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EVOLUTION OF ADDITIVE MANUFACTURING TECHNOLOGY IN CONSTRUCTION INDUSTRY & CHALLENGES ON IMPLEMENTATION A REVIEW

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Abstract: The development of Additive Manufacturing (AM) in the construction industry has become an innovative solution for sustainable built environment. Many researches are undertaken globally to elucidate the significance of additive manufacturing to create safer and more flexible future construction industry. There is no doubt that AM and digitalization is set to transform the construction industry on a worldwide scale in the next few years. However, it is notable that the construction industry is only at the initiation of its automation journey and application of AM in the present constructions is still fragmented. Therefore, the researchers and industrialist have the responsibility to understand and to implement the new technology carefully beside many disruptive concepts. Hence, a review is presented in this paper on the development of Additive manufacturing in construction industry over several limitations and challenges. Furthermore, absences and requirements of precise investigations intended for future are acknowledged. This paper is focused on the widely used additive construction technology and cementitious materials specifically used for the extrusion based concrete printing.

Keywords: Additive Manufacturing (AM); Construction Industry; 3D Printing; Cementitious materials; Fresh and Hardened Properties

1. Introduction & Development of Additive Manufacturing Technology

Digital technology is rapidly changing the whole world in which we live today. Additive Manufacturing (AM) is the process of joining the materials together layer by layer, under computer controlled program to create 3 dimensional objects (Weng *et al.,* 2018). AM is also termed as 3D Printing (3DP), Rapid Prototyping, Layer Manufacturing and Free Form Fabrication. 3D printing is specifically defined by the American society for testing and materials (ASTM, 2012) as the fabrication of objects through the deposition of a material using a print head, nozzle, or another printer technology. The data created from digital model is transferred to a machine which then builds up the model or component layer by layer with less waste material. The concept of building up a 3D object in layers is not really new to the construction industry. For example the pyramids of Egypt was developed this layering technique and the conventional brick or block construction also follows the layer by layer expansion process.

According to 3DPI (2014), 3D or AM printing has started in the early 1980's. Its growth over the last decade is creditable, as it has been used to overcome the limitations in the conventional engineering environment. From the time of discovery, this technology plays a major role in the manufacturing industries to produce intricate 3D geometrical structures of different materials. In the past 35 years an outstanding increase in innovation of 3D printed technology could be seen with a huge variety of polymers, metal alloys, ceramics, certain plastics and concrete like mixtures, been use in the additive manufacturing sector. For example, the medical industry uses 3DP technology to produce high quality bone and joint transplants, as well as anatomical models for research and analysis purposes (Murray *et al.,* 2015). Architects use 3DP to create complex 3D models for their clients; 3DP is even used in the aerospace industry to print air foils (Chen and Yossef, 2015). In recent years, 3DP technology has gotten a lot of attention from the construction industry as a promising and sustainable building method. Table 1 describes the growth of 3DP over years.

