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Review

Additive manufacturing technology and its implementation in construction as an eco-innovative solution

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A B S T R A C T

Additive manufacturing (AM) of construction materials has been one of the emerging advanced technologies that aim to minimise the supply chain in the construction industry through autonomous production of building components directly from digital models without human intervention and complicated formworks. However, technical challenges needs to be addressed for the industrial implementation of AM, e.g. materials formulation standardization, and interfacial bonding quality between the deposited layers amongst others. AM as one of the most highlighted key enabling technologies has the potential to create disruptive solutions, the key for its successful implementation is multidisciplinary effort in synergy involving materials science, architecture/design, computation, and robotics. There are crucial links between the material design formulations and the printing system for the manufacturing of the complex 3D geometries. Understanding and optimising the mix design for fresh rheology of materials and sufficient adhesion/cohesion of interface can allow the incorporation of complexity in the geometry.

1. Introduction

Additive manufacturing (AM) is a procedure that forms layers to create three-dimensional (3D) solid objects from digital models, allowing creatives, engineers, architects and designers to make customised designs in one-step process. The emergence of advanced technologies, coupled with demands for more sustainable and resource efficient practices and trends for futuristic structures/designs, are causing changes in the scale and distribution of construction. Approaches such as process automation offer a big retreat from conventional methods of construction. This has largely been investigated in terms of robotics [1–5]. Applications of robotics offer solutions to improve productivity, quality and quality control, working conditions, and skilled labour shortages. Automation technology is being implemented in construction, e.g. the utilisation of drone technology on construction sites has been investigated for applications such as safety inspection [6] and 3D modelling of the site [7]. Automated assembly solutions in construction have been developed independently of AM systems, a combination of the two could be considered for multi-purpose robotics solutions, for example, Williams et al. [2] present a RoboCrane, an autonomous system for additive construction of houses via deposition of concrete and similar materials.

The use of 6-axis industrial robot, not only allows non-horizontal and non-straight slicing of the printed structure, but also facilitates the prospect of an effective implementation of AM technologies in the construction industry. One of the main AM technologies developed for the construction industry is Contour Crafting, which is a layered fabrication technology that uses robotic arms and extrusion nozzles (see Fig. 1). This process uses a concrete-like material to form a building's walls via a programmed crane or scaffold [8]. These machines have a XYZ gantry system, a nozzle assembly with three motion control components (extrusion, rotation and trowel deflection) and a six-axis coordinated motion control system. The key feature of Contour Crafting is the use of two trowels, which basically act as two solid planar surfaces, to create smooth and accurate surfaces on the object being manufactured.

Other developments have also been carried out by concrete printing team of Loughborough University [9], using an automated extrusion based process. The sizes of the printing products were limited, as they could only handle a print dimension up to 5.4 m × 4.4 m × 5.4 m [9]. Such dimensions would produce enough capacity to print basic precast concrete components, such as precast concrete columns [10]. Compared to Contour Crafting, the concrete printing method has a smaller resolution of deposition (4-6 mm in terms of layer depth), which leads to a more precise control of complex geometries. A process called D-shape has also been developed by straining a binder on the material

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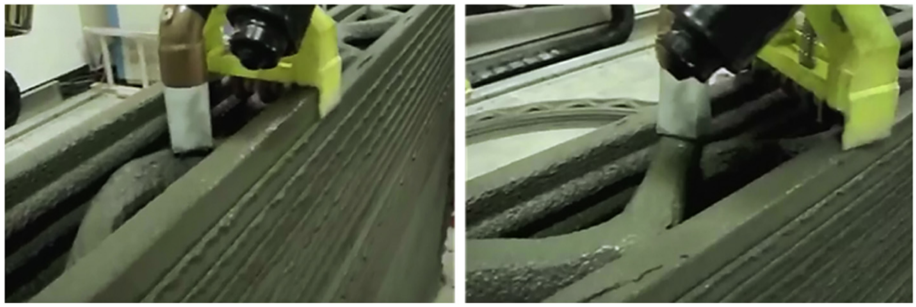

Fig. 1. Contour Crafting nozzle head printing cementitious materials.

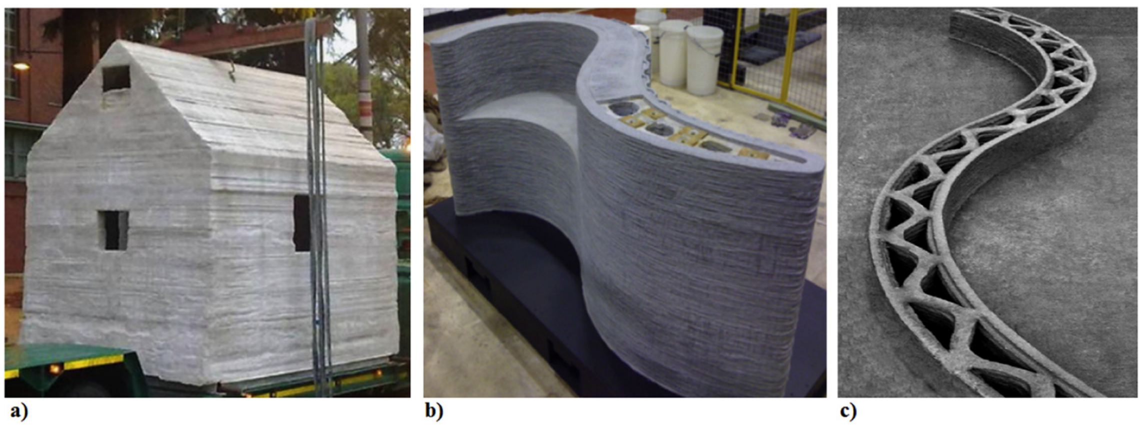

Fig. 2. a) D-shape example of large scale objects [11], b) Concrete printing [9] and c) Contour Crafting of curved wall [12].

layer. D-shape is a factory gantry-based powder-bed 3D printer, which claims to have an effective printing method for large scale objects [11]. The D-shape method uses a powder deposition process, which is quite similar to the inkjet powder printing process where a binder is used so that selective layers of printing materials are hardened. Contour Crafting along with concrete printing are wet processes while D-shape is mainly a dry process. Materials in all three methods harden through a curing process, which is essentially less controllable than the heat or UV based phase change methods in rapid prototyping. Contour Crafting, D-shape and concrete printing, all have demonstrated the construction of large size components (see Fig. 2).

The extrusion printing techniques are intended for both *on-site* and *off-site* applications such as large-scale components, while the powder printing technique can be an *off-site* process to manufacture precast components such as panels, permanent formworks and interior structures that can be assembled *on-site* [13]. The layer depth, i.e. print resolution in all three methods is against the speed of execution, i.e. the number of layers needed to build the wanted height. Additional influential factors are the minimum feature size (i.e. the smallest detail that can be built), and surface finish [9].

There has been a growing research on AM in construction sector [14–27], though, the developments are still in their initial stages. Printing of construction materials requires a mix formulation in which the setting time of the paste, shape stability of first few layers and, interlayer bonding between the layers are thoroughly controlled and investigated for optimisation. This paper attempts to collate the progress in construction industry to implement AM as an eco-innovative solution with the emphasis on material science, one of the major influential contributors for its successful employment. The cementitious and polymer-based material feedstocks for AM are reviewed, discussing the importance of mix design formulations and also presenting the new pathways for future propositions in the context of circular economy and the role that AM can play in achieving the circularity in construction sector. Moreover, this paper investigates the interlayer bonding by critically reviewing the limited research and further suggesting the pathways for improvements in this important area. The automated nature of layer deposition requires thorough investigation of interfacial bond strength and its influential parameters for enhancing the structural performance.

2. Innovation in construction industry

Innovation and research will play a key part in the systemic change of the industry, where taking advantage of the use of technologies from elsewhere will reinforce many competitive advantages. AM technology can have the potential to help construction industry to transition into a responsive and advanced sector, although, different grades of advanced printable feedstocks needs to be formulate/developed to make this technology more effective for the making of building structural elements. The generalised perception is that AM is most relevant for industries where the demand in customisation, flexibility, design complexity, and the cut on high transportation costs for the delivery of end products is crucial, therefore, making the construction industry a potentially lead beneficiary of the next Industry 4.0 revolution. The simple approach of layer-wise construction is a process that has already been practiced for a long time in the building sector, such as the conventional brick layering techniques. The true novelty for advanced construction technology is to combine new highly efficient and sustainable materials along with the most advanced tools of the digital age, using architectural design software as the front end and combine different components of robotic technology to automate and excel processes that have been proven manually. Thorough testing is essential to improve the way construction industry works by using cutting-edge technology to enhance the ability to anticipate and adapt.

