A Review on Recent Advances in Application of Digitally Fabricated Concreting: a Case Study on Use with Self Compacting Concrete

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A review on recent advances in application of digitally fabricated concreting : a case study on use with self compacting concrete

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Abstract. Construction of structures has been the age-old practice since early times and continuous till now. But with change in life style and needs, structural need of humans also comes under the influence. Construction is one of those industries where the practice involving joining brick to brick using manual labour continuous even to this date which has been going on since ages. Hence the changes in construction industry can be brought into by bringing changes in concrete because both these complement each other (construction & concrete). Though being widely used man made material in the world it faces tremendous challenges in terms of environmental impact, financial needs, and social acceptance. This industry thus is in need of some radical changes and making use of digitalization or use of robotics in this sector. One among them is the use of 3-D printing in construction. This review report explores and summarizes several researches done in some top universities of the world regarding 3-D Printing. It analyses the need for 3-D printing, the present scenario of this technology in research sector and industrial sector. Several Test results on printed specimen are presented and thus conclusions are drawn regarding the use and future of this technology as a major radical change in construction sector of Life. This papers also aims at studying all the recent advances that have been occurring over last 8-10 years where special supplementary cementitious materials (SCMs) have been used in the additive manufacturing industry. The paper also focuses on the effect of special concrete such as Ultra High-Performance concrete and Self Compacting concrete in digital concreting.

1 INTRODUCTION

One of the special types of concrete which flows and compacts under its own weight is Self-Compacting Concrete (SCC). When poured into moulds or shuttering, the concrete gets filled completely. The Compressive strength of SCC usually lie in the range of 60-100 N/mm2. One of the issues which Japanese contractors were facing was lack of durable concrete thus requiring highly skilled labours for compaction. Developed originally at Tokyo University, SCC can be mainly used for concreting of structures with high density of reinforcement. While using SCC there is now no need of vibration needles as it can place itself without causing any bleeding and segregation. The composition of SCC includes a bulk of fine powdered materials that help in gaining sufficient yield and viscosity. Now-a-days usage of large quantities of cement is not preferable as it costs more and causes temperature differences. “The cement is thus replaced with Supplementary Cementitious Materials or SCM's such as fly ash and ground granulated blast furnace slag (GGBFS)” [35]. The use of SCM's causes increase in the slump of the concrete mix considerably while keeping the cost same. Sometimes several constituents like admixtures, micro silica, pozzolanic cement and other chemical admixtures make up the composition of SCC which in turn gives the concrete properties of high flow, passing ability under highly reinforcement regions and resistances to various chemical and mechanical stresses

One of the major issues that critiques use against concrete is the unabated use of reinforcement in concrete and its impacts on the environment once the concrete structure completes its design life. From the start of boon of concrete in infrastructure sector, it is the use of reinforcement which has helped concrete being a success because of concrete’s weak tensile strength which has been improved by the use of reinforcement. Although developments like pre-stressed concrete starting utilizing more of concrete’s compressive strength rather than its weakness in tensile character, the use of reinforcement was still there. Actually, use of reinforcement only improves the tensile property of the element constructed not of the concrete itself. To improve that fiber use in concrete has been employed which has to a good extent helped to improve the above drawback. But work in terms of research and implementation in the infrastructure sector has still a long way to go to silence the critics and their genuine criticisms. In fact, after a lot of brain storming sessions scientists have been able to re-imagine how concrete reinforcement would work in future. They arrived at two main solutions. The first one is diversifying from age of old practice of providing reinforcement and designing a new type of novel corrosion free rebars. The second one is designing a new concrete altogether without the need of any reinforcement requirement. The latter seems

