Material Design, Additive Manufacturing, and Performance of Cement-Based Materials

Chapter · March 2022

DOI: 10.1007/978-3-030-95798-8_13

Biranchi Panda
Indian Institute of Technology Guwahati

Chapter 13
Material Design, Additive Manufacturing, and Performance of Cement-Based Materials

Biranchi Panda and Jonathan Tran

Abstract Important developments in additive manufacturing of concrete (AMoC) have been achieved in the past decades. Like other additive manufacturing processes, interdependence between material design, process effects, and part performance exists in AMoC. In this chapter, material design of various cement-based materials amenable for extrusion-based additive manufacturing, rheological responses that are influential in ensuring printability, and the performance of such novel materials is discussed. The need of adequate rheology to successfully develop printable concrete and tailoring mix design by addition of various admixtures is also presented. These results demonstrate that thixotropy of building materials is key for AMoC. The mechanical performance of AMoC is further discussed including interlayer bond strength and its consequence in terms of anisotropic properties. Finally, material development challenges for large-scale AMoC are discussed with new strategies to produce sustainable yet printable mixes.

Keywords Material design · Additive manufacturing · Cement-based materials · Extrusion rheology · Low carbon cement · Geopolymer

1 Introduction

Digital concrete fabrication including additive manufacturing of concrete (AMoC) has attracted the attention of academia and industry in recent years, due to its advantages of less labor requirements, and absence of formwork (Buswell et al., 2018). The process, first pioneered by Berokh Khoshnevis and branded initially as 'Contour Crafting', is the direct transfer to concrete of the well-known fused deposition modeling (FDM) process typically carried out with thermoplastics (Khoshnevis

B. Panda (✉)
Indian Institute of Technology, Guwahati, India
e-mail: pandabiranchi@iitg.ac.in

J. Tran
Department of Civil & Infrastructure Engineering, RMIT University, Melbourne, VIC, Australia

S. H. Ghaffar et al. (eds.), *Innovation in Construction*,
https://doi.org/10.1007/978-3-030-95798-8_13

et al., 2006). The term ‘Concrete Printing’, and/or ‘3D Concrete Printing’, was originally the name given to the process developed at Loughborough University to differentiate it from contour crafting (Lim et al., 2012). Literature reviews several reviews of AMoC that covers 3D printing processes, wide range of materials, properties of 3D printed materials, and some computational modeling of the process (Bos et al., 2016; Mechtcherine et al., 2019; Paul et al., 2018; Sanjayan et al., 2019; Tay et al., 2017; Wangler et al., 2019a). Despite availability of reviews, limited information is available on the topic ‘process-material design’ relationships of AMoC. The main of this chapter is to provide a review of building materials design for extrusion-based AMoC process considering process capabilities and limitations.

2 Extrusion-Based Concrete AM Process

In order to provide a baseline description of AMoC processes, extrusion-based gantry printing process is described as the paradigm approach to which other concrete printing processes are compared. Figure 1 shows a typical gantry-based concrete AM system developed at Indian Institute of Technology Guwahati, India.

In AMoC, the part building process starts with CAD modeling of the structure which is further processed as stack of sliced layers, and unlike other 3D printing processes, the layer thickness in concrete printing varies from 5 to 40 mm depending

Fig. 1 3D concrete printer facility at Indian Institute of Technology Guwahati, India. (author’s original)

on nozzle size and material flow rates. The digital processed file is then converted into machine language such as G-code and send to a numeric controller that translates the language into X, Y, Z motion. In most commercial 3D printers, the material delivery process is carried out by a grouting pump, but in some research laboratories, a plunger based or an extruder (Fig. 2) is used due to low cost and ease of extrusion. The advantage of pump-based delivery system can be reckoned as continuous supply of large volume of material, which is not possible in case of plunger extruder due to limited storage capacity of the barrel. However, for laboratory trials, such systems are very much helpful as miniature samples can be easily printed by extruding small volume of material. It is important to note that the material delivery mechanism is completely different in both the extrusion systems and according the material design need to be decided. More discussion about mix preparations is presented in the following sections.

The extruded layers get deposited layer by layer, and therefore, the printer (z axis) moves in vertically upward direction as the print bed remains stationary in this process. If the part design has any overhanging features, it is commonly not possible to print without support materials (Albar et al., 2020). An example is shown in Fig. 3, where additive manufacturing of overhanging structures is attempted by temporarily

Fig. 2 Extruder-based 3D concrete printing (author's original)

Fig. 3 Additive manufacturing of overhanging concrete structures at NTU Singapore (author's original)

providing support with help of other mechanical systems. In addition, some recent work shows that by optimizing the overhanging angle and using rapid hardening mixes, it is possible to print complex structure without the need of support materials (Sika Concrete 3D Printing; The Large-Scale 3d—XtreeE—3D Printed Wall).

Robotic AM systems are also available and used by some industries for concrete printing of complex geometrics. The process of a robotic AMoC is almost similar to a gantry-based 3D printer except the complex path programming method owing to higher degree of freedom of the robots. The material deposition occurs through a nozzle connected with a concrete pump, and in case of special concrete extrusion, advanced nozzle can be mounted considering the maximum payload capacity of the system. The main disadvantage of robotic printing system is the sizes of the printed structures which are constrained by the reach of the robot's arm, and therefore, advanced mechanical systems are now being developed which combines the benefits of both gantry and robotic 3D printers.

3 Material Design, Extrusion Rheology, and Early-Age Properties of Additive Manufactured Concrete

3.1 Background

AMoC differs significantly from traditional casting processes by virtue of the importance of control of the yield stress, and especially with respect to its evolution over time. More specifically, the requirements of material delivery and placement are rather similar to some processes seen in traditional construction processes, but the absence of a traditional formwork requires an additional aspect that of controlling structural build-up to ensure structural stability during production (Mechtcherine et al., 2020). In the printing process, appropriate workability is required to ensure extrudability, shape stability, and buildability after deposition. More specifically, to achieve printable concrete, it is needed to balance among these critical printing requirements. Workability of freshly printable concrete is commonly evaluated using slump test, flow test, or V-funnel test. In the slump test, workability is evaluated through the slump, which is the slumped height of concrete paste relative to the height of the cone after demolding. Additionally, V-funnel is used to evaluate flow ease by the flow time. Flow test, also called slump flow test, spread-flow test, or mini-slump test is the most widely used to measure workability of printable concrete because it is simple, fast, economical, and reliable. Rheological parameters such as static/dynamic yield stress and plastic viscosity obtained from rheological tests are also considered important properties to evaluate flowability of fresh concrete. For instance, static yield stress needs to be sufficiently low for being pumpable and high enough for carrying self-weight. Regarding the effect of mix compositions, the selection of fine aggregates in terms of shape, size, and dosage needs to be taken into consideration to achieve printability through a specific size of a nozzle.