2.1. Demonstrations of additive manufacturing technology in construction

Across the industry, there are some records claiming different levels

Fig. 3. Office building in Dubai printed by WinSun.

of success in printing buildings. For instance, WinSun, a Chinese construction company, claims to have 3D printed ten homes within just 24 h in 2014. A large-scale 3D printer: 150 m long, 10 m wide and 6 m deep was used along with a concrete material reinforced with special fiberglass. In 2016, WinSun presented the first 3D printed office in the world, measuring $250m^2$ (see Fig. 3). The building was printed using a mobile system featuring an automated robotic arm. The integration of a unique building design and 3D printing technology demonstrated the potential to include and offer pre-designed features for essential services within the building, such as water, electricity, and air-conditioning. While the full model took 17 days to print [21], the company claimed that the labour cost could be cut by more than 50%, when compared to conventional buildings of similar size.

In September 2015, the interior of a hotel suite in Philippines sizing 12.5 × 10.5 × 4 m, was printed by Andrey Rudenko, becoming the first operational and commercial oriented structure created using AM [28]. Fig. 4 shows the printer nozzle in action and the completed structures accomplished. The completion of the project took 100 h of print time, although the process was not continuous. A mixture of sand and local volcanic ash was used as the printable materials, which was found to be difficult to extrude. Even without a comprehensive quantitative characterisation reported, still a reliable process was developed, with strong walls and good bonding between layers [28].

Construction components of medium to large size are heavy and could weight up to five tonnes. Lifting and moving these parts is not easy and economical. Knowing this, Apis Cor™ company, has recently printed a house in Russia using mobile 3D printing technology (Fig. 5a) [29]. The automated printing of self-bearing walls, partitions and building envelope was done in 24 h, totalling a $38m^2$ printed building area. Apis Cor™ claims that this printer is easy to transport to any site and does not need long preparation before the start of construction work, taking advantage of its built-in automatic horizon alignment and stabilisation system.

This example attempts to demonstrate that an in-situ deposition approach (i.e. Contour Crafting and Apis Cor™ process), could be much easier and economical than *off-site* preassembled ones. Apart from the robotic arm and printing size (area and volume) limitations, an important potential disadvantage can also be the sensitivity of feedstock materials and the printing processes itself to ambient conditions, which can somehow hinder the *on-site* approach.

In light of some of these difficulties, Gosselin et al. [14] presented an AM process for ultra-high performance concrete. The proposed 3D printing process used is based on a fused deposition modelling (FDM) method, where the material is deposited layer by layer through an extrusion nozzle mounted on a 6-axis robotic arm. Gosselin et al. [14] claim that this process allows the production of 3D large-scale complex geometries, without the use of temporary supports. Their processing setup consists of a print head nozzle mounted on the robot and two peristaltic pumps, one for the premix compound mixer and one for the accelerating agent. Their production of a wall element sizing 1.36 m × 1.5 m × 0.17 m took approximately 12 h (139 layers). The final printed wall is shown in Fig. 6.

Bos et al. [19] at the Eindhoven University of Technology also have adopted the Contour Crafting strategy to print cementitious-based materials. A four degree of freedom gantry robot serving a print area of 9 m × 4.5 m × 2.8 m was used. Pressurised by the help of a pump, the material is forced towards the print head (shown in Fig. 7a), leaving the 3D printer nozzle as a relatively stiff and continuous filament shown in Fig. 7b.

An important milestone in AM for entire building projects is the 6 m tall KamerMaker 3D printer developed by the Amsterdam-based DUS Architects to fabricate a canal house. KamerMaker uses polypropylene as the printing material to produce components with large dimensions [30,31]. The printing material however can be too brittle for the use as load bearing and construction components which span horizontally, such as slabs and staircases. When using AM to fabricate load bearing components, the material can be printed in the form of mesh or truss-like systems, leading to another huge advantage of this technology, as it potentially eliminates de-moulding process, e.g. for a new concrete construction project, approximately 60% of the total cost is spent for the formwork and labour [26].

Platt Boys the developer of C-Fab™ (Cellular Fabrication) [32] have claimed that by only printing the support structure of the wall, this element could be readily integrated into modern construction and rather quicker than, for example, gantry-style printing used by WinSun.

Although, many developments are yet to be up-scaled and the works on the optimisation of printing parameters and material feedstock rheology are still ongoing, a summary of AM research efforts which could be implemented in the construction industry are presented in Table 1.

Fig. 8 illustrates the importance of multi-parameter interdependency of the main components of AM for construction. Each of the components constitutes a range of parameters and variables. For a successful implementation of AM in large scale construction, three main parameters which are interrelated in sequence, need to be carefully addressed:

Fig. 4. The hotel suite interior printed in Philippines.

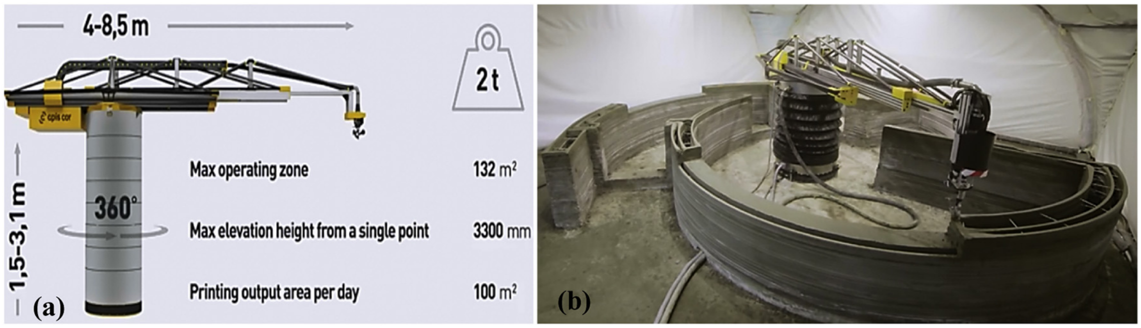

Fig. 5. Apis Cor™ mobile 3D printer and its specification (a) and the robotic 3D printer in action (b) [29].

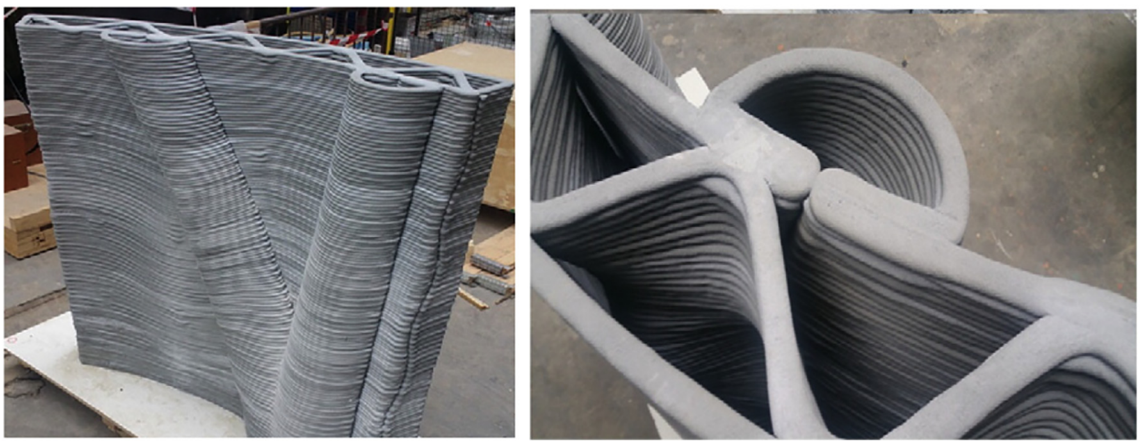

Fig. 6. The 3D printed concrete wall by Gosselin et al. [14].

1) Printable feedstocks: the source and composition, mix design with different additives and particle size all play an influential role in the core of feedstock developments. With the aim of optimised blending of feedstocks to have the appropriate open time and setting time to enable the continuous extrusion and delivery to the nozzle.
2) Printer: printer integrated with a pump is essential for the scale of manufacturing in construction industry. Therefore the pressure and flow rate have to be investigate in accordance with different mix designs. The speed and the size of the printer set up is also dominant in achieving a good print quality, i.e. smooth surface, square edges and dimensional consistency. Deposition rate of feedstock materials (e.g. in centimetres per hour) influences the construction speed, moreover, decreasing the setting time can risk feedstock hardening inside the printer system. Optimised printing system with continuous delivery of feedstock materials should extrude the material at a constant rate so it does not impede the interface between the layers.
3) Geometry: the tailored design and outcomes of previous two parameters will directly feed into the realisation of full size building blocks/objects with smart self-reinforced geometry. The shape stability of deposited filaments and 3D curvatures, truss-like structures could then provide the strength and stiffness of the printed objects/building blocks.

