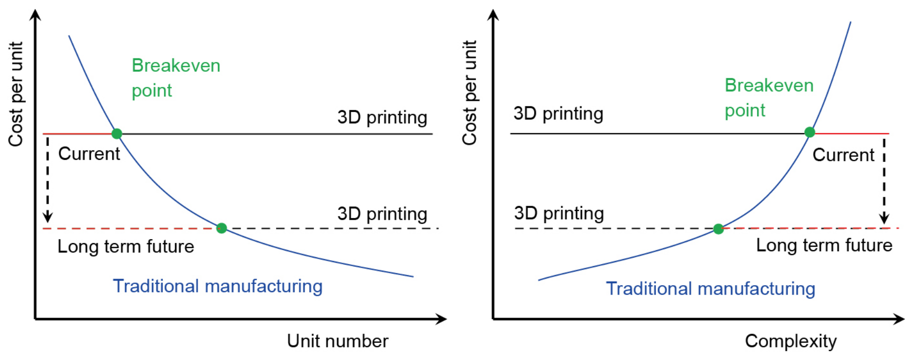

Figure 10 (Color online) Breakeven analysis comparing conventional and additive manufacturing process.

when it comes to mass production of flexibility and customized construction works and its advantages over traditional manufacturing methods will be greatly amplified by that moment.

5.2 Potential applications of 3D printing for cementitious material

The completed construction projects demonstrate the applicability of 3D printing in real-life practices. 3D printers have arrived and they promise a fascinating future. Versatile applications can be approached for 3D printing of cementitious material.

5.2.1 Adopting various material for printing

Currently, largescale 3D printing process can be classified into two categories, one is spreading dry powders and gluing them together by selectively spray binding liquid; the other one is extruding wet cementitious paste from nozzles. It is therefore feasible for these two processes to utilize a wide range of raw materials to prepare printable materials, such as tailing sand, recycled fine aggregate, limestone powder, blast furnace slag, polymer. Moreover, short fibers, such as glass fiber, basalt fiber, steel fiber, polypropylene fiber, can also be mixed in the preparation process to enhance the tensile strength and toughening effect of printed structures. Particularly, extrudable printing material can be added with functional properties such as self-sensing, self-compacting, self-healing and self-cleaning by mixing with relative functional constituents or chemical additives.

5.2.2 Irregular shaped structure

The layer by layer manufacturing process gives 3D printing significant design and build freedom. It is expected that 3D printing will find applications in the production of complicated structures, such as doubly curved cladding panels, acoustic damping wall element, hollow walls with corrugated internal structure, or other irregular shaped components that are difficult fabricated by conventional method. With the design of the component described digitally, before manufacture, the opportunity to add functionality, reduce weight and optimize structurally all become possible when there is a manufacturing process are capable of producing components of any geometry.

5.2.3 Integration with building information modeling

Building information model (BIM) is a rapid emerging method for digital representation of physical and functional characteristics of a facility and also an effective approach to simulate the complete assembly process and predict potential issues before real construction. The models established via BIM contain not only geometrical information but material types and characteristics, spatial relationships of components, and manufacture information, etc. Meanwhile, either remake one component or exchange information in BIM during the design stage, objects connected to it will be reorganized automatically. Both of which conventional 3D modelling programs cannot support [38,120,121]. Furthermore, BIM offers new opportunities to improve efficiency and effectiveness of the construction process [122,123]. The major superiority of 3D printing is the ability to produce complex geometries and BIM is powerful in complex construction design. It is therefore recommended to model the project, optimize and simplify the printing process with the help of BIM for the reduction of printing time and decrease of repeatable delivery path in printing process. The entire process from parametric design until printing the building can be controlled and optimized by means of BIM, intending to eliminating the overlapping works and shorten any wasted times. 3D printing integrated with BIM can significantly assist designing plan change and reduce the time and the cost of printing process when applied in the field of construction and building.

5.2.4 Application in planetary construction

Planetary construction is another candidate application domain for 3D printing. In recent years, there has been growing interest in constructing habits on the Moon and Mars [124]. Largescale 3D printing keeps the feasibility to construct supportless buildings using *in-situ* materials. Figure 11 shows a imagine picture of 3D-print infrastructure project on Mars sponsored by NASA. Electric power for the largescale 3D printer can be transferred from the solar energy. The lunar regolith may be used as the construction material, which can be sintered using microwave [125], or be adhered together with cementitious material using some binding material to create multiform structures. Kading and Straub [126] proposed an overview of a prospective approach to build infrastructures on the Martian by means of 3D printers. It is feasible to utilize *in situ* resource basalt as the material for 3D printing. However, it is significant to master the mechanical properties of materials taken from moon surface and the structural properties of 3D printed buildings. Although there are lots of barriers to overcome, we believe that largescale 3D printing technology utilizes *in-situ* materials is very promising for successful planetary construction.

5.3 Challenges of 3D printing for cementitious material

3D printing of cementitious materials presents an innovative and promising technique in the real-life construction practices. Although some clear advantages and potentials of largescale 3D printing for cementitious material are apparent in building and construction industry, there still remain some difficulties and challenges that hinder its widespread use.

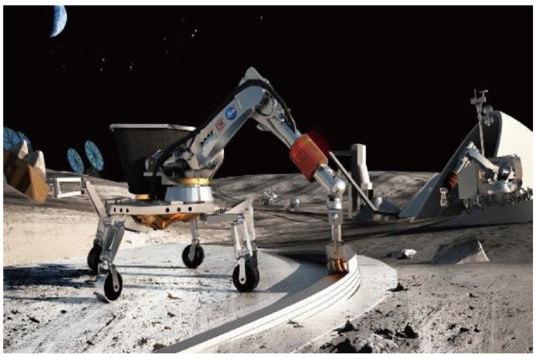

Figure 11 (Color online) Imagine drawing of 3D-printed infrastructure project on Mars sponsored by NASA [124].