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more possible in a foreseeable future as concrete can be designed to cater for higher tensile strength as well as ductility. But taking all the criticism into account, and if we work on these criticisms in a positive sense, we can make concrete a material that can last a long time without having huge negative impact on the environment we live in. In other words, making concrete an eco-friendly material. The need of the hour is to forego the usual material-centric approach to concrete and explore further considering system centered integrated approach of the concrete taking digital and unconventional Construction opportunities into account such as digitally fabricated concrete. Henri et al. [15] “has researched deep into this field and came up with two objectives. These include :

a.) Improved durability: which dictates the need to reimagine and reinvent rebars or minimize the use of rebars.
b.) Improved strength: which would require optimization of granular formation resulting in further improved workability, carbon foot-print and less binder material [15]

“Currently the most straightforward way to get rid of formworks is use of vacuum induced jamming to build reconfigurable free-formwork for 3D Printing” [30]. This helps in construction of difficult and complex geometry and shapes. They not only form the aesthetic part of construction but also ensure minimum tensile stresses and thus minimizing need of reinforcement”.

2. 3D Printing

The process that includes joining or solidifying materials under computer control to create a 3-D object is referred to as 3D printing. While printing the materials are added together which is called additive manufacturing process. With this technology objects of any geometry are produced typically using digital model Data (C.A.D file). This technology has been a boon in the manufacturing industry as it gives the manufacturer his creative freedom of any shape, it reduces manpower and also helps in reducing the waste generated from the manufacturing process. The 3d printing process mainly comprises of deposit of a binder material onto a powder bed with the use of inkjet print heads layer by layer. This is a different process from rom a stock in the conventional manufacturing where materials are removed. “Thus, 3DCP or AM generates a three-dimensional object from a computer-aided design (CAD) model by successively adding material layer by layer. This technology shares the process of material addition or joining throughout a 3D work envelope under automated control” [31].

3. 3-D Printing in Construction:

3-D Printing or additive manufacturing process has a considerable and a significant impact on the manufacturing industries as it helps in reducing manpower, reduces use of mould or formwork (as in construction) and helps in manufacture of complex shapes with ease and within less time. Many of the current challenges faced by the construction sector at present do find their remedies in the use of this technology. Currently this technology in construction industry is at research stage and much more work has to be done to introduce it in the construction industry. The motive behind taking advantage of additive manufacturing tech particularly in construction is the free form works and designs of any geometry, shapes etc. “This also permits complex aesthetic characteristics. Unlike subtractive technologies, additive manufacturing involves utilization of moulds in combination with formative technologies to achieve desired shape of the object” [15]. “Often times structural engineers use multiple identical elements in a project to save materials and reduce costs of labor and moulds” [13]. “3DCP is going to revolutionise this pattern by changing the approach in the way that components are produced” [36]. Thus, it would be much easier to make each component exclusive without inviting any costs. 3DCP technology will also reduce duration of whole construction, provide safety to highly skilled employees, also better quality and reliability. “Currently additive manufacturing processes which are using 3DCP using above mentioned principles are as follows:

1. Layered Extrusion (Contour Crafting, Concrete printing, Freeform construction)
2. Binder Jetting
3. Slip Forming (Smart Dynamic Casting)” [13]

4. Previous Work Done On 3d Digitally Fabricated Concrete till Date

As of now, layered extrusion technology has been the centre of focus in digital fabrication of concrete. This includes methods such as contour crafting. However, for this model to get implemented on construction field, it requires much larger printers or robotic arm. Typically, a digitally controlled moving printing head is used for layered extrusion by the automated machinery. “The head or nozzle accurately pours the concrete material layer-by-layer to print or cast specialised concrete which in turn forms unique and complex structures while maintaining sustainability” [13]. A difference is made here between automation methods for mould manufacture and material shaping and extrusion method. “Further difference is made between the discrete layer deposition processes that are based on a particle bed approach and those based on extrusion. Over half the processes currently under development employ extrusion” [12].