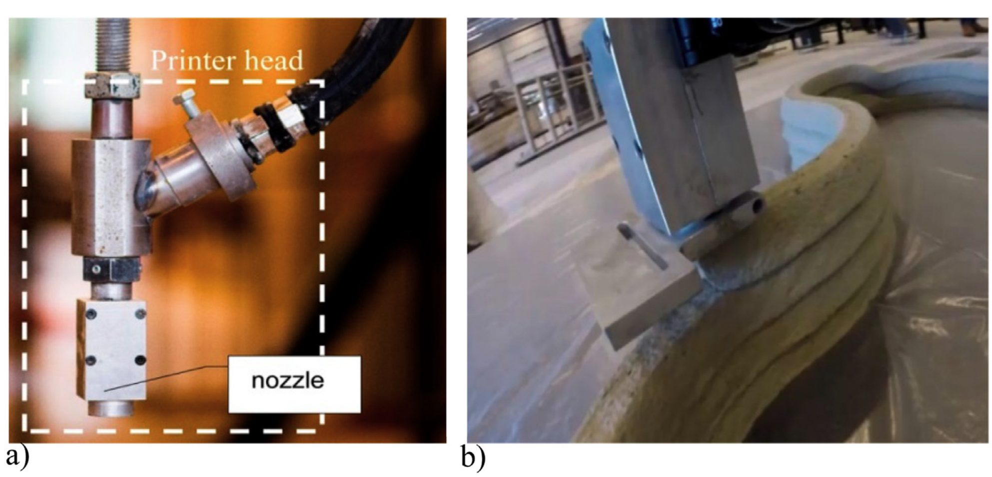

Fig. 7. The printer head (a), and 3D printer in operation (b) [19].

Table 1
Some of the developments of AM for potential implementation in construction sector.

AM technology used	Printed materials and products	Refs.
Stereo lithography	Ceramic products	[33]
Contour Crafting	Concrete (mortar), plaster and ceramic products	[12,34]
Concept modelling	Polyester parts	[35]
Concrete printing	Concrete (mortar) products	[9]
Fused Deposition Modelling (FDM) and Selective Laser Sintering (SLS)	Space frame, rotunda and IBM Pavilion architectural models	[36]
3D printer	Plaster model	[37]
KamerMarker	Polypropylene structures	[31]
3D printer	Entire house	[38]
FDM	Entire house	[39]
Powder based 3D printer	Geopolymer-based materials	[13]

2.2. Benefits and challenges of additive manufacturing for construction

AM has many ground-breaking benefits for the construction sector and could offer multiple advantages over traditional techniques, including reduced material waste (up to 30%) [20], lower energy use, in-situ production, extended architectural/design freedom with lesser resource demands and related CO_2 emissions over the entire product life cycle [40]. It also induces changes in labour structures, including gender equality, plus safer working environment and generates shifts towards more digital and localised supply chains. From architect's point of view, AM can provide a powerful tool for their business, by being able to create a physical model faster and with better resolution which is able to realise the complexity of their designs. AM also enables customers to co-design products that can perfectly fit their demands and ambitions. On the other hand, several restrictions limit the AM wide spread application. Certifying new components and characterising them is and probably will be for a longer time one of the biggest hurdles for the AM construction industry. Especially in Europe, where the construction industry primarily depends on established standards in processes and material selection to ensure the consistency and quality, the lack of those related with AM will inhibit the use of AM for parts mass production in the upcoming years. Additionally, it is unknown if AM in the construction industry would lead to cost increase or cost reduction, as the industry still remains too much cost sensitive in the aftermath of the latest economic crisis. In this sense, it will be important that the life cycle costing of AM is evaluated according to the material feedstocks and printing systems. Table 2 summarises the main benefits and challenges with AM in construction.

3. Socioeconomic and environmental impacts of additive manufacturing in construction

The modern construction industry is under a period of dramatic policy shift, following a priority change from a profit-charged business to an ever adapting socioeconomic and environmentally driven entity. Under this context, material feedstocks aimed for AM should be carefully selected for this technology to demonstrate its impact as an environmental and eco-innovative solution. With the help of AM and the right circular models, the reuse and recycling of construction demolition waste (CDW) could potentially guide the successful implementation of circular economy in the construction industry. Nevertheless, this will always require efficient processing-sorting of wastes and smart dismantling building operations, in close collaboration with an in-depth feedstock formulation research (i.e. selecting the appropriate admixture and mix designs) to create technical advanced and commercially viable printable feedstocks using construction wastes as the main resource. If this ambition can be accomplished, with AM it will be possible to a large extent decouple growth from resource extraction in the construction industry and pioneer huge environmental, social and economic benefits. AM as an eco-innovation in the context of construction will imply the establishment of a novel and competitively priced process and/or system, fully focused upon satisfying human needs with minimal amount of toxic substances and wastage. When assessing the sustainability of AM driven products, their entire life cycle must be considered to attain its impact. The actual manufacturing process is only one of the many environmental impacts associated with the product life cycle [43]. One measure of success for the implementation of AM technology in construction is its ability to reduce the total environmental impact on a life-cycle basis as it enables outstanding

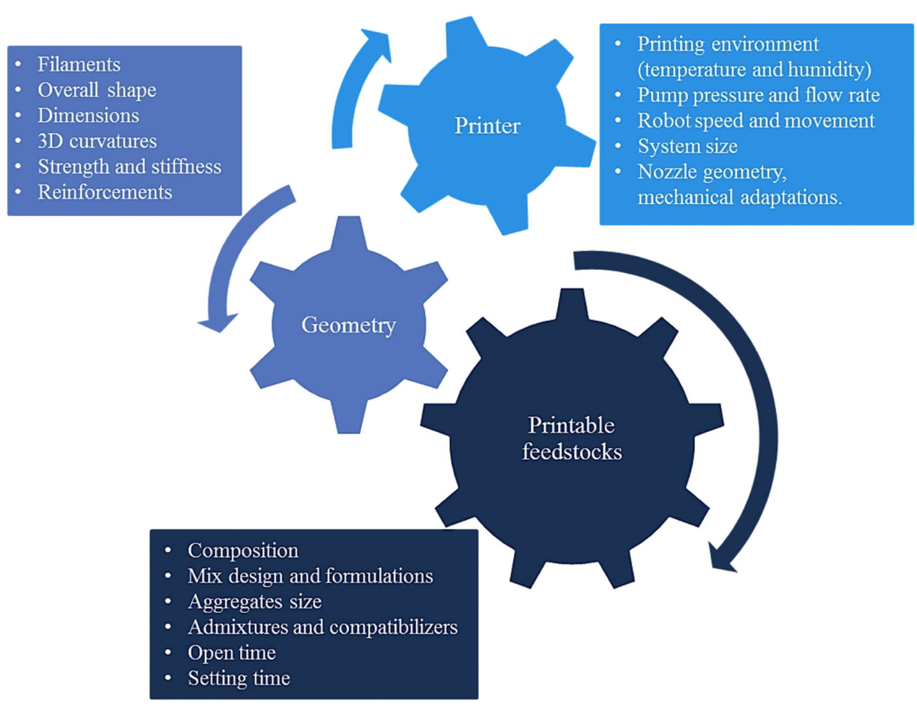

Fig. 8. The relationship of systematic parameters for large-scale AM implementation in construction.

Table 2
Main benefits and challenges of AM technology in construction.

Benefits of AM in construction	Remarks
Lower cost	Dramatically cut materials/labour costs and increase site workers efficiency
Fasters rate	Large-scale production of parts (i.e. urban furniture/facilities) and structural elements in less time
Strength and durability	There are 3D printed concrete-based houses which can withstand 8.0 Richter scale earthquakes [41]
Novel shapes and design potentials	Releases current major design and technical constraints, given peerless opportunities for curvilinear/hollow structures and single customisation i.e. fabricating functionally light weight parts, while maintaining strength
Added sustainability	Capable of being made out of environmentally friendly recycled and bioplastic materials
Safer and genderless working environments	Represents a cultural shift that promotes a better society for everyone
Challenge to be addressed	Remarks
Large scale printers are expensive	Up to several million pounds in addition to ongoing maintenance costs, although the industrial competition is bringing the prices down fast
The surface quality may be rough	End results may not be as smooth as current standards, improvements and a later human-made finishing step can always be performed
Potential legal issues	Design IPR concerns and lack of performance standardization, translating to policies/regulations which still need to adapt to this new technology
Quality issues are a concern	The printed parts from certain grade of materials may lack resistance to environmental influences and fail with exposure to high stresses [42]
The precision of the produced parts still needs improvement	To assure the reproducibility with uniformity in their functionality
The high levels of abrasiveness of concrete-type materials	Effects the essential pump maintenance

improvements towards resource efficiency and potentially triggers new models of sustainable production and consumption. Efforts at closing or slowing the material's resource loop can be attained at different stages and scales in AM, with the highest value recovery possible to be realised locally during the manufacturing process, when unused AM material (powder or resin) can be easily reclaimed [44]. Ultimately, in-situ recycling systems can be linked to AM; channelling products at their end-of-life stage to waste-resource streams and generate new raw material for the same use or any other broader alternative application.