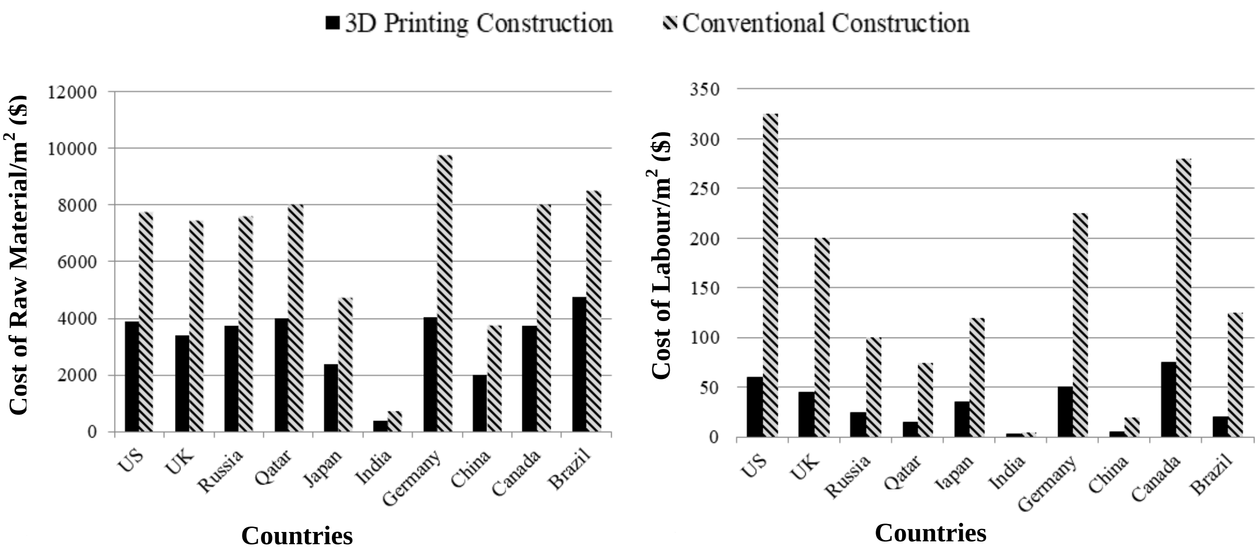
Table 1: Development of 3D printing over years (Goldberg, 2014), (Kidwell, 2017) & (Chen and Yossef, 2015)

Year	**Description**
1981(Early 1980's)	Dr. Hideo Kodama: Nagoya Municipal Industrial Research Institute, Japan Rapid Prototyping (RP) technology: A system of printing solid layers of quick-drying photopolymers that corresponded with a cross-sectional slice of a CAD model
Mid 1980's	Charles Hull: Patented Stereolithography, which is a technique that uses the reaction between a liquid photopolymer and a UV laser beam.
1984	Hull went on to co-found 3D Systems, The first organization nowadays operating in 3D printing. The STL format file was born
1988	Crump: Patented the Fused deposition modelling (FDM) Extrudes a narrow bead of hot plastic, which is selectively deposited where it fuses to the existing structure and hardens as it cools.
1992	Carl Deckard, University of Texas Patented the Selective Laser Sintering machine (SLS) which is a similar technology that utilizes a powder photopolymer reaction instead of liquid. Carl Deckard, Joe Beaman and Paul Forderhase developed the ideas of Chuck Hull and filed a patent in the US for the selective Laser Sintering (SLS)
1993	The Electron beam melting (EBM) was patented
2005	Mcor Technologies Ltd, Irish Starts the Paper 3D laminated printing, a machine, which superimposes sheets of paper and prints on them. The result is an additive method, which includes the use of colours
2005	Self-replicating rapid Prototyper, a 3D printer which prints itself is first realised (open-source RepRap and FAB@Home projects).
2008	Bre Pettis, Adam Mayer, and Zach "Hoeken" Smith found MakerBot Industries.
2012	The term **Additive Manufacturing (AM)** is defined by ASTM as 'a process of joining materials to make objects from 3D model data, usually layer upon layer'
2012	3D Printing (3DP) Based on inkjet printer technology. The inkjet selectively deposits a liquid binder onto a bed of powder. The binder effectively 'glues' the powder together.
2012 - 2019	Development of 3DP with different materials and Numerical Analysis

2. Development of AM in Concrete Construction

Large scale cement based additive manufacturing processes, often referred as 3D Concrete printing have been under development for the past decade and more than 30 international groups are currently involved in researches. Pegna (1997) was the first to implement additive manufacturing technology using cementitious materials. In this study an intermediate process also was used to attach sand layers together with a Portland cement paste (Nematollahi *et al.*, 2017). The construction industry faces a number of challenges such as productivity, sustainability and economic competitiveness, as well as meeting the need to create better building and stronger communities. Digital transformation has huge potential to transform construction both in its performance and its attractiveness. It can help construction industry to become more efficient, productive, profitable and sustainable.