In AMoC process, the extruded layers are hardened by hydration reaction of the material, and therefore, it is very important to design the material so that it can harden rapidly while retaining the nozzle shape. In case of extrusion by pump, the material design is even more challenging as it needs to be very fluid during pumping, and after deposition, it should be stiff enough to hold its own weight and the load of other layers (Rahul et al., 2019).

After successful extrusion, buildability of fresh concrete must be ensured, which can be described as layer build-up capacity of the material. Layer build-up capacity depends on shape stability of each filament, which is also an essential prerequisite for build-up capacity. As discussed above, fresh concrete is required to have appropriate workability to meet two competing requirements, i.e., 'extrudability' and 'buildability'. From the standpoint of rheological behavior, these two requirements depend on thixotropic properties of cement-based materials which is governed by flocculation mechanism. Thixotropy' is shear thinning property of building materials. This behavior allows breakup of the material under shear and their reformation when shear force is removed. Shear thinning results in smooth extrusion of material, while the reformation ability helps in shape retention of the extruded filament.

In a nutshell, following critical properties should be satisfied for an extrusion-based AM process (Le et al., 2012a).

(a) Extrudability: It refers to ability of the material to be extruded out continuously from a nozzle or orifice.
(b) Shape retention: This property indicates shape stability characteristic of the extruded filament according to nozzle opening shape and size.
(c) Buildability: Buildability of a material indicates the ability of material to be buildable layer by layer without failure of the bottom layer and the entire structure during printing.
(d) Open time: It indicates the material workability (the ability to work with concrete) time for which it is extrudable.

There are no standards to measure these properties, and therefore, depending on the material processing technique, researchers have developed 3D-printable building materials by optimizing the mix design with the help of different admixtures. In the following section, two most common approaches of material design have been discussed for realizing extrudable 3D-printable mixes.

3.2 Material Design Approaches

The most widely used building material for AM-based applications involves the use of blended materials to obtain required recipe fulfilling the abovementioned criteria. Literature reveals that yield stress and viscosity (Bentz et al., 2018; Nair et al., 2019) have been often used to measure 3D printability, and some researchers have focused on thixotropy (Chen et al., 2020a; Kruger et al., 2019) aspect of building materials including other rheological properties.

Thixotropy property allows building material to become less viscous when subjected to an applied stress, and on removal of stress, the material turns in to more viscous fluid which can produce stable filament. The low viscosity property will ensure smooth and continuous flow during the extrusion, if the material is extrudable. Thixotropy characterization can be done by measuring structural breakdown and viscosity recovery as these two phenomena mimics the extrusion-based AMoC process. The material is usually sheared at high shear rate in structural breakdown protocol mimicking extrusion or pumping process. Two important parameters such as thixotropy index and breakdown time are calculated in this test which indicates the ease of material pumping or extruding from a nozzle. Similarly, in the recovery test, viscosity values before and after extrusion are compared to ensure the material has ability to recovering initial high viscosity (after extrusion) for better shape retention and buildability property.

While measuring yield stress and viscosity, researchers have used (static) yield stress as an indicator of extrudability and viscosity to indicate shape retention of the extruded filament. The structural build-up measured by increasing yield stress of material is often used to explain buildability of the structure. Therefore, by combining yield stress and viscosity, it is thus possible to confirm printability properties of building materials. There are various methods available in the literature to measure these rheological properties; however, the choice of test method selection depends on the type of 3D printer and extrusion process. Researchers using a pump to deliver the material have conducted additional characterization to check pumpability of the material, which may not be recommended if a regular piston is used for extruding the material, instead of using pumping mechanism.

The material design for AMoC can be broadly categories into two groups: (1) the ‘infinite brick extrusion’ and (2) layer pressing strategy. The consequences of these strategies on the extruded material properties are described by Roussel in Carneau et al. (2020) with in the first case a high initial yield stress layer (around 1000 Pa) which takes the form of the nozzle. And in the second case, a layer with a low initial yield stress (around 100 Pa) whose section can vary by playing with the printing parameters. More details about 3D-printable materials and mix design optimization are discussed in the following sections.

3.3 Effect of Material Design on Extrusion Rheology and Early-Age Properties

The development of AMoC materials can be considered as multi-material blending, and among all, ordinary Portland cement (OPC) remains popular material choice due to presence of inherent thixotropy. The origin of thixotropy as mentioned by Roussel et al. is due to colloidal flocculation and hydration reaction. However, recently, there is an increasing interest in studying the properties of sustainable printable concrete in which OPC is partially replaced by supplementary cementitious material (SCM), including fly ash (FA), silica fume (SF), ground blast furnace slag (slag), and rice husk ash (RHA). The effect of mix design on rheology (required for additive manufacturing) and early-age properties of different concrete is discussed in this section.

3.3.1 Research on 3D-Printable OPC-Based Mixes

The addition of SCM into OPC-based cementitious materials can affect the extrusion rheology depending on the properties of SCM. Panda and Tan 2019) investigated the rheological property of cementitious materials with different replacement levels of FA and SF. The results show that increasing FA content up to 80% led to the decrease in static yield stress due to ball-bearing effect, whereas the effect of SF addition up to 5% resulted the opposite effect. SF particles have large surface area with an ideal thixotropic material behavior. As reported in Panda and Tan (2019), the addition of SF improved the structural build-up rate (steeper slope), and similar results were also reported by Yuan et al. (2018), who observed that the addition of 5% SF nearly doubled the build-up rate compared with pure cement-based mortar, due to ionization of SF surfaces and potential ion bridging effect that promoted C–S–H gel formation (Panda & Tan, 2019). The structural build-up rate can be linked with material buildability, and it can be further improved with addition of chemical admixtures.