Gebler et al. [40] assessed the sustainability implications of industrial AM both qualitatively and quantitatively from a global perspective. The model calculations showed that by 2025, AM has the potential to reduce the production costs by 170–593 billion US$, the total primary energy supply by 2.54–9.30 EJ and the associated CO_2 emissions by 130.5–525.5 Mt. The wide range expected saving potentials can be justified with the juvenile state of the technology and the related uncertainties of predicting associated market and robotic performance evolutions.

AM in construction still generates a fair scepticism that it will lead to the loss of jobs. As much of this can be true, it is also predicted that traditional production jobs shall be not lost but, in fact, replaced by new and more qualified ones with the firm implementation of AM technology in the construction industry and with groups of people being potentially employed for more creative activities. Complementary, it is envisaged that the advent of these new technologies will allow, not only a much more gender equality industry, but also a superior improvement when it comes to health and safety issues, dramatically reducing working accidents and extending the active timeframe of workers.

4. Materials feedstocks for additive manufacturing in construction

Material science inevitably counts as a vital work force that dictates the success of AM technology in the sector. The printable feedstocks formulations are typically a combination of bulk materials (e.g. soil, sand, crushed stone, clay, recycled aggregates) mixed with a binder (e.g. Portland cement, fly ash, polymers) and workability additives/chemical agents.

4.1. Cementitious-based materials

Cementitious-based materials are the most studied option for widespread use in additive construction. This is because of their unique fresh and hardened characteristics and the extensive variety of possible feedstocks to be generated (including rheology modifying agents) and admixtures available to tailor their performance. There are no relevant guidelines or set of procedures for assessing mixtures suitable for printing with cementitious-based materials. Missing guidelines currently make it harder for non-experts to optimise mix designs. Extruded cementitious-based materials require fast-setting and low slump [45], as the material is unsupported after leaving the extrusion nozzle. The controlling parameters are highly dependent on parameters such as the density, particle size and especially viscosity, which is a function of the mix composition and water to cement ratio. Admixtures are applied to achieve specific properties such as self-compaction (i.e. superplasticizers), high cohesion/strength (i.e. silica fume), low CO_2– footprint and increased workability (i.e. fly ash), ductility (i.e. micro-fibres), viscosity modifying agents and so on. An optimised cementitious-based feedstock formulation often requires a thorough investigation to determine the links between mixture parameters. Even a slight variation in the mix design has a definite impact on the fresh state material behaviour, which is crucial for the extrusion procedure and for the subsequent hardening and curing stages, up until the final properties of the products. There are careful balances required, keeping the materials sufficiently workable for adhesion, but developing enough rigidity to support its self-weight. The rheological properties of cementitious-based materials are crucial to its flow characteristics, i.e. pumping pressure required. In this context, Mechtcherine et al. [46] studied a new device, the sliding pipe rheometer (slipper), to provide a more accurate approximation of pumping pressures and flow rates.

Table 3 collates main considerations for AM of concrete-like materials and where it is possible to realise the strong interdependency between material processing and design optimisation.

4.1.1. Properties of printable cementitious-based materials

A comparative analysis of materials feedstocks and the subsequent formulations used by researchers and companies is commonly difficult due to trade secret competitive considerations that prevent crucial technical details from being publicly shared. Still some examples are given such as the ones from the Concrete Printing research group of Loughborough University [9,18,47], that provided some information on the material mix used, which mainly consisted of 54% sand, 36% reactive cementitious compounds, and 10% water by mass. The binder material used was a mix of CEM I cement, fly-ash, and un-densified silica fume. A retarder, superplasticizer and an accelerator were also used, though not presented with full details. Their mix contained polypropylene micro fibres to reduce shrinkage and deformation in the

Table 3
Procedures and configurations to be considered for the AM of cementitious-based materials.

Parameters	Considerations
Interval between the mixing and printing	The mixing process is not a continuous steady process, but rather a step-wise process, therefor the age of the concrete in the system varies where stagnation can also be an issue.
Mixing temperature	The environmental conditions, start temperature of the printing, setting reaction and friction in the printing system (i.e. pump pressure, section dimension, hose length, curves and angle) all play a role in temperature of the mix.
Mix internal pressure	The low-slump mix will require a particularly high pump pressure to move through the printing system.
Density of printed materials	The quality of cementitious-based materials not only depends on the chemical reaction, but also significantly on the physical compaction. The presence of voids which can form at the intersection of filaments, can affect the hardened properties significantly
The pumping of cementitious-based feedstock	It can control the implementation of the technology on larger scales. Pumping pressure is still being estimated using conventional methods such as the slump test, viscometer, and flow table test which are not sufficient.

plastic state. The resulted cementitious-based print had a density of 2350 kg/m^3, a compressive strength of 75–102 MPa, a flexural strength of 6–17 MPa and a tensile bond strength between layers of 0.7–2 MPa [47]. In another study from the same group, Le et al. [48] concluded that a mix of 70% cement, 20% fly ash and 10% silica fume, together with 1.2 kg/m^3 micro-polypropylene fibres resulted in a maximum compressive strength of 110 MPa after 28 days, and an optimum open time of up to 100 min.

Jeon et al. [49] obtained a maximum compressive strength of 55 MPa after 28 days, as well as registering values for the most suitable setting times (initial set of 60 min and final set up to185 min), using a mortar mix comprising 30% of fly ash and 10% of silica fume with the rest being Portland cement acting as the binder. Bos et al. [19] used a custom cementitious-based mix which was comprised of Portland cement (CEM I 52,5 R), siliceous aggregate (particle size of 1 mm), limestone filler, specific additives for ease of pumping, rheology modifiers, and a small amount of polypropylene fibres. The cementitious-based material had a 28 day compressive strength of 30 MPa, and flexural tensile strength of 5 MPa.

Hambach and Volkmer [50] used 61.5% by weight of type I 52.5 R Portland cement with 21% by weight of silica fume, 15% by weight of water and 2.5% by weight of a water reducing agent, they also added 1 vol% of short (3-6 mm) carbon fibres, this yielded a flexural strength of 30 MPa, and compressive strength of 83 MPa, with an overall mix design density of around 2000 kg/m^3.

Khalil et al. [51] reported an optimised mix ratio of 93% Ordinary Portland Cement (OPC) and 7% Calcium Sulfo-aluminate cement with water to cement ratio of 0.35, sand to cement ratio of 2, and 0.26% of superplasticizer of the total weight of the binder which was suitable for 3D printing. The compressive strength of the aforementioned mix ratio was 79 MPa for printed specimen compared to 88 MPa for casted specimen. The printed specimens are expected to be weaker than the casted ones due to additional porosity related to the 3D printing process.

It was found by Feng et al. [52] that the printing process of plaster cementitious material led to an apparent orthotropic behaviour that was relevant to its compressive strength and elastic modulus. Their results confirmed that due to the anisotropic nature of material distribution, extrusion-based printing processes are likely to create components that are also strongly anisotropic [52], which will have a significant effect on the load-bearing capacity of the printed structure. The same conclusions were reached by Le et al. [47] who measured the effects of voids that appeared between deposited filaments on the orthotropic compressive and flexural strengths of extruded concrete. Similarly, it has been shown that the print direction has an impact on the mechanical properties of the printed specimens [26] depending on the direction of testing (i.e. applying the load).

4.1.2. Print quality assessment

Suitable and comprehensive list of performance requirements and test methods for printing mixtures have not yet been established. However, different approaches for characterising the fresh cementitious-based material behaviour have been proposed. Kazemian et al. [23] introduced a laboratory testing procedure for evaluation of fresh cementitious-based printing mixtures. They studied four printable mixtures where the effects of nano-clay, silica fume and fibre inclusions were investigated. Their proposed procedure was designed in such a way to be applicable to different printer systems of fresh cementitious-based materials, as it concentrates on the properties of printed layers rather than on pumping or extrusion mechanisms. With respect to print quality, three requirements were proposed: surface quality, squared edges and dimension conformity and consistency [23]. As for shape stability, a cylinder stability test was proposed for evaluation and comparison of the effects of different admixtures. In this regard, Kazemian et al. [23] showed that inclusion of silica fume and a highly-purified Nano-clay can enhance shape stability of fresh printing mixture and Perrot et al. [22] used a similar cylinder stability test procedure to simulate the load imposed on the first deposited layer. Another key consideration for a fundamental study of shape stability is thixotropy. This is defined as build-up and breakdown of internal 3D structure within cementitious paste which happens respectively as a result of flocculation or coagulation due to van der Waals attractive forces of cement particle or their dispersion, either way resulting from inter-particle forces and chemical connections [53].