There are excellent advantages of 3D concrete printing technique over the conventional formwork concreting method such as labour efficiency, time and cost savings, environmental and economic impacts, and improved design complexity (Kidwell, 2017). As the demand for precast concrete solutions is growing, clients increasingly preferring an offsite manufactured product for building complex shapes which can be delivered to site as a whole. Hence, it also enables potential of multi-functionality for structural or architectural elements by taking advantage of the complex geometry and provides the ability to 3D print very detailed and complex structural features combined into the building, including ventilation, plumbing and wiring. Moreover, it increases sustainability in construction by reducing wastages and construction costs by eliminating formwork. In addition, reduction of on-site construction time, minimizing the chance of errors by highly precise material deposition, reduction of injury rates and increased level of safety in construction can be achieved by this 3D concrete printing technology. Figure 1(a) & Figure 1(b), taken from International Construction Cost Survey 2016, indicates the average cost savings of raw materials and labour using conventional construction methods compared to 3DP.



1(a) 1(b)

Figure 1: (a) Raw materials and Cost Savings, (b) Labour and Cost Savings

2016 International Construction Cost Survey 2016 (Kidwell, 2016)

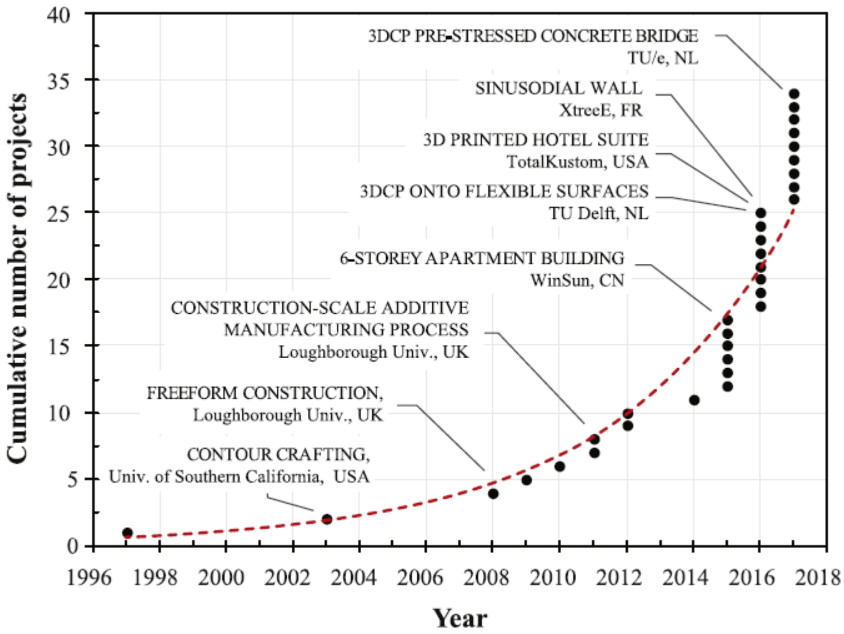


Figure 2: Development of large-scale additive manufacturing for construction applications (Buswell *et al.,* 2018)

Buswell *et al.* (2007), Buswell *et al.* (2008) conducted a review over rapid manufacturing technologies for construction, based on which they developed a Freeform Construction method. The term of Freeform Construction was well defined for approaches that deliver large scale components for construction without the necessity of formworks using additive manufacturing. They identified that freeform construction could reduce the construction cost and provide freedom of selecting preferred geometry with better performance than conventional concreting method. According to Nematollahi *et al.* (2017), 3D Printing technologies are mainly based on two techniques specifically; extrusion-based and powder-based. Lim *et al.* (2009) and Dams *et al.* (2017) state that additive manufacturing methods can be divided into three main types; Contour Crafting developed by the University of Southern California, USA, Concrete Printing developed by Loughborough University, UK which are considered as extrusion-based process and D-shape printing which lays under powder based process developed by Enrico Dini of D shape Enterprises, Italy. Figure 2 shows the development in large-scale additive manufacturing for construction applications since 1997 (Buswell *et al.,* 2018). This study is mainly focused into extrusion based concrete printing.