Muthukrishnan et al. (2020) have investigated the effect of RHA on the fresh properties of printable cementitious materials, and flowability was found to be decreased for 20% cement replacement by the RHA. Interestingly, the green strength (at 15 and 30 min) was observed to increase significantly with the addition of RHA, which could be explained by the filler effects of RHA particles promoting cement hydration, and the densification of cement transition zones resulting from free water absorption by porous RHA particles. Like structural build-up, material green strength indicates load bearing capacity of the extruded layers. To improve green strength, packing density and material cohesion property need to be improved which can be achieved by optimizing the mix design. The applications of statistical methods such as analysis of variance (ANOVA) analysis can be helpful in this regard, as Liu et al. (2019) adopted it to investigate the effects of different composites (cement, sand, FA and SF) on the rheological properties, and their modeling results showed when the volume fraction of sand was fixed at 0.235 or above, replacing cement with FA had minor effects on the static yield stress of fresh mortar. A reasonable explanation for this could be under the high-volume fraction of sand; the static yield stress was mainly governed by the interlocking and friction resistance. A similar study was also conducted by Tay et al. (2019a) who investigated the relationship between the mix components (such as water, FA and SF) and workability of fresh mortar via ANOVA analysis.

In recent years, more focus has been given on improving the material rheological properties by addition of nanomaterials and other admixtures. Panda et al. (2019b) studied the effect of nanoclay on the rheology of high-volume FA cementitious materials, and they found that nanoclay addition up to 0.5% can significantly increase both static yield stress and viscosity which resulted in higher buildability property (see Fig. 4). In another study, the structure build-up rate of cementitious material with nearly 70% FA was improved by 50% with the addition of 0.5% nanoclay. The increase in rheological properties can be explained by the electrical attraction force induced by the oppositely charged nanoclay surface, which densified the microstructures (Ma et al., 2018). Depending on the type of additives, in some cases, there is an optimum dosage of the additives to be added into OPC-based sustainable concrete.

Fig. 4 3D printing of high-volume fly ash mortar with nanoclay inclusion (author's original) (Panda et al., 2019b)

van den Heever et al. (Heever et al.) studied the effect of nano-silica carbide (nSiC) on the yield strength development of OPC-based material incorporated with FA (20%) and SF (10%). Interestingly, despite the positive correlation between nSiC dosage and yield stress, the increasing dosage of nSiC resulted in a decreased value of A_thix (rate of yield strength development at structuration stage) indicating the buildability was negatively influenced by nSiC.

Some studies were focused on the effect of fiber addition on properties of 3D-printable concrete as fiber inclusion not only produces ductile behavior but also increases the buildability of the material in the early age (before setting). Figueiredo et al. (2019) investigated the effects of PVA fibers on the shear yield stress and bulk yield stress of the cementitious materials with FA or slag. In most cases, the increased fiber content had a positive effect on both bulk and shear yield stress. The increase in bulk yield stress suggested an improved buildability, while higher shear yield stress due to the friction of fibers and concrete matrix indicated a lower pumpability. Similar results were also reported by Weng et al. (2018), who found the addition of 1 vol% PVA fibers promoted both flow resistance and thixotropic behavior of fresh mortar with at most two-third of cement replaced by FA.

3.3.2 Research on Low Carbon Cement Mixes

In recent year, 3D-printable low carbon building materials are getting increasing popularity compared to other cementitious materials due to demand in achieving sustainable built environment (Dey et al. 2022). Here, different green building materials and their respective advantage for AMoC is discussed.

Additive Manufacturing of Geopolymer

The term ‘geopolymer’ was first introduced in the literature in 1978, characterizing a new class of materials with the ability to poly-condense at low temperatures like ‘polymers’. This process involves the chemical reaction of aluminosilicate materials (e.g., fly ash, metakaolin, granulated blast furnace slag, and silica fume) with alkali activators. When mixed with the alkaline activators, setting and hardening take place, yielding a material with good binding properties. The binder constituents of geopolymer materials such as FA, slag and SF can significantly affect the printability properties of mixtures along with dosage of alkali activator. In a study by Panda et al. (2019c), the static yield stress and viscosity of geopolymer mortars were found to have increased by 80% and 20%, when the slag content was increased from 15 to 40%, respectively, and it was attributed to the angular shape of slag particles that enhance the yield stress through interlocking effects. The improvement of yield stress can allow deposition of more layers. Alghamdi et al. (2019) investigated rheological properties of sodium-alkali-activated FA-based materials and found that by replacing FA with limestone, material shear yield stress, and viscosity significantly decreased. The addition of slag can also affect structural build-up rate of FA-based

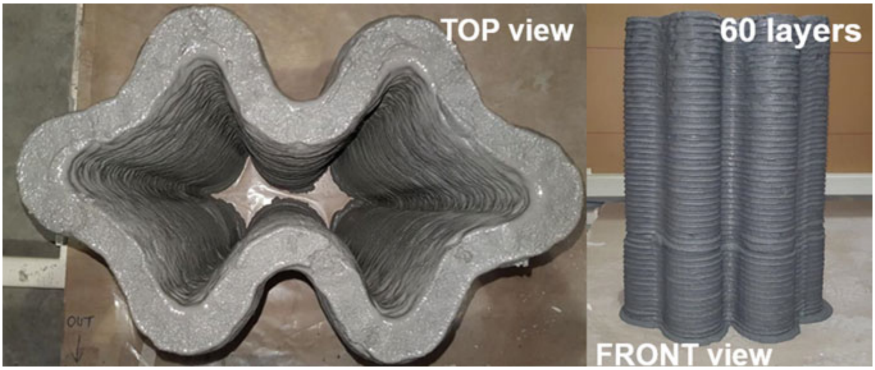

Fig. 5 Additive manufacturing of fly ash-based geopolymer (author's original)

geopolymers by accelerating the mixture (Saha & Rajasekaran, 2017), and on the other hand, SF addition can promote the thixotropy of geopolymer. Alkali activators can also play a critical role in the rheology of geopolymer as alkali-based solution activates the polymerization process which controls stiffening of the material. Based on Panda et al. (2019d) study on the effects of molar ratio and activator-to-binder ratio on the rheology of geopolymer material, it was noticed that increasing molar ratio (MR) from 1.8 to 2 resulted in significant increase in both static yield stress and viscosity, which can be explained by higher activator viscosity having higher MR. It was also concluded that regardless of MR, the static yield stress and viscosity consistently decreased as the activator solution-to-binder ratio increased, which was mainly attributed to the decrease in particle concentration. Thus, it is recommended to properly tailor the activator-to-binder ratio as it can affect the rheology of geopolymer for 3D printing. Figure 5 shows an example of 3D printed geopolymer composite, optimized for 900 mm print height.