Figure 1: The printing processes (colour print) “Domenico Asprone et al. (2017)” [13]

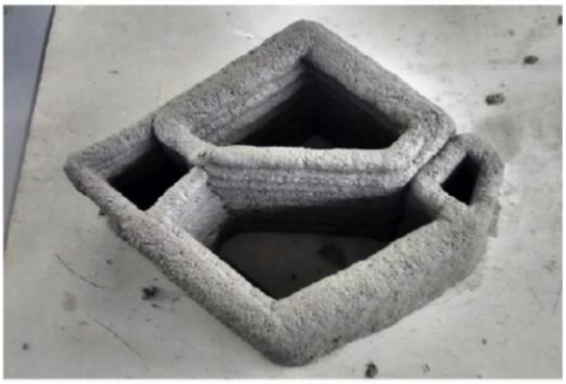

Figure 2: A printed Concrete segment (colour print) “Domenico Asprone et al. (2017)” [13]

As of now, layered extrusion technology has been the centre of focus in digital fabrication of concrete. This includes methods such as contour crafting. However, for this model to get implemented on construction field, it requires much larger printers or robotic arm. “Typically, a digitally controlled moving printing head is used for layered extrusion by the automated machinery. The head or nozzle accurately pours the concrete material layer-by-layer to print or cast specialised concrete which in turn forms unique and complex structures while maintaining sustainability” [13].

“The method of layered extrusion of concrete must have some specific rheological properties as follows:

- Pumpability: the ability to move to the printing head through a pumping system throughout a given time interval.
- Extrudability: the capability to be extruded properly through the printing head.
- Buildability: the ability to remain stacked in layers after extrusion and sustain the weight of the succeeding layers” [13].

Thus, it becomes a pre-requisite that the rheological properties of concrete must be optimized so as to strike a balance between the need for workability and extrudability on the one hand and the requirement of buildability on the other. The mechanical properties of the printed elements may get affected due to speed of the printing nozzle or head. The speed must comply with rheological properties of printed concrete and nozzle size as well as the size of the object to be printed. “ In fact, the time passed between the deposition of two layers must be adequate enough to let the first layer sufficiently become capable of supporting the weight of the second layer, but brief enough to assure that the first layer is still fresh enough to develop a strong bond with the second layer” [14].

5. 3-D Printing in Construction:

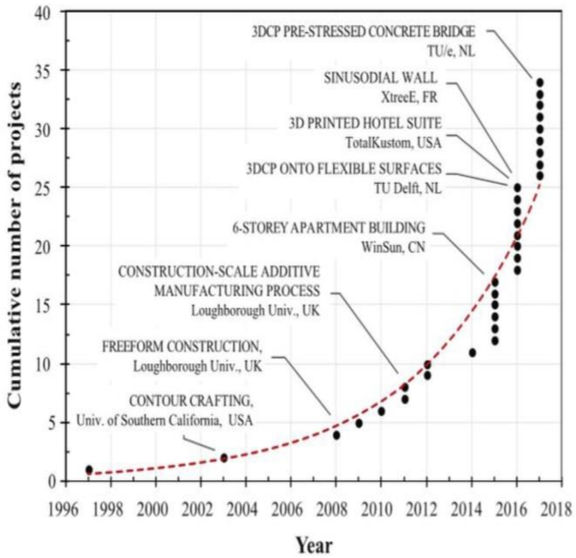

Figure 3:“The rise in large-scale additive manufacturing for construction applications since the concept inception in 1997(R.A. Buswell et al. (2018))” [19]

Sass et al (2006), P. Wu et a l(2016) and Buswell et al(2007) studied “application of digital fabrication of 3D freeform architectural design” [17] [18] [19]. Not much substantial amount has this technology been used in industry sector apart from some, which will be discussed below. Most of the work done in some of the top universities in the world is at T.U Dresden, University of Naples Federico Italy, Loughborough University UK, University of Southern California U.S.A and several Australian Universities. The research is a multi-disciplinary research and while the prime objective is dealt by a civil engineer but an expertise of a Robotics and a computer Science engineer along with others is included to achieve the required results. In all the research(some of which is being discussed in this paper),the researchers have tried to present a way by which this technology will be implemented in the construction sector and bring those radical changes in the construction sector which can remove several constraints in whatever terms to make it more reliable, efficient and economical. In the industry, some companies have started their foothold solely based on this technology like Win Sun and Apis Cor.