2.1 Extrusion based Concrete Printing

The extrusion-based technique is a method that extrudes cementitious material from a nozzle, pioneered by Lim *et al.* (2011) from the department of Civil Engineering at Loughborough University. This technique has been intended at on-site construction applications such as large-scale building components with complex geometries. A robotically controlled nozzle pours layers of concrete one on top of the other to produce freeform shapes. Layer upon layer of wet concrete is extruded to rapidly produce components several metres high. The extrusion based concrete printing can be discussed under two methods; contour crafting and concrete printing.

2.1.1 Contour Crafting (CC)

This process was patented by Prof. Behrokh Khoshnevis at the University of Southern California. CC is an additive construction technology that utilizes computer control to achieve the superior surface forming ability of trowelling to produce smooth and precise planar and freeform surface (Khoshnevis, 1998). In Contour Crafting, a nozzle is supported on a gantry, move backward and forward in two parallel lanes to create a layer at one level, before being moved upwards where the process starts over. It extrudes two layers of cementitious mixture to build a vertical concrete formwork. Unique to Contour Crafting is a trowel attached to the nozzle to sculpt the surface and give a smooth finish. Once the extruded formwork is completed, concrete is then manually poured. The main advantages of the CC technology are the superior surface finish that forming paint-ready surface, greatly enhanced speed of fabrication and it permits the installation of internal components such as pipes, electrical conductors, and reinforcement modules before pouring concrete

Lim *et al.* (2009) acknowledged some limitations of CC such as the limitation of size and reach of the nozzle, the mould is not disposed and becomes a part of the wall and CC method requires excessive steps including moulding, installing reinforcement, and placing concrete to build layers up to 20 mm high. Gosselin *et al.* (2016) reported the following drawbacks: this technology is limited to vertical extrusion, hence yielding 2.5D topologies (vertical extension of a planar shape); initial formwork and trowel system can be rather complex to implement for production, depending on the size and shape of the object being printed; and the interrupted sequential casting of concrete within the formwork due to hydrostatic pressure and weak mechanical properties of the extruded concrete may result in weakened interfacial zones between the layers. These limitations encouraged them to develop another Freeform Construction method called Concrete Printing.

2.1.2 Concrete Printing

This technology also uses the extrusion based technique and to some level is similar to the CC technology. However, the Concrete Printing technology has been developed to retain 3D freedom and has a smaller resolution of deposition, which allows for greater control of internal and external geometries. Lim *et al.* (2011) from the department of Civil Engineering at Loughborough University were the pioneers to study and develop a high-performance 3D printable concrete. Furthermore, the material used in Concrete Printing is a high performance fibre-reinforced fine-aggregate concrete, resulting in superior material properties (Lim *et al.*, 2012). They used a 3D printer that had a small print head to 3D print in many layers a bench-looking structure.

The primary drawback of this technology is, it requires additional support to create overhangs and other freeform features and it requires an additional deposition device. Gosselin *et al.* (2016) reported the following drawbacks: the trade-off necessary for maintaining its dimensional accuracy makes the process quite slow with regards to the proposed industrial application; although the technology initially aimed at the generation of 3D topologies rather than 2.5D, the use of second material to support overhangs reduces the efficiency and flexibility of the process while increasing its material cost; and dimensions and possibilities in terms of shape design are limited by the dimensions of the printing frame.

2.2 Challenges in Extrusion based 3DCP

Concrete Printing technologies are subjected to some inherent limitations and challenges as it is in its initial stages in concrete construction industry with increasing demand. The crucial challenges this technology has to overcome to be applicable in the future industry are; developing suitable printing machine or tool and developing suitable printable materials with fluctuation of material properties with the machine setup. The manufacturing technics and materials are the main component of this study, to ensure their functionality under real life scenarios. Moreover this is still an expensive technology as the initial cost is higher than the conventional constructions (Shakor *et al.*, 2019).