Apart from binder and activator, researchers have supplemented additives like nanoclay for improving printability of geopolymer, as reported in Panda et al. (2019d) and Chougan et al. (2021). Other additives such as sodium carboxymethyl starch (CMS) and hydromagnesite seeds have also been incorporated into geopolymer mixtures and investigated. According to Sun et al. (2020), the addition of CMS (up to 8%) promoted both yield stress and viscosity at different rates, which could reduce the risk of segregation while avoiding filament collapse. However, the porosity of printed filaments rose with increasing CMS dosage, leading to weak internal structures and lower strength. On the other hand, the addition of 1–2% hydromagnesite seeds was found to exert minor influence on the rheological properties of the alkali-activated slag binders (Panda et al., 2020). Different fibers also have been incorporated to tailor the rheological behavior of printable geopolymers (Al-Qutaifi et al., 2018).

Additive Manufacturing of Limestone Calcined Clay Cement Material

Limestone calcined clay cement (LC3) is a low carbon cement material, and due to higher structure built-up rate capability (Beigh et al., 2020), this material is found to be an excellent choice for 3D printing applications. Chen et al. (2019) investigated green strength (early-age property) of LC3-based concrete with different grades of calcined clay and found that with higher proportion of hydraulic cement concrete resulted shorter initial setting time and higher growth rate of green strength indicating an improved buildability. This result could be explained by the higher surface area of metakaolin particles such that these fine particles provide nucleation sites to accelerate early-age cement hydration (Lothenbach et al., 2011). Meanwhile, some extra MK particles in the matrix accelerate the phase transition from flocculation to structuration (Chen et al., 2019), resulting in a decreased setting time.

Additive Manufacturing of Calcium Sulfoaluminate Cement (CSAC)

Calcium sulfoaluminate cements (CSACs) are a promising low-CO_2 alternative to ordinary Portland cements and are as well of interest concerning their use as binder for waste encapsulation. A study from Huang et al. (2019) suggested the buildability of cementitious material containing CSAC is influenced by the percentage of CSAC in the binder. They found an evident positive correlation between the ratio of CSAC replacing OPC and structure build-up rate at structuration stage. This result could be explained by the positive effect of CSA on hydration kinetics of hydrates and the formation of network between needle-like AFt and rod-like gypsum, which increased interparticle frictional force. The fresh property of CSAC-based materials for printing purposes can also be tailored via the supplement of additives. According to Chen et al. (2020a), the addition of bentonite (up to 3%) could significantly improve the thixotropic behavior and increase material viscosity simultaneously. The optimal bentonite dosage was determined to be 2% since the significant increase in viscosity due to excessive amount of bentonite could cause blockage in the nozzle. The optimal dosage of additives again highlights the necessity to balance viscosity (ease to transport) and green strength development (less filament deformation) via careful monitoring of additive supplement. A comprehensive study conducted by Ding et al. (2018) showed increasing dosage of hydroxypropyl methylcellulose (HPMC) and lowering water/cement ratio (W/C) could both reduce the setting time, whereas the addition of HPMC and the increase in sand/cement ratio (S/C) had negative effects on the flowability of sulfoaluminate cement (SAC) mortar simultaneously. A higher S/C ratio led to increased friction forces between grains which decreased the fluidity of fresh material. The addition of HPMC resulted in the formation of 3D network gel due to its gelation behavior, and the resulting thickening effect increased the resistance against penetration (Poinot et al., 2014), thus decreased the setting time. Besides, the interlocking effect of gel originated from HPMC also accounted for the negative correlation between flowability and addition of HPMC (Ding et al., 2018).

In another study, Chen et al. (2020b) studied the effects of retarders (borax acid and sodium gluconate) and diatomite on the rheological properties of SAC materials for 3D printing. The addition of either borax acid or sodium gluconate resulted in lower yield stress and plastic viscosity, whereas the addition of diatomite showed adverse effects. A lower percentage of retarder within cementitious matrix increased the free water content between particles, thus stimulating the formation of flocculation network that accounted for the increase in yield stress. On the other hand, the high water absorption of diatomite due to its large specific area and superficial Si–OH groups increased the frictional force between cement particles, thus giving higher values of rheological properties.

Additive Manufacturing of Other Low Carbon Building Materials

This category mainly refers to processing of earth-based material and cementitious materials incorporated with recycled waste materials, including glass and plastics. The research works on feasibility of printing cementitious materials with recycled glass were pioneered by Annapareddy et al. (2018) and Ting et al. (2019). According to Ting et al. (2019), completely replacing sand with waste glass as raw ingredient could significantly decrease the static yield stress that made material less buildable, and adversely impacted the hardened mechanical property. For materials with natural sand fully replaced by recycled glass, the material properties could be influenced by gradation of glass particles. In specific, a higher percentage of super fine glass (0.15–0.71 mm) in the mixture improved thixotropic property and static yield stress (better buildability), whereas filament with majorly medium-sized glass (1–1.7 mm) exhibited lower compressive strength due to the increased void contents. Besides, the replacement of fine glass was also found to yield a higher risk of bleeding and segregation in fresh mortar (Taha & Nounu, 2008, 2009), which is linked to the occurrence of blockage in 3DCP. A few research papers are found to be focused on development of 3D-printable light-weight mortar followed by earth-based building materials. Research pioneered by Perrot et al. (2018) focused on the fast development of early strength in pure clay-based soils for 3D printing. Their solution was to incorporate soils with alginate, which is an alginic salt processed from cell walls of brown seaweed and can be used as a fast-setting binder. Some recent research on development of 3D-printable foam materials focuses on foam stability issue which is very important in extrusion-based concrete printing, and in this regard, different mixing style and admixtures are opted to tailor the mix design amenable to 3D printing (Cho et al., 2021; Markin et al., 2019; Mohammad et al., 2020; Wang et al., 2020).

3.4 Mechanical Performance of AMoC

In traditional casting method, mechanical properties of hardened concrete mainly depend on mix compositions and casting procedure. Meanwhile, those of printed concrete are determined by the mix components and printing strategy such as printing path direction, extrusion pressure, and time interval (Panda et al., 2017, 2019a). In AMoC, layer-by-layer deposition process and time gap between layers are the leading causes for anisotropic behavior (Sanjayan et al., 2018; Wolfs et al., 2018; Zareiyan & Khoshnevis, 2017) and depending on material structuration (hardening) rate, decreasing trend of bond strength was found with increase in time gap between the layers (Tay et al., 2019b). Additionally, mechanical characteristics and durability of printed components could be affected by large voids which are formed between filaments and layers as shown in Fig. 6. To improve the mechanical properties, many attempts have been made to print reinforced concrete using steel rebar, rods, wires, fibers, and mesh (Asprone et al., 2018). However, extensive quantified characterization of their performance is generally still lacking and requires further research.