The Contour Crafting research group has applied uniaxial plate stacking tests and, subsequently, a more controlled method to apply uniaxial loads on fresh cylinders was presented [54]. However, it is questionable whether this uniaxial test provides sufficient information on the failure behaviour in different 3D stress states. On the other hand, the Concrete Printing research group considered the pre-set concrete material as a Bingham plastic fluid and performed shear vane tests to obtain the relevant rheological parameters [48]. The study only mentions determination of the shear strength, whereas also the plastic viscosity needs to be determined to obtain a complete Bingham fluid model. It should be considered that for buildability assessment, actually the stiffness of the printed filament is important, even before failure and plasticity occurs. Development of test methods should aim at obtaining accurate stress–strain relations for the pre-set cementitious-based materials.

4.1.3. Interlayer bonding of cementitious-based materials

The subjects of interlayer bonding quality and the cohesion mechanisms of cementitious-based materials for AM have not been extensively researched. Interlayer adhesion can be the interaction of the materials in both the micro and macro scale, for instance in the micro scale, chemical reactions, and in macro scale surface roughness can be influential for creating the intimate cohesion between layers. The bond strength between the layers of printed cementitious-based materials is perhaps the critical mechanical property of objects produced by an AM process, creating potential flaws between consecutive extrusions levels can induce stress concentrations. On the other hand, the fabrication speed must be designed to allow the layers establish intimate cohesiveness and have enough shape stability/strength to sustain their own weight and the weights of successive layers above them. This is significantly dependent on the bonding which is also a function of time between layer depositions. Lengthier interlayer time gaps can cause lower bond strength (e.g. cold joints at the interface of layers), therefore leading to the lower structural properties of printed structures or elements. It is essential for the cementitious-based materials to develop strength in a minimal amount of time such that the first layer can sustain the weight of the layers on the top, where no deformation should happen while the following layers are deposited.

Zareiyan and Khoshnevis [55], analysed the interlayer bond strength of Contour Crafted structure, the results indicated a 16% improvement at interface by altering the fabrication conditions. They investigated the effects of extrusion rate and layer thickness on interlayer adhesion, where it was found that thickness of the layer depends on the fresh properties of the concrete mixture, the design of the nozzle and speed of the fabrication process. In another investigation, Zareiyan and Khoshnevis [25], tested the bond strength of specimens manufactured with interlocking at interface, the results revealed that bonding strength is increased by the interlocking layers (i.e. of 1.27 cm depth) as a result of increased contact surface of layers. Panda et al. [56], investigated the tensile bond strength of 3D printed geo-polymer mortar with regards to the time interval between layers, nozzle speed and stand-off distance, where it was shown that the bond strength is a function of state of interface material between two nearby layers that can be influenced by the rate of material strength development and 3D printing system parameters. It is believed that larger time intervals between the layers reduces the strength while lower printing speed and lower stand-off distance lead to better interlayer strength. Improvements in the interlayer adhesion can also come from the material formulation and mix designs, for instance it was shown that low percentage calcium aluminate cement can lead to stronger interlayer adhesion [57].

4.2. Polymer-based materials

Polymers could be considered for AM in construction [58,59] since they combine both low cost and low density, while enabling storage in a ready to be deposited and controllable state, unlike cementitious-based feedstocks. AM of polymers has been widely explored for many possible and diverse applications such as in aerospace industries for creating complex lightweight structures [60], in architectural industries for structural models [59], in art fields for artefact replication or in education, and medical fields for printing tissues and organs [61]. Nevertheless, most of these products are still used as conceptual prototypes instead of functional mechanisms, since pure polymer products built by AM lack strength as fully functional and load-bearing components. Polymer materials such as photosensitive resin, nylon, elastomer, acrylonitrile-butadiene-styrene (ABS) and wax can be used to produce parts with the Stereo lithography (SLA), Selective Laser Sintering (SLS), Fused Deposition Modelling (FDM) and Three Dimensional Printing (3DP) processes [62]. While nylon, i.e. polyamide (PA) [63,64], is one of the most widely used and investigated polymers in the SLS process for melts and bonding much better than other polymers [65], ABS is a popular material for use in the FDM process [66]. Different polymers have also been processed by the 3DP process, such as waxes, elastomeric, and starch-based polymers [67]. Nylon, elastomers, ABS and wax are thermoplastics, meaning that they will change from a harder (solid and glassy) structure to a softer structure, before melting into a viscous flowing liquid when heated to high temperatures (180–200 °C). On the other hand, biopolymers, such as polycaprolactone (PCL), polyether ether ketone (PEEK), starch-based polymers and polylactic acid (PLA) [68–70] have also been used for AM using the SLS [71,72], FDM [73,74] and 3DP processes [67].

Common technologies to produce fibre reinforced polymer composites are FDM and direct write techniques. Polymer pellets and fillers/fibres are mixed in a blender first and then delivered to extruder to be fabricated in the form of filaments for the FDM processing. An additional extrusion process can be carried out to ensure the homogenous distribution of fibres. For direct writing processing, polymer and fibres are mixed first and directly extruded out [75]. One common drawback of FDM printing is that the composite materials have to be in a filament form to enable the extrusion process. Additionally, FDM materials are limited to thermoplastic polymers with suitable melt viscosity. However, multiple extrusion nozzles with loading of different materials can be set up in FDM printers, so that printed parts can be multi-functional with optimised compositions. Examples like the FDM filament “Woodfill fine” with a diameter of 2.85 mm used for printing wood fibre bio-composites (fibre content of 10–12 wt%) [70] and other commercial products such as Laywoo-D3 (40 wt% wood fibre) and EasyWood Coconut from FormFutura (40 wt% coconout fibre) are also available for FDM. Woodfill fine filament is described as a blend of PLA and polyhydroxyalkanoate (PHA) matrix, reinforced with recycled wood fibres. FDM of wood fibre reinforced bio-composites leads to mechanical properties that are strongly dependent on printing orientation (0 or 90°) due to fibre anisotropy. Mechanical properties depend also on the printing width (overlapping of filaments), with a lower Young's modulus than the products made by hot-pressing. Not surprisingly, printed bio-composites have a microstructure with relatively high porosity (around 20%) that tends to lead to damage mechanisms and also higher levels of water absorption [70].

4.2.1. Properties of printable polymer-based materials

Most of the printed composites still have low mechanical performance and are not able to meet the functional requirements and standards of construction, when compared with ones made by conventional processes. The main reason for their lower mechanical strength is the presence of voids in the printed parts. The addition of reinforcement may further increase the porosity due to the poor interfacial bonding with matrix. To homogeneously disperse reinforcements and remove the voids formed, suitable compatibilizers should be used to enhance the compatibility i.e. interfacial bonding between the polymer matrix and fibres/fillers.

Table 4 illustrates the AM technology and materials used for printing fibre reinforced polymer composites with their corresponding mechanical property improvements. Short fibres including glass fibres [48] and carbon fibres (CFs) [76–80] are used as reinforcements to improve the mechanical properties of printable polymer composites.

While an increasingly higher fibre content results in composites

Table 4
The techniques and materials used for AM of polymer composites.

Technique	Materials (fibres/polymer)	Fibre loading	Max. tensile strength (MPa)	Strength improvement % compared to pure polymer	Ref.
FDM	Glass fibre/ABS	18 wt%	59	140	[81]
	Carbon fibre/ABS	40 wt%	70	115	[76]
	Carbon fibre/PLA	27 wt%	335[a]	–	[80]
Direct wire	Carbon fibre/epoxy	35 wt%	66	127	[82]
FDM based extrusion	Carbon fibre/nylon	34 vol%	464	446	[83]
	Carbon fibre/PLA	7 vol%	185	335	[84]

[a] Flexural strength.

with better mechanical properties, typically the maximum adding content of fibres is restricted to around 40 wt%, as the composites with more fibres are difficult to print due to nozzle clogging issues. Also, making them into continuous filaments for FDM is hindered by their loss of toughness. The detail rheological properties of printable polymer-based materials are essential for finding correct compatibilizers to enable increased content of reinforcing fibres. The filaments must have the right composition and strength with low-viscosity for extrusion [85].

5. Additive manufacturing in a construction research prospective

A collective and multidisciplinary research approach is the pathway to successful impact realisation for AM and its successful implementation as an eco-innovative solution in construction. Interactions from different fields of science in conjunction with technology will enable the realisation of eco-efficient design through AM. All actions should facilitate the market uptake of solutions developed through industrially and user-driven multidisciplinary associations, covering the construction value chain. From the materials point of view, i.e. printable feedstocks and formulations, to the printing technology configurations, i.e. type of robotic assisted machinery, printing resolution, nozzles type, shape and size must be developed, optimised and finally demonstrate from lab to close to the market large pilot scales.