One of the future tech firm based in Shanghai China with the aim of revolutionizing the 3D printing technology in construction is Winsun. They have already invented he first continuous 3D printer for construction. The company printed the first batch of 10 houses in 2013. The printing material consisted of a special element made of cement, sand and fiber, together combined with additive properties. This arrangement lead printing head to print layer after layer the walls of its Suzhou based factory which were then assembled on site. They have also 3D printed their office building in Dubai in 2016. The printing material for this technology comes from demolition waste or mine tailings. Thus, it produces zero waste and is very environmentally friendly. Another aspect which affect the construction process is the overall construction time. 3DCP tech. handles this issue very efficiently as well. When a 1,100 sq. two storey mansion was to be 3D printed, it took just one day for printing. Of course, internal bar structures were erected in advance and the duration of assembly was two days. “Winsun being a pioneer in 3DCP technology has advanced beyond prototyping and has sold more than 100 houses to date. However, it faces several barriers to scaling up its production from scepticism of designers to lack of regulation” [33].

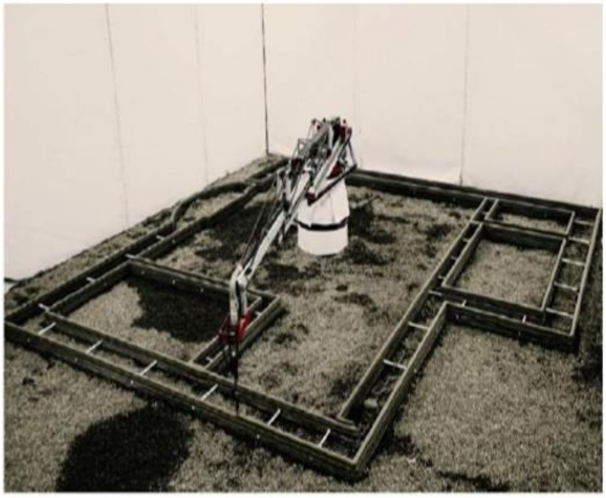

Figure 4: “Crane developed by Apis Cor” [8]

“Another Russian firm Apis Cor is the inventor of state-of-art type of mobile construction 3D printing technology allowing the use of additive manufacturing technologies directly on construction site” [7]. The 3D printing Nozzle prints the entire building on-site by printing walls and structures which can then be completed by traditional construction methods.

T. Wanglar et al. (2016) in his paper aimed to provide a state-of-the-art review related to key areas of material research. He identified the interdependent factors affecting component design, mechanics and control of the process. These issues were then collated to create research and developmental matrix. The matrix brought insights to aid structures. “He then concluded with the vision of capabilities of design and manufacturing using 3DCP processes in order to inspire creative thinking” [22].

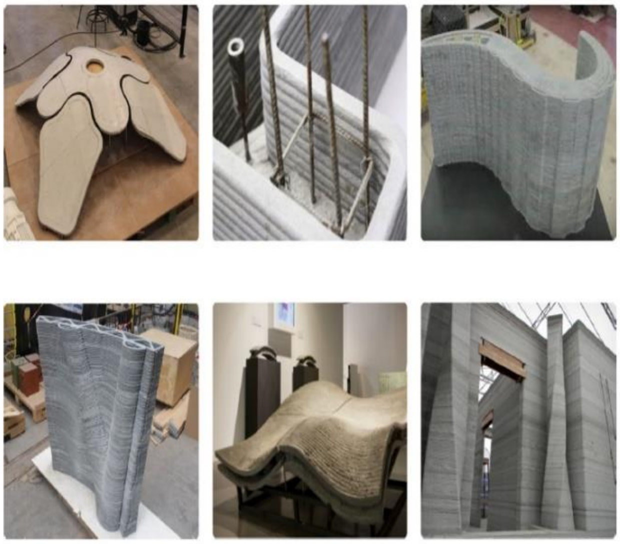

Figure 5: “Examples of 3DConcrete Printing application type and orientation of the manufactured components across various universities across the world (R.A. Buswell et al. (2018)” [19]