Directional dependence of mechanical performance such as compressive, flexural, and tensile strengths is observed in almost all studies on AMoC, which is an unavoidable feature of the extrusion process (Le et al., 2012b; Nerella et al., 2019; Wolfs et al., 2019). Le et al. (2012b) observed that the degree of anisotropy in compression tests is less pronounced than that in flexural tests. Besides, there is not much difference in compressive strengths between cast and printed specimens, but a significant discrepancy is found in flexural and tensile strengths. The great difference in flexural strengths at different loading directions results from underperformed interlayer bond

Fig. 6 Voids in 3D-printed concrete at NTU Singapore (author's original)

strength, which is the reason for the high degree of anisotropy in flexural strength tests.

The bond mechanism between new and old concrete interfaces experiences three stages, namely adhesion, friction, and mechanical interlock (Momayez et al., 2005). In particular, the adhesion resistance of the interface, which is considered a chemical bond, mainly depends on the physical and chemical characteristics of the mixture compositions. Following that, the frictional mechanism acting against slip at the interface appears right after the adhesion mechanism disappears. Finally, after the adhesion and friction actions, the mechanical interlock acts to boost bond strength depending on the roughness of the surface (e.g., size and shape of aggregate particles, surface texture, etc.). It is confirmed that apart from the adhesion resistance, the bond capacity is fundamentally dependent on the mechanical interlocking which contributes to extra resistance for the interface bond strength.

Interlayer bond strength is one of the key aspects of AMoC (Kruger & Zijl, 2021). To evaluate bond performance, bond test methods can be categorized into four main groups based on the reviews in existing studies, including shear test with different test protocols (direct shear and slant shear), indirect tensile test, known as flexural test, and prismatic or cylindrical splitting tests; direct tensile test; and pull-out test. It is worth noting that there is no reasonable concordance between the results obtained from different test methods; therefore, it is not possible to compare them. In these types of tests, the authors also observed that the splitting tensile and pull-out tests are considered efficient and straightforward test procedures to obtain consistent and conservative results. In the AMoC, three prevalently used methods to determine the interface bond strength of printed elements are found in the literature review, including flexural strength tests, direct tensile test, and splitting tensile tests. More details about theses testing methods and results can be found in Babafemi et al. (2021).

3.5 Material and Machine Design for Large-Scale AMoC

Literature reveals most of the AMoC was limited to lab scale printing and testing for evaluating 3D printability of building materials. A few academic researchers (Bos et al., 2018; Weng et al., 2020) and some pioneer construction companies (Apis cor, 2021; COBOD, 2021; Winsun, 2021) have demonstrated successful fabrication of large-scale AMoC; however, the term 'large scale' is not defined properly in the literature. In this section, some important challenges related to material development is discussed while highlighting the need of new print head design for large-scale AMoC.

Considering different types of material design of large-scale AMoC, it can be well summarized that increasing structural built-up via addition of accelerators is the most popular approach. Structural built-up of building materials is an important property which has been characterized by various rheological tests (Jeong et al., 2019; Marchon et al., 2018; Perrot et al., 2016; Reiter et al., 2018) with respect to time, and it indicates buildability of the 3D structures. This property is not only useful in AMoC but also in other digital fabrication techniques (Wangler et al., 2016) such as slip dynamic casting and hardening of material have been controlled with accurate dosage of chemical additives. Increasing of structural built-up via adding accelerators needs complete understanding of material chemistry, selection of a proper accelerator, its reaction mechanism, and dosage control. Currently, there are many guidelines available in the literature (Boscaro et al., 2021; Reiter et al., 2020; Wangler et al., 2019b) for selection of appropriate chemical admixtures to retard or accelerate the concrete. However, controlling the dosage and mixing technology is the critical challenge for large-scale AMoC.

The dosage of these admixtures mainly depends on material chemistry and required structural built-up rate. Different binder systems need different admixtures, and their dosage can be tailored based on target buildability property. Admixture compatibly is also one of the well-known issues in building materials, and therefore, it is necessary to always optimize the mix design with proper understanding of multi-component materials behavior. In large-scale AMoC, two different types of material design schemes have been noticed such as:

(1) AM of rapid hardening concrete: In this approach, low viscosity retarded concrete (mortar) is extruded, and in the print head, appropriate amount of accelerator is added to deposit rapid hardening mortar.
(2) AM of high thixotropic (zero slump) concrete: Here, a high thixotropic mix is extruded, and accelerator may or may not be added, depending on material mixing process.

The first approach is commonly found for large-scale AMoC via pumping low viscosity mortar, but the key challenges are print head design and dosage control with respect to printing parameters. There are many advanced print heads developed in this regard for accurate control of mixing of retarded mortar with other chemical admixtures. During mixing, residence time plays a main role, and Boscaro et al. (2021) have pointed out measurement of this residence time distribution for smart dynamic casting which can be applied to other digital fabrication processes.

On the other hand, extruding high thixotropic mix may not need addition of accelerator for batch mixing conditions as more layers can be deposited (without failure) due to the high thixotropic nature of the material, but extruding such stiff material requires high pumping pressure. In case of continuous mixing, accelerator addition is required for large-scale AM as material in the bottom layer may not be able to resist the load of more layers despite the high thixotropy nature of the mix. The AM of such high thixotropic mix sometimes causes poor surface roughness due to low slump character. Figure 7 shows examples of AMoC carried out by some academic research institutes using high thixotropic mixes.

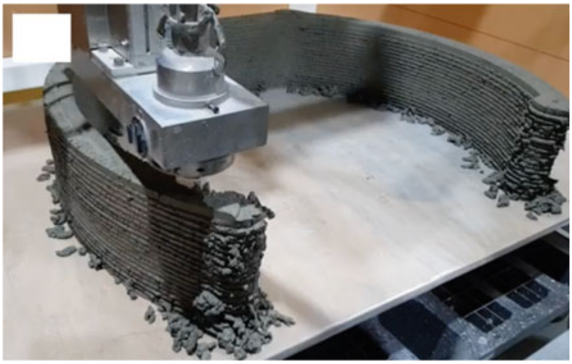

Fig. 7 Example of highly thixotropic concrete 3D printing at NTU Singapore (author's original)

4 Conclusions and Future Directions

The additive manufacturing of concrete presented in this book chapter can be grouped under the term of digital fabrication processes, and this disrupting technology can reduce the need for formwork, while allowing fabrication of highly complex geometries without formwork. A major challenge in this process is the development of material with a contradicting criterion such as low viscosity during extrusion and high yield stress after the extrusion. To fully exploit the potential of additive manufacturing, low carbon materials and structures can be designed, and numerical simulation can greatly contribute in this regard to analyze material flow, buildability, and structural capability of the optimized structure. In addition to low carbon materials, functional materials can be developed using nano/micro-particles and graded functionally can also be achieved by mimicking bio-inspired structure. While developing innovative materials of additive manufacturing of concrete, now, the focus should shift to development of new standards of testing material fresh as well as hardened properties.