Performance assets such as mechanical reinforcements for load-bearing capacity and/or smart self-reinforced geometries should also be thoroughly investigated to achieve: i) superior capabilities, ii) standardization compliance and, iii) market entrance unique competitive features, all of which can make the AM a significant positive impact to the construction industry.

In an evermore circular economy approach, future market driven research should generally attempt to include all six ReSOLVE (Regenerate, Share, Optimise, Loop, Virtualise and Exchange) [86] principles in a systematic way to help the construction industry further adopting circular resource efficiency. For instance, material scientists are currently investigating/developing printable cementitious-based formulations for AM based feedstocks using processed construction and demolition waste (CDW). Outcomes and evidence-based knowledge should be disseminated by dedicated demonstrations, prototypes, business plans, technical documents and life cycle/cost analysis reports, which will validate the economic and environmental feasibility of the circular economy vision for the construction sector. It is envisaged that AM should initially enter the building market in less restrictive and standardized segments such as the urban furniture and public temporary or medium-term facilities, all with marked and unique architectural and functional/aesthetics designs unmatchable by any other conventional technology. These niche segments are expected to trigger an easier pathway for AM in the building sector and a higher potential for a swifter market acceptance, as the regulations and standards for this branch are more lenient than structural load bearing elements for buildings.

From a multidisciplinary point of view, investigations of AM for construction should also be targeting the development of concepts for monitoring and controlling the printing process, i.e. camera and image processing. This can allow an early detection of malfunctioning and anomalous events, leading to an improved system reliability and lower fault tolerance. The basic idea for the image processing monitoring is strictly related to the nature of the layer by layer printing process and consists in capturing a 2D image of each layer and comparing it with the correspondent section of the designed 3D model.

6. Conclusions

This paper highlights the key roles of interdisciplinary research and importance of material formulations. It is gathered from this review that for successful implementation of AM in construction scale, (e.g. structural robustness), the detailed understanding of the materials and their curing mechanisms with correctly selected admixtures are crucial. Focus should be on the fresh rheology and chemical additives/agents to optimise material formulations for the extrusion and deposition in printing system, i.e. learning from relevant similar technologies of extrusion and shotcrete and also robotics applications for printing system. AM implementation in construction might be disruptive but certainly its potential as an eco-innovative solution has been demonstrated. The summarised information presented in this paper shall serve as scientific insights and directives for researchers and industries for further investments in 3D printing of construction materials. If the potentials of AM in construction are to be realised, the process should have a flawless configuration, (i.e. continuous feedstocks delivery for ensuring the consistency and cohesiveness between interlayers, including appropriate mixer/pump settings), and accurate selection of material grades and their formulations (i.e. admixtures/compatibilizers). Further contributions for successful implementation of AM in construction should focus on performance standardization, standards for materials, interlayer bonding, and structural design. The adoption of AM as an advanced technology appears to have a secure place in the future of construction, one that will most likely be unbeatable when it comes to, amongst others: shorten localised value chains and production expenses, increase resource efficiency and environmental sustainability by the inclusion of recycled materials and cutting on transportation costs. Architectural/design freedom will allow end-users interaction and create a dynamic open source collaborative construction platform, as well as the promotion of safer, equal and more qualified jobs.

References

[1] R.A. Buswell, R.C. Soar, A.G.F. Gibb, A. Thorpe, Freeform construction: mega-scale rapid manufacturing for construction, Autom. Constr. 16 (2007) 224–231, http://dx.doi.org/10.1016/j.autcon.2006.05.002.

[2] R.L. Williams, J.S. Albus, R.V. Bostelman, Self-contained automated construction deposition system, Autom. Constr. 13 (2004) 393–407, http://dx.doi.org/10.1016/j.autcon.2004.01.001.

[3] E. Gambao, C. Balaguer, F. Gebhart, Robot assembly system for computer-integrated construction, Autom. Constr. 9 (2000) 479–487, http://dx.doi.org/10.1016/S0926-5805(00)00059-5.

[4] C. Balaguer, M. Abderrahim, J.M. Navarro, S. Boudjabeur, P. Aromaa, K. Kahkonen, S. Slavenburg, D. Seward, T. Bock, R. Wing, B. Atkin, FutureHome: an integrated construction automation approach, IEEE Robotic and Automation Magzine, 9 2002, pp. 55–66, , http://dx.doi.org/10.1109/100.993155.

[5] A.M. Lytle, K.S. Saidi, R.V. Bostelman, W.C. Stone, N.A. Scott, Adapting a teleoperated device for autonomous control using three-dimensional positioning sensors: experiences with the NIST RoboCrane, Autom. Constr. 13 (2004) 101–118, http://dx.doi.org/10.1016/j.autcon.2003.08.009.

[6] J. Irizarry, M. Gheisari, B.N. Walker, Usability assessment of drone technology as safety inspection tools, Electron. J. Inf. Technol. Constr. 17 (2012) 194–212 doi: http://www.itcon.org/2012/12.

[7] J. Irizarry, D. Bastos Costa, Exploratory study of potential applications of unmanned aerial systems for construction management tasks, J. Manag. Eng. 32 (2016), http://dx.doi.org/10.1061/(ASCE)ME.1943-5479.0000422.

[8] B. Khoshnevis, Automated construction by contour crafting - related robotics and information technologies, Autom. Constr. 13 (2004) 5–19, http://dx.doi.org/10.1016/j.autcon.2003.08.012.

[9] S. Lim, R.A. Buswell, T.T. Le, S.A. Austin, A.G.F. Gibb, T. Thorpe, Developments in construction-scale additive manufacturing processes, Autom. Constr. 21 (2012) 262–268, http://dx.doi.org/10.1016/j.autcon.2011.06.010.

[10] W. Peng, L.S. Pheng, Managing the embodied carbon of precast concrete columns, J. Mater. Civ. Eng. 23 (2011) 1192–1199, http://dx.doi.org/10.1061/(asce)mt.1943-5533.0000287.

[11] G. Cesaretti, E. Dini, X. De Kestelier, V. Colla, L. Pambaguian, Building components for an outpost on the lunar soil by means of a novel 3D printing technology, Acta Astronaut. 93 (2014) 430–450, http://dx.doi.org/10.1016/j.actaastro.2013.07.034.

[12] B. Khoshnevis, D. Hwang, K.-T. Yao, Z. Yah, Mega-scale fabrication by contour crafting, Int. J. Ind. Syst. Eng. 1 (2006) 301–320, http://dx.doi.org/10.1504/IJISE.2006.009791.

[13] M. Xia, J. Sanjayan, Method of formulating geopolymer for 3D printing for construction applications, Mater. Des. 110 (2016) 382–390, http://dx.doi.org/10.1016/j.matdes.2016.07.136.

[14] C. Gosselin, R. Duballet, P. Roux, N. Gaudillière, J. Dirrenberger, P. Morel, Large-scale 3D printing of ultra-high performance concrete - a new processing route for architects and builders, Mater. Des. 100 (2016) 102–109, http://dx.doi.org/10.1016/j.matdes.2016.03.097.