“Use of this technology saves up to 25-40% of building construction costs in comparison with traditional construction. This is achieved thanks to manual labor minimization, process automation, and faster construction time. This reduces construction time of a typical single-story house to a couple of days and decreases the amount of material required to build it. Apis Cor’s 3D printing solution is a technology which enables whole house printing in any place within 24 hours. The system consists of a mobile 3D printer and an automated Mobile Automated mix and supply unit (MAU). The main difference from other well-known construction 3D printing devices is that Apis Cor’s 3D printer constructs whole buildings directly on the construction site while being mobile and transportable using regular construction machinery” [34].

A novel approach FOR 3DCP technology for on-site construction is being developed at T.U Dresden, known as CONPrint 3D Technology. It is a formwork free, monolithic construction process which constitutes a time, labor band resource efficient in nature. In order to increase its acceptance in construction industry, this technology also focuses on making use of existing construction and production techniques as much as possible and adopting new process to construction constraints e.g. developing a custom developed print head, using concrete pump for material delivery at specific positions automatically and accurately.

Figure 6: "Illustration of CONPrint 3-D (V. Nerella et al.)" [14]

6. Use of Self-Compacting Concrete (Scc) In 3d Concrete Printing (3dcp)

Shashank and Rishab et. al (2020) in their paper proposed a new method to print concrete through controlled heating of printed layers. "In this method self-compacting concrete mix could achieve minimum strength up to 30 Pa as initial yield strength" [3]. Their method has potential advantages over existing practices because it offers

1) Better bonding between adjacent layers,
2) Sharper rise in buildability of the printed layers, and
3) Smaller possibility of choking in the printing set-up.

Properties of printed concrete in the fresh state were evaluated. It was concluded that a "stable" layer thickness for the considered SCC mixes can be 6 mm. The buildability was found greater for a smaller water-to-cement ratio and/or a longer duration of heating. Another observation made was that the early-age shrinkage in a printed layer was greater if the layer was subjected to heating for 60 seconds compared to when it was not. The difference was smaller for a greater water-to cement ratio. For the mixes considered in the present study, the shrinkage strain was smaller than 200x10-6.

They also found that the size of the largest pore was 1 mm, and that most pores were smaller than 0.4 mm. Shear and compressive strength of printed cubes were found smaller when the direction of loading was parallel to the printed layers compared to when it was perpendicular. The effect of duration of heating was greater in the former case.

The strength for the corresponding printed specimen was 61.5 MPa when the direction of loading was parallel to the layers and each layer was heated for 60 seconds. The strength was 49.1 MPa corresponding to 180 seconds of heating. For loading perpendicular to printed layers, the average compressive strength for the two durations of heating was 65.7 MPa and 56.4 MPa, respectively.

6.1 Concrete Printing Setup

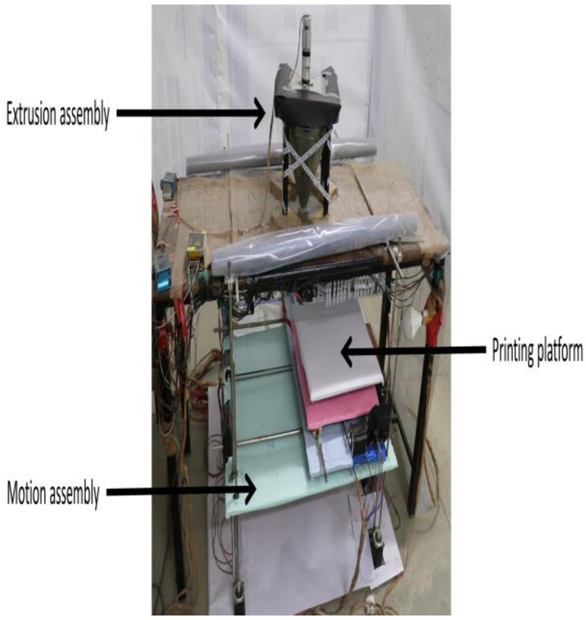

Figure 7: "Concrete printing set-up at IIT Gandhinagar (adapted)" [3]