2.2.1 Extrusion based 3D Concrete Printer

The key limitations are the necessity of using new and advanced machinery with small aggregate sizes and limited size of the printed elements. For example the size of the 3D printer should be larger than the size of the element to be printed. Other issues related to the printer setup are nozzle diameter, print speed, extrusion rate, print height, print path, printing environment such as temperature and humidity. The findings of Paul et al (2018) identified the printed sample using rectangular orifice showed almost similar tendency in the strength development as control specimens while the circular nozzle showed a large variation. Although, circular nozzle is good for printing any complicated object with changeable rotational angles and it can sustain a symmetric section, it might create many voids or holes in the printed object. Nerella *et al.* (2019) identified an absence in tests for extrudability in the extruder nozzle or print head as the previous researches have done only offline tested for the extrudability. Hence, that research proposed a method for characterizing the extrudability of cement-based materials for 3D printing, both quantitatively by measuring the electric power consumed and inline.

2.2.2 Material Selection

Another major challenge of extrusion based concrete printing technology is to produce a paste like material mixture, strong enough that without support will withstand the structures forces (Panda and Tan, 2018). Malaeb *et al.* (2015) clearly defined the optimum mix selection criteria as; the compressive strength has to be optimized while maximize the workability, the material has to achieve the required flow in the system yet maximize buildability upon pouring and the speed of concrete setting time has to be maximized while maintain the suitable setting rate so as to ensure bonding with the subsequent layer.

Kazemian *et al.* (2017) argued that, ordinary Portland cement (OPC) is the most feasible option as the prime binder material for printable concrete, because of the well-defined fresh and hardened properties of concrete, along with the variety of admixtures existence to customize its performance. Moreover, cement is the easily available, highly manufactured construction material worldwide, amounting to nearly 4 billion tonnes a year (Nagaratnam *et al.,* 2019). But, Vaitkevičius *et al.* (2018) opposed that the setting time (~1 hr) and hardening time (~12 hr) of OPC is relatively very high for 3D printing material. Similar idea was also addressed by Weng *et al.* (2018) as the material must be pumpable while ensuring it could self-support as it sets and gain enough strength to carry the load from successive layers. The use of cement hydration accelerators is the usual method to increase setting time (hydration kinetics) of OPC. However, most accelerators considerably increase shrinkage of concrete over time and it might initiate cracks in the structure (Samouh *et al.,* 2017).

A study by Nerella *et al.* (2016) introduces the mix design of high performance printable mortar known as 3M3 was used to obtain the higher early strengths and well distributed micro silica suspension, fly ash, very fine and fine sands were used to achieve the high filling density of solid components. Panda *et al.* (2017) were also introduced a new fly ash based geopolymer mixture extrusion based 3D concrete printing with the addition of ground granulated blast-furnace slag (GGBS) and silica fume (SF), where OPC was replaced by geopolymer as the main binder. The production of OPC contributes to high energy demands and CO2 emissions, hence geopolymer is not only reduce the requirement on OPC, but also potentially has lower environmental impacts (Panda *et al.,* 2018). But. Nagaratnam *et al.* (2013) identified that only a smaller amount of fly ash incorporation in concrete mixture will result higher compressive and tensile strengths in the long term. Since the geopolymer mix behaved like a shear thinning material, even if the apparent viscosity dropped during the extruding process, its recovery was not fast enough to hold another layer on top of it. Therefore to have better viscosity recovery property and high yield stress when material is at rest, Panda and Tan (2018) added some Nano-clay (attapulgite clay) to a selected mix. Some clay and micro fibres were also used to further improve the buildability properties and to reduce shrinkage and deformation in the plastic state.