[15] B. Berman, 3-D printing: the new industrial revolution, Bus. Horiz. 55 (2012) 155–162, http://dx.doi.org/10.1016/j.bushor.2011.11.003.
[16] I. Hager, A. Golonka, R. Putanowicz, 3D printing of buildings and building components as the future of sustainable construction? Proc. Eng. 151 (2016) 292–299, http://dx.doi.org/10.1016/j.proeng.2016.07.357.
[17] R.A. Buswell, A. Thorpe, R.C. Soar, A.G.F. Gibb, Design, data and process issues for mega-scale rapid manufacturing machines used for construction, Autom. Constr. 17 (2008) 923–929, http://dx.doi.org/10.1016/j.autcon.2008.03.001.
[18] T.T. Le, S.A. Austin, S. Lim, R.A. Buswell, A. Gibb, T. Thorpe, Mix design and fresh properties for high-performance printing concrete, Mater. Struct. 45 (2012) 1221–1232, http://dx.doi.org/10.1617/s11527-012-9828-z.
[19] F. Bos, R. Wolfs, Z. Ahmed, T. Salet, Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing, Virt. Phys. Proto. 2759 (2016) 1–17, http://dx.doi.org/10.1080/17452759.2016.1209867.
[20] I. Perkins, M. Skitmore, Three-dimensional printing in the construction industry: a review, Int. J. Confl. Manag. 15 (2015) 1–9, http://dx.doi.org/10.1080/15623599.2015.1012136.
[21] N. Labonnote, A. Rønnquist, B. Manum, P. Rüther, Additive construction: state-of-the-art, challenges and opportunities, Autom. Constr. 72 (2016) 347–366, http://dx.doi.org/10.1016/j.autcon.2016.08.026.
[22] A. Perrot, D. Rangeard, A. Pierre, Structural built-up of cement-based materials used for 3D-printing extrusion techniques, Mater. Struct. (2016) 1213–1220, http://dx.doi.org/10.1617/s11527-015-0571-0.
[23] A. Kazemian, X. Yuan, E. Cochran, B. Khoshnevis, Cementitious materials for construction-scale 3D printing: laboratory testing of fresh printing mixture, Constr. Build. Mater. 145 (2017) 639–647, http://dx.doi.org/10.1016/j.conbuildmat.2017.04.015.
[24] P. Wu, J. Wang, X. Wang, A critical review of the use of 3-D printing in the construction industry, Autom. Constr. (2016), http://dx.doi.org/10.1016/j.autcon.2016.04.005.
[25] B. Zareiyan, B. Khoshnevis, Effects of interlocking on interlayer adhesion and strength of structures in 3D printing of concrete, Autom. Constr. 83 (2017) 212–221, http://dx.doi.org/10.1016/J.AUTCON.2017.08.019.
[26] S.C. Paul, Y.W.D. Tay, B. Panda, M.J. Tan, Fresh and hardened properties of 3D printable cementitious materials for building and construction, Arch. Civil Mech. Eng. 18 (2018) 311–319, http://dx.doi.org/10.1016/j.acme.2017.02.008.
[27] R. Duballet, O. Baverel, J. Dirrenberger, Classification of building systems for concrete 3D printing, Autom. Constr. 83 (2017) 247–258, http://dx.doi.org/10.1016/J.AUTCON.2017.08.018.
[28] E. Krassenstein, https://3dprint.com/94558/3d-printed-hotel-lewis-grand/, (2015) , Accessed date: 2 March 2018.
[29] ApisCor, The first On-site House has Been Printed in Russia|Apis Cor. We Print Buildings, http://apis-cor.com/en/about/news/first-house, (2017) , Accessed date: 2 March 2018.
[30] R. Bogue, 3D printing: the dawn of a new era in manufacturing? Assem. Autom. 33 (2013) 307–311, http://dx.doi.org/10.1108/AA-06-2013-055.
[31] 3D Print Canal House, 3DPRINTCANALHOUSE by DUS Architects, http://3dprintcanalhouse.com/, (2016) , Accessed date: 2 March 2018.
[32] Branch Technology 3D Printed Walls - 3D Printing Industry, https://3dprintingindustry.com/news/branch-technology-is-3d-printing-the-future-of-construction-one-wall-at-a-time-54149/, (2017) , Accessed date: 2 March 2018.
[33] C. Hinczewski, S. Corbel, T. Chartier, Stereolithography for the fabrication of ceramic three- dimensional parts, Rapid Prototyp. J. 4 (1998) 104–111, http://dx.doi.org/10.1108/13552549810222867.
[34] S. Bukkapatnam, B. Khoshnevis, H. Kwon, J. Saito, Experimental investigation of contour crafting using ceramics materials, Rapid Prototyp. J. 7 (2001) 32–42, http://dx.doi.org/10.1108/13552540110365144.
[35] G. Ryder, B. Ion, G. Green, D. Harrison, B. Wood, Rapid design and manufacture tools in architecture, Autom. Constr. 11 (2001) 279–290, http://dx.doi.org/10.1016/S0926-5805(00)00111-4.
[36] I. Gibson, T. Kvan, L.W. Ming, Rapid prototyping for architectural models, Rapid Prototyp. J. 8 (2002) 91–95, http://dx.doi.org/10.1108/13552540210420961.
[37] D. Dimitrov, K. Schreve, N. de Beer, Advances in three dimensional printing–state of the art and future perspectives, Rapid Prototyp. J. (2006) 136–147, http://dx.doi.org/10.1108/13552540610670717.
[38] J. Kietzmann, L. Pitt, P. Berthon, Disruptions, decisions, and destinations: enter the age of 3-D printing and additive manufacturing, Bus. Horiz. 58 (2015) 209–215, http://dx.doi.org/10.1016/j.bushor.2014.11.005.
[39] L. Feng, L. Yuhong, Study on the status quo and problems of 3D printed buildings in china, Glob. J. Hum. Soc. Sci. 14 (2014) Online ISSN: 2249-460x.
[40] M. Gebler, A.J.M. Schoot Uiterkamp, C. Visser, A global sustainability perspective on 3D printing technologies, Energ Policy 74 (2014) 158–167, http://dx.doi.org/10.1016/j.enpol.2014.08.033.
[41] 3DPrint.com, Chinese Construction Company 3D Prints an Entire Two-Story House On-Site in 45 Days|3DPrint.com|The Voice of 3D Printing/Additive Manufacturing, https://3dprint.com/138664/huashang-tengda-3d-print-house/, (2016) , Accessed date: 2 March 2018.
[42] V. Petrovic, J. Vicente Haro Gonzalez, O. Jordá Ferrando, J. Delgado Gordillo, J. Ramón Blasco Puchades, L. Portolés Griñan, Additive layered manufacturing: sectors of industrial application shown through case studies, Int. J. Prod. Res. 49 (2011) 1061–1079, http://dx.doi.org/10.1080/00207540903479786.
[43] M. Mani, K.W. Lyons, S.K. Gupta, Sustainability characterization for additive manufacturing, J. Res. Natl. Inst. Stand. Technol. 119 (2014) 419–428, http://dx.doi.org/10.6028/jres.119.016.
[44] S. Ford, M. Despeisse, Additive manufacturing and sustainability: an exploratory study of the advantages and challenges, J. Clean. Prod. 137 (2016) 1573–1587, http://dx.doi.org/10.1016/j.jclepro.2016.04.150.
[45] T. Di Carlo, B. Khoshnevis, Y. Chen, Manufacturing additively, with fresh concrete, Proceedings of the ASME 2013 International Mechanical Engineering Congress and Exposition IMECE, 2013, http://dx.doi.org/10.1115/IMECE2013–63996.
[46] V. Mechtcherine, V.N. Nerella, K. Kasten, Testing pumpability of concrete using sliding pipe rheometer, Constr. Build. Mater. 53 (2014) 312–323, http://dx.doi.org/10.1016/j.conbuildmat.2013.11.037.
[47] T.T. Le, S.A. Austin, S. Lim, R.A. Buswell, R. Law, A.G.F. Gibb, T. Thorpe, Hardened properties of high-performance printing concrete, Cem. Concr. Res. 42 (2012) 558–566, http://dx.doi.org/10.1016/j.cemconres.2011.12.003.
[48] T.T. Le, S.A. Austin, S. Lim, R.A. Buswell, A. Gibb, T. Thorpe, Mix design and fresh properties for high-performance printing concrete, Mater. Struct. 45 (2012) 1221–1232, http://dx.doi.org/10.1617/s11527-012-9828-z.
[49] K.-H. Jeon, M.-B. Park, M.-K. Kang, J.-H. Kim, Development of an automated freeform construction system and its construction materials, International Association for Automation and Robotics in Construction (IAARC), 33 2013, pp. 1359–1365.
[50] M. Hambach, D. Volkmer, Properties of 3D-printed fiber-reinforced Portland cement paste, Cem. Concr. Compos. 79 (2017) 62–70, http://dx.doi.org/10.1016/j.cemconcomp.2017.02.001.
[51] N. Khalil, G. Aouad, K. El Cheikh, S. Rémond, Use of calcium sulfoaluminate cements for setting control of 3D-printing mortars, Constr. Build. Mater. 157 (2017) 382–391, http://dx.doi.org/10.1016/j.conbuildmat.2017.09.109.
[52] P. Feng, X. Meng, J.-F. Chen, L. Ye, Mechanical properties of structures 3D printed with cementitious powders, Constr. Build. Mater. 93 (2015) 486–497, http://dx.doi.org/10.1016/j.conbuildmat.2015.05.132.
[53] J. Wallevik, Rheological properties of cement paste: thixotropic behavior and structural breakdown, Cem. Concr. Res. 39 (2009) 14–29, http://dx.doi.org/10.1016/j.cemconres.2008.10.001.
[54] T. Di Carlo, B. Khoshnevis, A. Carlson, Experimental and numerical techniques to characterize structural properties of fresh concrete, ASME 2013 International Mechanical Engineering Congress and Exposition, 2013, http://dx.doi.org/10.1115/IMECE2013-63993.
[55] B. Zareiyan, B. Khoshnevis, Interlayer adhesion and strength of structures in contour crafting - effects of aggregate size, extrusion rate, and layer thickness, Autom. Constr. 81 (2017) 112–121, http://dx.doi.org/10.1016/j.autcon.2017.06.013.
[56] B. Panda, S.C. Paul, N.A.N. Mohamed, Y.W.D. Tay, M.J. Tan, Measurement of tensile bond strength of 3D printed geopolymer mortar, Measurement 113 (2018) 108–116, http://dx.doi.org/10.1016/j.measurement.2017.08.051.
[57] G.P.A.G. Van Zijl, S. Chandra, M. Jen Citation Van Zijl, G. Pag Van Zijl, S. Chandra Paul, M. Jen Tan, Properties of 3D printable concrete, 2nd international conference on, Addit. Manuf. (2016) 421–426 http://hdl.handle.net/10220/41820.
[58] G. Hunt, F. Mitzalis, T. Alhinai, P.A. Hooper, M. Kovac, 3D printing with flying robots, IEEE International Conference on Robotics and Automation (ICRA), 2014, pp. 4493–4499, , http://dx.doi.org/10.1109/ICRA.2014.6907515.
[59] K.V. Wong, A. Hernandez, A review of additive manufacturing, ISRN Mechanical Engineering, 2012 2012, pp. 1–10, , http://dx.doi.org/10.5402/2012/208760.
[60] E. Kroll, D. Artzi, Enhancing aerospace engineering students' learning with 3D printing wind-tunnel models, Rapid Prototyp. J. 17 (2011) 393–402, http://dx.doi.org/10.1108/13552541111156522.
[61] S.V. Murphy, A. Atala, 3D bioprinting of tissues and organs, Nat. Biotechnol. 32 (2014) 773–785, http://dx.doi.org/10.1038/nbt.2958.
[62] N. Guo, M.C. Leu, Additive manufacturing: technology, applications and research needs, Front. Mech. Eng. 8 (2013) 215–243, http://dx.doi.org/10.1007/s11465-013-0248-8.
[63] B. Caulfield, P.E. McHugh, S. Lohfeld, Dependence of mechanical properties of polyamide components on build parameters in the SLS process, J. Mater. Process. Technol. 182 (2007) 477–488, http://dx.doi.org/10.1016/j.jmatprotec.2006.09.007.
[64] H. Zarringhalam, C. Majewski, N. Hopkinson, Degree of particle melt in Nylon-12 selective laser-sintered parts, Rapid Prototyp. J. 15 (2009) 126–132, http://dx.doi.org/10.1108/13552540910943423.
[65] J.P. Kruth, G. Levy, F. Klocke, T.H.C. Childs, Consolidation phenomena in laser and powder-bed based layered manufacturing, CIRP Ann. Manuf. Technol. 56 (2007) 730–759, http://dx.doi.org/10.1016/j.cirp.2007.10.004.
[66] S. Ahn, M. Montero, D. Odell, S. Roundy, P.K. Wright, Anisotropic material properties of fused deposition modeling ABS, Rapid Prototyp. J. 8 (2002) 248–257, http://dx.doi.org/10.1108/13552540210441166.
[67] C.X.F. Lam, X.M. Mo, S.H. Teoh, D.W. Hutmacher, Scaffold development using 3D printing with a starch-based polymer, Mater Sci Eng C Mater Biol Appl 20 (2002) 49–56, http://dx.doi.org/10.1016/S0928-4931(02)00012-7.
[68] B.M. Tymrak, M. Kreiger, J.M. Pearce, Mechanical properties of components fabricated with open-source 3-D printers under realistic environmental conditions, Mater. Des. 58 (2014) 242–246, http://dx.doi.org/10.1016/j.matdes.2014.02.038.
[69] P. Tran, T.D. Ngo, A. Ghazlan, D. Hui, Bimaterial 3D printing and numerical analysis of bio-inspired composite structures under in-plane and transverse loadings, Compos. Part B 108 (2017) 210–223, http://dx.doi.org/10.1016/j.compositesb.2016.09.083.
[70] A. Le Duigou, M. Castro, R. Bevan, N. Martin, 3D printing of wood fibre biocomposites: from mechanical to actuation functionality, Mater. Des. 96 (2016) 106–114, http://dx.doi.org/10.1016/j.matdes.2016.02.018.
[71] M. Schmidt, D. Pohle, T. Rechtenwald, Selective laser sintering of PEEK, CIRP Ann. Manuf. Technol. 56 (2007) 205–208, http://dx.doi.org/10.1016/j.cirp.2007.05.097.
[72] K.F. Leong, F.E. Wiria, C.K. Chua, S.H. Li, Characterization of a poly-epsilon-caprolactone polymeric drug delivery device built by selective laser sintering,