Concrete additive manufacturing system development in terms of higher degree of automation (from mixing to material deposition) is also required with in-line process monitoring capabilities so that material and printing process can be optimized simultaneously. In a nutshell, in AMoC material behavior, part design, printing process parameters, and other aspects need to be considered collectively for producing robust concrete components.

References

Albar, A., Chougan, M., Al-Kheetan, M. J., Swash, M. R., & Ghaffar, S. H. (2020). Effective extrusion-based 3D printing system design for cementitious-based materials. *Results in Engineering*, *6*, 100135.

Alghamdi, H., Nair, S. A., & Neithalath, N. (2019). Insights into material design, extrusion rheology, and properties of 3D-printable alkali-activated fly ash-based binders. *Materials & Design*, *167*, 107634.

Al-Qutaifi, S., Nazari, A., & Bagheri, A. (2018). Mechanical properties of layered geopolymer structures applicable in concrete 3D-printing. *Construction and Building Materials, 176*, 690–699.

Annapareddy, A. S. H. O. K. R. E. D. D. Y., Panda, B., Ting, A. G. H., Li, M. I. N. G. Y. A. N. G., & Tan, M. J. (2018, May). Flow and mechanical properties of 3D printed cementitious material with recycled glass aggregates. In *Proceedings of the 3rd International Conference on Progress in Additive Manufacturing (Pro-AM 2018), Singapore* (pp. 14–17).

Apis cor: https://www.apis-cor.com/. Retrieved on June 10, 2021.

Asprone, D., Menna, C., Bos, F. P., Salet, T. A., Mata-Falcón, J., & Kaufmann, W. (2018). Rethinking reinforcement for digital fabrication with concrete. *Cement and Concrete Research, 112*, 111–121.

Babafemi, A. J., Kolawole, J. T., Miah, M. J., Paul, S. C., & Panda, B. (2021). A Concise Review on Interlayer Bond Strength in 3D Concrete Printing. *Sustainability, 13*(13), 7137.

Beigh, M. A., Nerella, V. N., Schröfl, C., & Mechtcherine, V. (2020). Studying the Rheological Behavior of Limestone Calcined Clay Cement (LC 3) Mixtures in the Context of Extrusion-Based 3D-Printing. In *Calcined clays for sustainable concrete* (pp. 229–236). Springer.

Bentz, D. P., Jones, S. Z., Bentz, I. R., & Peltz, M. A. (2018). Towards the formulation of robust and sustainable cementitious binders for 3-D additive construction by extrusion. *Construction and Building Materials, 175*, 215–224.

Bos, F., Wolfs, R., Ahmed, Z., & Salet, T. (2018, September). Large scale testing of digitally fabricated concrete (DFC) elements. In *RILEM International Conference on Concrete and Digital Fabrication* (pp. 129–147). Springer, Cham.

Bos, F., Wolfs, R., Ahmed, Z., & Salet, T. (2016). Additive manufacturing of concrete in construction: Potentials and challenges of 3D concrete printing. *Virtual and Physical Prototyping, 11*(3), 209–225.

Boscaro, F., Quadranti, E., Wangler, T., Mantellato, S., Reiter, L., & Flatt, R. J. (2021). Eco-friendly, set-on-demand digital concrete. *3D Printing and Additive Manufacturing.*

Buswell, R. A., De Silva, W. L., Jones, S. Z., & Dirrenberger, J. (2018). 3D printing using concrete extrusion: A roadmap for research. *Cement and Concrete Research, 112*, 37–49.

Carneau, P., Mesnil, R., Roussel, N., & Baverel, O. (2020). Additive manufacturing of cantilever-from masonry to concrete 3D printing. *Automation in Construction*, *116*, 103184.

Chen, M., Li, L., Wang, J., Huang, Y., Wang, S., Zhao, P., & Cheng, X. (2020). Rheological parameters and building time of 3D printing sulphoaluminate cement paste modified by retarder and diatomite. *Construction and Building Materials*, *234*, 117391.

Chen, M., Liu, B., Li, L., Cao, L., Huang, Y., Wang, S., ... & Cheng, X. (2020). Rheological parameters, thixotropy and creep of 3D-printed calcium sulfoaluminate cement composites modified by bentonite. *Composites Part B: Engineering*, *186*, 107821.

Chen, Y., Li, Z., Chaves Figueiredo, S., Çopuroğlu, O., Veer, F., & Schlangen, E. (2019). Limestone and calcined clay-based sustainable cementitious materials for 3D concrete printing: A fundamental study of extrudability and early-age strength development. *Applied Sciences, 9*(9), 1809.

Cho, S., Kruger, J., van Rooyen, A., & van Zijl, G. (2021). Rheology and application of buoyant foam concrete for digital fabrication. *Composites Part B: Engineering*, 108800.

Chougan, M., Ghaffar, S. H., Sikora, P., Chung, S. Y., Rucinska, T., Stephan, D., & Swash, M. R. (2021). Investigation of additive incorporation on rheological, microstructural and mechanical properties of 3D printable alkali-activated materials. *Materials & Design*, 202, 109574.

COBOD: https://cobod.com/. Retrieved on June 10, 2021.

Ding, Z., Wang, X., Sanjayan, J., Zou, P. X., & Ding, Z. K. (2018). A feasibility study on hpmc-improved sulphoaluminate cement for 3d printing. *Materials, 11*(12), 2415.

Figueiredo, S. C., Rodríguez, C. R., Ahmed, Z. Y., Bos, D. H., Xu, Y., Salet, T. M., & Bos, F. P. (2019). An approach to develop printable strain hardening cementitious composites. *Materials & Design*, *169*, 107651.