In order to achieve "buildability" digitally fabricated concreting is carried out on a printing platform and depositing layers of concrete. The layer is heated sufficiently until desired ''buildability'' is achieved. It is followed by depositing another concrete layer under controlled heating and the procedure is repeated. Using such a laboratory-scale printing machine will result in time, cost as well as material savings. The developed system can print up to 10 concrete layers each 1.2 m in length. Similar to the mechanism offered by Contour Crafting machine, the nozzle uses an extrusion mechanism to print concrete layers of 38.1 mm by 25.4 mm.

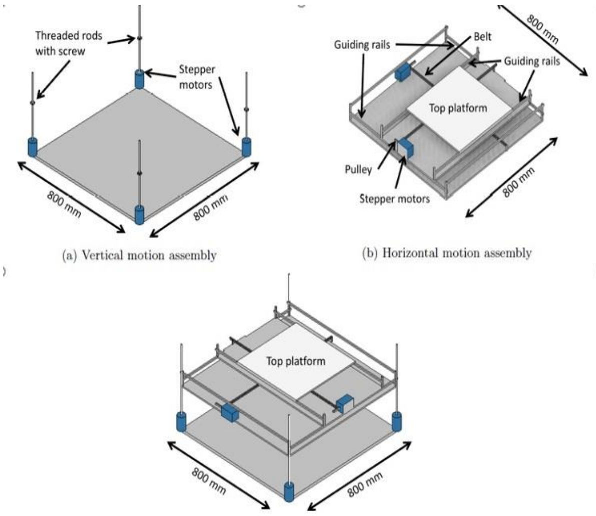

Figure 8: "Vertical and Horizontal Motion assembly of the concrete printer (adapted)" [3]

6.2 Self-compacting concrete mixes

A target SCC mix with a mean strength of 80 Mpa after 28 days was proposed. Cement used was OPC grade 53 as per IS 12269. Water-to-cement and cement-to-sand ratios were kept at 0.32 and 1.65 (by mass), respectively. Table 2 summarizes the details of the three mixes.

Table 1. Proportion (by mass) of ingredients in concrete mixes

Mix ID	OPC	Silica Fume	Sand	Water-Cement ratio	Super Plasticizer
HSC1	1	0.1	1.65	0.32	0.001
HSC2	1	0.1	1.65	0.36	0.005
HSC3	1	0.1	1.65	0.40	0.002

7. Conclusions

The digitalization of construction industry is an inevitable thing in future going by the effect that digitalization had on other major industries. Moreover, a detailed overview of a part of digitalization with respect to Self Compacting concrete (SCC) as one the main ink or printing material to be used depicts a bright future of this technology in the industry. The concepts of form work free construction, labor free and ease of construction which the combination of 3DCP and SCC technology will provide are some of the benefits of this technology. Along with that this technology can help in reducing the impact that current use of concrete or other building materials have had on the environment. Along with that use of other digitalization methods like machine learning can also help in research field of concrete in finding the optimum mix required according to the given field conditions. The free flowing and passing capabilities of SCC will be an added advantage when it comes to bond strength of subsequent deposited layers.

“If 3-D Concrete Printing Technology and SCC as ink material will be used to construct entire buildings in future, this technology may significantly reduce building costs courtesy to its ability of material savings and increased productivity. Furthermore, such additive manufacturing processes will provide architects with a completely new range of opportunities for designing of buildings, so that this technology has the potential of not only revolutionizing and bringing radical changes in constructional processes but also in structural forms” [5]. The commercial success of 3DCP lies in the robustness of the design and manufacturing process and the ability for engineers to design special concrete mixes such as SCC.

3D Concrete Printing has the potential provide the design of additional functionality and digitally controllable the manufacturing process.

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