Biomed. Mater. Eng. 17 (2007) 147–157.
[73] H.S. Ramanath, C.K. Chua, K.F. Leong, K.D. Shah, Melt flow behaviour of poly-epsilon-caprolactone in fused deposition modelling, J. Mater. Sci. Mater. Med. 19 (2008) 2541–2550, http://dx.doi.org/10.1007/s10856-007-3203-6.
[74] H.S. Ramanath, M. Chandrasekaran, C.K. Chua, K.F. Leong, K.D. Shah, Modelling of extrusion behaviour of biopolymer and composites in fused deposition modelling, Key Eng. Mater. 334–335 (2007) 1241–1244, http://dx.doi.org/10.4028/www.scientific.net/KEM.334-335.1241.
[75] X. Wang, M. Jiang, Z. Zhou, J. Gou, D. Hui, 3D printing of polymer matrix composites: a review and prospective, Compos. Part B 110 (2017) 442–458, http://dx.doi.org/10.1016/j.compositesb.2016.11.034.
[76] H.L. Tekinalp, V. Kunc, G.M. Velez-Garcia, C.E. Duty, L.J. Love, A.K. Naskar, C.A. Blue, S. Ozcan, Highly oriented carbon fiber-polymer composites via additive manufacturing, Compos. Sci. Technol. 105 (2014) 144–150, http://dx.doi.org/10.1016/j.compscitech.2014.10.009.
[77] F. Ning, W. Cong, J. Qiu, J. Wei, S. Wang, Additive manufacturing of carbon fiber reinforced thermoplastic composites using fused deposition modeling, Compos. Part B 80 (2015) 369–378, http://dx.doi.org/10.1016/j.compositesb.2015.06.013.
[78] L.J. Love, V. Kunc, O. Rios, C.E. Duty, A.M. Elliott, B.K. Post, R.J. Smith, C.a. Blue, The importance of carbon fiber to polymer additive manufacturing, J. Mater. Res. 29 (2014) 1893–1898, http://dx.doi.org/10.1557/jmr.2014.212.
[79] G. Griffini, M. Invernizzi, M. Levi, G. Natale, G. Postiglione, S. Turri, 3D-printable CFR polymer composites with dual-cure sequential IPNs, Polymer 91 (2016) 174–179, http://dx.doi.org/10.1016/j.polymer.2016.03.048.
[80] X. Tian, T. Liu, C. Yang, Q. Wang, D. Li, Interface and performance of 3D printed continuous carbon fiber reinforced PLA composites, Compos. A: Appl. Sci. Manuf. 88 (2016) 198–205, http://dx.doi.org/10.1016/j.compositesa.2016.05.032.
[81] W. Zhong, F. Li, Z. Zhang, L. Song, Z. Li, Short fiber reinforced composites for fused deposition modeling, Mater. Sci. Eng., A 301 (2001) 125–130, http://dx.doi.org/10.1016/S0921-5093(00)01810-4.
[82] B.G. Compton, J.A. Lewis, 3D-printing of lightweight cellular composites, Adv. Mater. 26 (2014) 5930–5935, http://dx.doi.org/10.1002/adma.201401804.
[83] F. Van Der Klift, Y. Koga, A. Todoroki, M. Ueda, Y. Hirano, 3D printing of continuous carbon fibre reinforced thermo-plastic (CFRTP) tensile test specimens, Open J. Comp. Mat. 6 (2016) 18–27, http://dx.doi.org/10.4236/ojcm.2016.61003.
[84] R. Matsuzaki, M. Ueda, M. Namiki, T.-K. Jeong, H. Asahara, K. Horiguchi, T. Nakamura, A. Todoroki, Y. Hirano, Three-dimensional printing of continuous-fiber composites by in-nozzle impregnation, Sci. Rep. 6 (2016) 23058, , http://dx.doi.org/10.1038/srep23058.
[85] S. Kumar, J.P. Kruth, Composites by rapid prototyping technology, Mater. Des. 31 (2010) 850–856, http://dx.doi.org/10.1016/j.matdes.2009.07.045.
[86] Circular Economy Policy - A Toolkit For Policymakers, https://www.ellenmacarthurfoundation.org/programmes/government/toolkit-for-policymakers, (2017) , Accessed date: 2 March 2018.