5.3.1 Design of mega-scale 3D printer

The size of 3D printer greatly restricts the scale of building and project it could print. The current application of 3D printing technologies in the field of civil and building engineering is limited to construct structural components and low-rise buildings. It might not be well suited to construct high-rise residential or other type of largescale building projects [127,128]. Mega-scale 3D printers are expected to be transportable and can be set up on site to accommodate the rigor operating requirement at construction site. The design of proper largescale 3D printers for cementitious material would undoubtedly improve and expand the applicability of 3D printing technique. Make 3D printing into real architectural construction domain and realize the construction of multilayer and high-rise buildings depend on solving a series of problems such as optimization of the material storage, delivery and deposition system, and stable climbing of 3D printer.

5.3.2 Cementitious material compatible with 3D printer

Compatible cementitious materials may be the most important limitation for 3D printing in construction. It is a key challenge to balance all the wet-properties of cementitious material to coordinate with the printing system. Cementitious material should have some basic features in coordination with corresponding 3D printer, such as easy-flowing, easy-pumping, easy-deposition, dimension stability, and low-shrinkage. For example, the setting time of printing material should be set enough long to facilitate the transportation in delivery system, reducing blockages in pipes, and also should be set short to make printing paste harden quickly to acquire sufficient stiffness to support subsequent layers without collapse. Meanwhile, the rheology of material should meet the need of continual deposition. These properties can be controlled to a certain extent by using chemical admixtures, taking account of the size of printing model, the printing speed (i.e. moving speed of nozzles), the deposition speed (i.e. volume of material extruded from nozzle in unit time), etc. Various materials, such as plaster and clay that used as printing materials sometimes perform low strength, large shrinkage and poor dimension stability, which prevent their applicability in printing largescale buildings [129]. Cement-based mixtures or concrete has been modified and proved to be effective printing material with acceptable degree of flowability, extrudability, buildability and high strength. However, due to the types of raw materials and adoption of admixtures of printing material are quite different from regular cement composite, the 3D printed structures were prohibitively more expensive than that produced by common used materials. Therefore, it is necessary to develop cheap, viable, and easily obtained construction materials, such as recycled building materials, tailing sand, waste rubber powder. Dedicated researches regarding to preparation cementitious material for use in 3D printing shall be carried out continually, along with testing of strength and durability to ensure the final structure long-term stability.

5.3.3 Implementing reinforcement

Implementation of reinforcement is a further challenge for 3D printing to replace traditional construction method in terms of manufacturing load bearing structures. Conventional reinforced concrete structure cannot be achieved by extruded cementitious paste. Similar to casted concrete, printed specimen is still brittle and weak in tension. Although fiber reinforcement can enhance the ductility and improve the brittleness of concrete materials, tensile behavior and crack controlling of reinforced structures still cannot be reached by fiber reinforced composite. Existing largescale AM concerned this issue. Contour crafting uses extra robotic arms to imbed steel reinforcements in the construction process. And concrete printing creates some voids in the printed components for the post inserting of steel bars to improve tensile capacity [60,130].

5.3.4 Coordination of printing precision and efficiency

Printing precision or the smallest feature that can be handled by printer is directly proportional to the accuracy of printed structures. One printing process with higher precision can ensure a higher accuracy of printed structures with designed prototypes, however, at the cost of decreasing construction efficiency and increasing final cost. Improvement of printing speed would inevitably sacrifice the printing accuracy. Hence, model design shall take considering of both machinery control precision and manufacturing speed so as to reach a maximum potential of automatic construction.

5.3.5 Development of evaluation standard

Cementitious materials used for 3D printing are different from the regular cement composite in respect to raw materials, mix method, cast process, etc. Evaluation standards and testing methods for conventional concrete material and structures are not suitable to printing materials and printed structures. This requires revising criteria and new regulations to measure and assess the mechanical performance, rheological performance and long-term service behavior of printing materials, as well as new theoretical models, service-life prediction models for the assessment of printed structures and whole buildings [131,132]. When 3D printing is adopted to construct real life buildings, new design standards and evaluation criterions are of importance to guarantee the printed components and structures are with enough bearing capacity to withstand various complex loads, including gravity, snow, wind, seismic, etc., and satisfy the durability requirements to resist the carbonization, corrosion, and freezing and thawing cycles.

6 Conclusion

3D printing technique for cementitious material is a promising method may revolutionize the traditional building and construction processes in terms of apparent benefits in low-cost, high-efficient automatic construction, architectural design freedom, and reduction of labor requirement and risks during construction. This paper has discussed the different types of 3D printing system that are available commercially in terms of their general benefits and drawbacks. Specially, largescale 3D printing process of cementitious material are reviewed, which has the potential to reshape the way we think about architectural buildings. However, 3D printing technology still faces certain challenges associated with mechanical strength, reinforcement, curing, and durability and correlation properties like flowability, extrudability and buildability. It is of great challenges to study printable cementitious materials compatible with 3D printers. Moreover, basic and unified standards are needed to be established for effective and accurate evaluation for the mechanical behaviour of specimens, components and structures manufactured with cementitious material by means of 3D printing. In order to master these problems, ongoing research could focus on interdisciplinary works involving materials science, manufacturing method, robotic, architecture and design. Although still in the proof of concept and preliminary manufacturing stages, it is promising that by tackling these challenges, 3D printing can reach its maximum potential in the construction field.

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