Dey, D., Srinivas, D., Panda, B., Suraneni, P., & Sitharam, T. G. (2022). Use of industrial waste materials for 3D printing of sustainable concrete: A review. Journal of Cleaner Production, 130749.

Huang, T., Li, B., Yuan, Q., Shi, Z., Xie, Y., & Shi, C. (2019). Rheological behavior of Portland clinker-calcium sulphoaluminate clinker-anhydrite ternary blend. *Cement and Concrete Composites*, *104*, 103403.

Jeong, H., Han, S. J., Choi, S. H., Lee, Y. J., Yi, S. T., & Kim, K. S. (2019). Rheological property criteria for buildable 3D printing concrete. *Materials, 12*(4), 657.

Khoshnevis, B., Hwang, D., Yao, K. T., & Yeh, Z. (2006). Mega-scale fabrication by contour crafting. *International Journal of Industrial and Systems Engineering, 1*(3), 301–320.

Kruger, J., & van Zijl, G. (2021). A compendious review on lack-of-fusion in digital concrete fabrication. *Additive Manufacturing, 37*, 101654.

Kruger, J., Zeranka, S., & van Zijl, G. (2019). An ab initio approach for thixotropy characterisation of (nanoparticle-infused) 3D printable concrete. *Construction and Building Materials, 224*, 372–386.

Le, T. T., Austin, S. A., Lim, S., Buswell, R. A., Gibb, A. G., & Thorpe, T. (2012a). Mix design and fresh properties for high-performance printing concrete. *Materials and Structures, 45*(8), 1221–1232.

Le, T. T., Austin, S. A., Lim, S., Buswell, R. A., Law, R., Gibb, A. G., & Thorpe, T. (2012b). Hardened properties of high-performance printing concrete. *Cement and Concrete Research, 42*(3), 558–566.

Lim, S., Buswell, R. A., Le, T. T., Austin, S. A., Gibb, A. G., & Thorpe, T. (2012). Developments in construction-scale additive manufacturing processes. *Automation in Construction, 21*, 262–268.

Liu, Z., Li, M., Weng, Y., Wong, T. N., & Tan, M. J. (2019). Mixture Design Approach to optimize the rheological properties of the material used in 3D cementitious material printing. *Construction and Building Materials, 198*, 245–255.

Lothenbach, B., Scrivener, K., & Hooton, R. D. (2011). Supplementary cementitious materials. *Cement and Concrete Research, 41*(12), 1244–1256.

Ma, S., Qian, Y., & Kawashima, S. (2018). Experimental and modeling study on the non-linear structural build-up of fresh cement pastes incorporating viscosity modifying admixtures. *Cement and Concrete Research, 108*, 1–9.

Marchon, D., Kawashima, S., Bessaies-Bey, H., Mantellato, S., & Ng, S. (2018). Hydration and rheology control of concrete for digital fabrication: Potential admixtures and cement chemistry. *Cement and Concrete Research, 112*, 96–110.

Markin, V., Nerella, V. N., Schröfl, C., Guseynova, G., & Mechtcherine, V. (2019). Material design and performance evaluation of foam concrete for digital fabrication. *Materials, 12*(15), 2433.

Mechtcherine, V., Nerella, V. N., Will, F., Näther, M., Otto, J., & Krause, M. (2019). Large-scale digital concrete construction–CONPrint3D concept for on-site, monolithic 3D-printing. *Automation in construction*, *107*, 102933.

Mechtcherine, V., Bos, F. P., Perrot, A., da Silva, W. L., Nerella, V. N., Fataei, S., & Roussel, N. (2020). Extrusion-based additive manufacturing with cement-based materials–Production steps, processes, and their underlying physics: A review. *Cement and Concrete Research*, *132*, 106037.

Mohammad, M., Masad, E., Seers, T., & Al-Ghamdi, S. G. (2020, July). High-performance lightweight concrete for 3D printing. In *RILEM International Conference on Concrete and Digital Fabrication* (pp. 459–467). Springer, Cham.

Momayez, A., Ehsani, M. R., Ramezanianpour, A. A., & Rajaie, H. (2005). Comparison of methods for evaluating bond strength between concrete substrate and repair materials. *Cement and Concrete Research, 35*(4), 748–757.

Muthukrishnan, S., Kua, H. W., Yu, L. N., & Chung, J. K. (2020). Fresh properties of cementitious materials containing rice husk ash for construction 3D printing. *Journal of Materials in Civil Engineering, 32*(8), 04020195.

Nair, S. A., Alghamdi, H., Arora, A., Mehdipour, I., Sant, G., & Neithalath, N. (2019). Linking fresh paste microstructure, rheology and extrusion characteristics of cementitious binders for 3D printing. *Journal of the American Ceramic Society, 102*(7), 3951–3964.

Nerella, V. N., Hempel, S., & Mechtcherine, V. (2019). Effects of layer-interface properties on mechanical performance of concrete elements produced by extrusion-based 3D-printing. *Construction and Building Materials, 205*, 586–601.

Panda, B., & Tan, M. J. (2019). Rheological behavior of high volume fly ash mixtures containing micro silica for digital construction application. *Materials Letters, 237*, 348–351.

Panda, B., Paul, S. C., & Tan, M. J. (2017). Anisotropic mechanical performance of 3D printed fiber reinforced sustainable construction material. *Materials Letters, 209*, 146–149.

Panda, B., Noor Mohamed, N. A., Paul, S. C., Bhagath Singh, G. V. P., Tan, M. J., & Šavija, B. (2019a). The effect of material fresh properties and process parameters on buildability and interlayer adhesion of 3D printed concrete. *Materials, 12*(13), 2149.

Panda, B., Ruan, S., Unluer, C., & Tan, M. J. (2019b). Improving the 3D printability of high volume fly ash mixtures via the use of nano attapulgite clay. *Composites Part b: Engineering, 165*, 75–83.

Panda, B., Singh, G. B., Unluer, C., & Tan, M. J. (2019c). Synthesis and characterization of one-part geopolymers for extrusion based 3D concrete printing. *Journal of Cleaner Production, 220*, 610–619.

Panda, B., Unluer, C., & Tan, M. J. (2019d). Extrusion and rheology characterization of geopolymer nanocomposites used in 3D printing. *Composites Part B: Engineering*, *176*, 107290.

Panda, B., Ruan, S., Unluer, C., & Tan, M. J. (2020). Investigation of the properties of alkali-activated slag mixes involving the use of nanoclay and nucleation seeds for 3D printing. *Composites Part B: Engineering*, *186*, 107826.