Recently, Nematollahi *et al.* (2018a) investigated the effect of polypropylene (PP) fibres on the fresh and hardened properties of 3D-printed fibre-reinforced geopolymer mortars, Nematollahi *et al.* (2018b) investigated the effect of type of fiber on inter-layer bond and flexural strengths of extrusion-based 3D printed geopolymer and Bos *et al.* (2018) studied the effect of adding short straight steel fibres on the failure behaviour of print mortar has been studied through several tests on cast and printed concrete, on different scales.

Other than these additives, most of the researchers were used Silica Fume (SF) as an additive to increase the cohesiveness, while Fly Ash (FA) and Limestone fine powder as binders. Additionally, Viscosity Modifying Admixture (VMA) to increase the plastic viscosity and cohesion, Polycarboxylate based High-Range Water Reducing Admixture (HRWRA) to achieve the required flowability for the mixtures and Polycarboxylate based Superplasticizer to lower the water/binder (w/b) ratio and hence increase workability (delays the hardening) & strength and to improve the extrudability were also used in the printable concrete mixture.

Paul *et al.* (2018) identified, the mixed isotropic and anisotropic properties of printed concrete structures in different direction distinct to the cast specimens, as one of the key drawbacks. Therefore, a high strength in compression, flexural, tensile bond will be the main objectives in developing this printable concrete. Moreover, the freeform components are built without formwork and this might result in cracking. Hence, a low shrinkage also should be achieved with the end product. (Kazemian *et al*., 2017). Similarly, Kazemian *et al.* (2017) identified the layered structures are likely to be anisotropic as voids can form between layers to weaken the structural capacity. Thus, layered concrete might create weak joints in the specimens and reduce the load bearing capacity under compressive, flexural and tensile action that needs stress transfer across or along these joints (Paul *et al.,* 2018).

Paul *et al.* (2018) and Sanjayan *et al.* (2018) investigated the influence of testing direction in the mechanical properties of 3D printed concrete and produced relatively acceptable results. Both increase and decrease tendency in the mechanical strength was found in the printed specimen depend on the testing direction, when compared to the strength of cast specimen. The bond strength of a 3D printed concrete specimen is interconnected with many parameters such as material viscosity, time gap between printing the layers and contact area between the successive layers (Paul *et al.,* 2018).

3. Conclusion and Recommendations

This paper considered the evolution of additive manufacturing technology into the construction industry and identified the possible challenges of extrusion based concrete printing techniques. Regardless of the low industrial development of 3D concrete printing processes, this technology remains to be promising for global optimization of architectural production. Even though numerous showcases of 3D printed concrete structures are available currently, many challenge are still remain with structural and mechanical stability. Observing the existing state of the 3D printing materials, it is perceived that there is still not enough focusing on material properties.

From the previous researches, it is apparent that, although there are many research studies on various perspectives of 3D concrete printing, key ingredients of the compositions and mechanical properties were excluded in some instances. The necessities for future research to increase the application of this new technology can be identified as follows:

- A suitable mixture design and effective curing measures should be developed to ensure the expected mechanical and physical performance
- Investigation on the printer-independent optimum and most efficient mix design for 3D concrete printing
- Determination of optimum initial setting time for the base layer and subsequent layers for better bonding conditions
- Detailed examination on the fluctuating behaviour of compressive, flexural strength and inter layer bonding with the increasing delay time

- Solution for the reduction of inter layer bond strength with the addition of fibres
- Lack of knowledge on the drying shrinkage and delayed crack issues
- Impact of different shape and size of the extruder and nozzle
- Effect of different curing techniques
- Influence of interlocking between layers on bond strength of the extrusion based concrete printing is not discussed at all

This study has sought to assess the significance, usability, completeness and level of consensus of additive manufacturing technology across current construction industry. It is expected to be useful for future researchers working on additive construction field, by creating a knowledge which may be better shared across the industry, for expand the applicability and to have better consumption in the future.

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