Paul, S. C., van Zijl, G. P., Tan, M. J., & Gibson, I. (2018). A review of 3D concrete printing systems and materials properties: Current status and future research prospects. *Rapid Prototyping Journal*

Perrot, A., Rangeard, D., & Courteille, E. (2018). 3D printing of earth-based materials: Processing aspects. *Construction and Building Materials, 172*, 670–676.

Perrot, A., Rangeard, D., & Pierre, A. (2016). Structural built-up of cement-based materials used for 3D-printing extrusion techniques. *Materials and Structures, 49*(4), 1213–1220.

Poinot, T., Govin, A., & Grosseau, P. (2014). Importance of coil-overlapping for the effectiveness of hydroxypropylguars as water retention agent in cement-based mortars. *Cement and Concrete Research, 56*, 61–68.

Rahul, A. V., Santhanam, M., Meena, H., & Ghani, Z. (2019). 3D printable concrete: Mixture design and test methods. *Cement and Concrete Composites, 97*, 13–23.

Reiter, L., Wangler, T., Anton, A., & Flatt, R. J. (2020). Setting on demand for digital concrete–principles, measurements, chemistry, validation. *Cement and Concrete Research*, *132*, 106047.

Reiter, L., Wangler, T., Roussel, N., & Flatt, R. J. (2018). The role of early age structural build-up in digital fabrication with concrete. *Cement and Concrete Research, 112*, 86–95.

Saha, S., & Rajasekaran, C. (2017). Enhancement of the properties of fly ash based geopolymer paste by incorporating ground granulated blast furnace slag. *Construction and Building Materials, 146*, 615–620.

Sanjayan, J. G., Nazari, A., & Nematollahi, B. (2019). *3D concrete printing technology: Construction and building applications*. Butterworth-Heinemann.

Sanjayan, J. G., Nematollahi, B., Xia, M., & Marchment, T. (2018). Effect of surface moisture on inter-layer strength of 3D printed concrete. *Construction and Building Materials, 172*, 468–475.

Sika Concrete 3D Printing: www.sika.com/en/knowledge-hub/3d-concrete-printing.html. Retrieved on October 11, 2021

Sun, C., Xiang, J., Xu, M., He, Y., Tong, Z., & Cui, X. (2020). 3D extrusion free forming of geopolymer composites: Materials modification and processing optimization. *Journal of Cleaner Production*, *258*, 120986.

Taha, B., & Nounu, G. (2008). Properties of concrete contains mixed colour waste recycled glass as sand and cement replacement. *Construction and Building Materials, 22*(5), 713–720.

Taha, B., & Nounu, G. (2009). Utilizing waste recycled glass as sand/cement replacement in concrete. *Journal of Materials in Civil Engineering, 21*(12), 709–721.

Tay, Y. W. D., Panda, B., Paul, S. C., Noor Mohamed, N. A., Tan, M. J., & Leong, K. F. (2017). 3D printing trends in building and construction industry: A review. *Virtual and Physical Prototyping, 12*(3), 261–276.

Tay, Y. W. D., Qian, Y., & Tan, M. J. (2019a). Printability region for 3D concrete printing using slump and slump flow test. *Composites Part B: Engineering*, *174*, 106968

Tay, Y. W. D., Ting, G. H. A., Qian, Y., Panda, B., He, L., & Tan, M. J. (2019b). Time gap effect on bond strength of 3D-printed concrete. *Virtual and Physical Prototyping, 14*(1), 104–113.

The Large-Scale 3d—XtreeE—3D Printed Wall with Integrated Window Frame. https://www.youtube.com/watch?v=0byQtXW5Gm8. Retrieved on October 11, 2021

Ting, G. H. A., Tay, Y. W. D., Qian, Y., & Tan, M. J. (2019). Utilization of recycled glass for 3D concrete printing: Rheological and mechanical properties. *Journal of Material Cycles and Waste Management, 21*(4), 994–1003.

van den Heever, M., Bester, F. A., Kruger, P. J., & van Zijl, G. P. A. G. Effect of Silicon carbide (SiC) nanoparticles on 3D printability of cement-based materials.

Wang, L., Jiang, H., Li, Z., & Ma, G. (2020). Mechanical behaviors of 3D printed lightweight concrete structure with hollow section. *Archives of Civil and Mechanical Engineering, 20*(1), 1–17.

Wangler, T., Lloret, E., Reiter, L., Hack, N., Gramazio, F., Kohler, M., & Flatt, R. (2016). Digital concrete: Opportunities and challenges. *RILEM Technical Letters, 1*, 67–75.

Wangler, T., Roussel, N., Bos, F. P., Salet, T. A., & Flatt, R. J. (2019a). Digital concrete: A review. *Cement and Concrete Research*, *123*, 105780.

Wangler, T., Scotto, F., Lloret-Fritschi, E., & Flatt, R. J. (2019b). Residence time distributions in continuous processing of concrete. In *Rheology and processing of construction materials* (pp. 448–456). Springer.

Weng, Y., Li, M., Ruan, S., Wong, T. N., Tan, M. J., Yeong, K. L. O., & Qian, S. (2020). Comparative economic, environmental and productivity assessment of a concrete bathroom unit fabricated through 3D printing and a precast approach. *Journal of Cleaner Production*, *261*, 121245.

Weng, Y., Lu, B., Li, M., Liu, Z., Tan, M. J., & Qian, S. (2018). Empirical models to predict rheological properties of fiber reinforced cementitious composites for 3D printing. *Construction and Building Materials, 189*, 676–685.

Winsun: http://www.winsun3d.com/En/About/. Retrieved on June 10, 2021.

Wolfs, R. J., Bos, F. P., & Salet, T. A. M. (2018). Early age mechanical behaviour of 3D printed concrete: Numerical modelling and experimental testing. *Cement and Concrete Research, 106*, 103–116.

Wolfs, R. J. M., Bos, F. P., & Salet, T. A. M. (2019). Hardened properties of 3D printed concrete: The influence of process parameters on interlayer adhesion. *Cement and Concrete Research, 119*, 132–140.

Yuan, Q., Zhou, D., Li, B., Huang, H., & Shi, C. (2018). Effect of mineral admixtures on the structural build-up of cement paste. *Construction and Building Materials, 160*, 117–126.

Zareiyan, B., & Khoshnevis, B. (2017). Interlayer adhesion and strength of structures in Contour Crafting-Effects of aggregate size, extrusion rate, and layer thickness. *Automation in Construction, 81*, 112–121.