Additive Manufacturing of Concrete: Challenges and opportunities

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Abstract. A modern incipient trend is being witnessed in the construction industry wherein concrete is pumped which flows through a nozzle connected to a robotic arm in successive layers in order to develop structural load bearing members generally referred as “Additive manufacturing of Concrete(AMOC)” or 3D Printing of Concrete (3DPC). Numerous challenges are being faced by the construction industry for implementation of Additive manufacturing of concrete to a large scale due to the scarcity of information available w.r.t this technology. This technology has opened up new opportunities which requires intensive research to be carried out to ensure that concrete gets pumped through the pipe(pumpability), extrudes through the nozzle (extrudability), retains its shape once this concrete is extruded from the nozzle(buildability). In addition to this, concrete has to be strong enough to withstand loads induced by upper layers without any deformations (shape retentivity). If the challenges related to pumpability, extrudability, buildability and shape retentivity can be addressed in a better manner, this technology of 3D concrete printing can be utilized to construct houses/building components at a rapid rate and bring down the overall construction costs exponentially with optimal usage and minimal wastage of resources. This paper addresses the various challenges which are commonly encountered in the Additive manufacturing of Concrete (AMOC) summarizing the potential solutions to it discussing some of the case studies of projects which have used this technology.

1. Introduction
The earliest use of 3D Printing was to develop a tabletop scaled model. It was much economical option to erect these models compared to hand crafted model that had been and still in use. By the 1990s, many organizations were experimenting to use 3D Printing concept to build a full-scale project. By 2000s, the application was in full use and was getting a start to transform the entire construction industry. In 2006, Khoshnevis at the University of Southern California uncovered the Contour Crafting (CC) system [5]. It is a huge 3D Printer developed for building a whole building in place. It is similar to desktop 3D Printer but uses a crane to print and concrete as a medium to build the structure. In 2014, Dutch firm (DUS Architect) was able to showcase the use of 3D Printing by building a canal house in Amsterdam [7]. They used a giant crane printing arm called “Kamemaker” which mean
“Room Builder”. In June 2016, a Chinese company Hua Shang Tenda announced that they had constructed an entire mansion in 45 Days [4]. The building frame was erected first followed by placing the plumbing and electrical fixtures in it and then printed the structures using a computer-controlled printer extruding concrete through it. The building comprised of 2 storeys with 4305 sq.ft carpet area. In April 2016, another Chinese company WinSun claimed to have constructed 10 houses in a span of 24hrs [6]. The walls of the houses were constructed using a mixture of recycled construction material and cement. They stated, this is both economical and environmentally friendly than the traditional practice. According to the United Nations world population prospects, the overall population is set to reach 9.6 billion people by 2050. A surge increase in population at this rate means requirement of more housing for people within a short period of time. With the traditional methods and current pace at which the construction industry is moving, it is a herculean challenge to provide housing to cater to this population. Hence, it is time to adopt to newer technologies which can increase the pace of construction industry in an efficient way with minimal wastage of materials and resources. 3D printable concrete is an emerging trend in the construction industry which runs on the principle of additive manufacturing wherein concrete is designed in a way such that it is pumped through a nozzle which is connected to a gantry girder. This nozzle moves in the direction specified by the user which results in the formation of a 3D concrete model which when constructed on a larger scale can build houses and other buildings. Since this concrete is passed through a nozzle, there are minimal wastages taking place to construct a building when compared to traditional construction practices. This technology being an offspring in the construction industry, a lot of challenges are put in front due to the fact that not much research is being held in this field. This paper reviews the various challenges pertaining to 3D printable concrete. Possible solutions to these challenges which can be adopted are also discussed in this paper.

2. Challenges in 3D Printable Concrete(3DPC)

2.1 Pumpability
Concrete pumpability is defined as its ability to flow through a pipe using a pump and also the ability of confined concrete to flow under pressure while maintaining its initial properties [9]. The pumpability and buildability of 3D printable concrete is measured in terms of the pumpability index (the ratio of concrete flow rate to water flow rate of 2890 rpm), surface performance and maximum height printed [19]. Mixtures with low slump and slump-flow values tend to have a rough texture on the surface of the filaments with high persistence of form, large voids / cracks and poor pumpability index. [19]. Higher flowability (such as low 192 mm spread diameter during flow table testing) may also cause congestion and interruption of printing, poor printable material property can result in increased concrete filament voids [14].

2.2 Extrudability
Extrusion is a process in which a rigid paste is forced to pass through a rigid die with a high shear, resulting in a liquid behavior [17]. The size of the nozzle plays a crucial role in concrete extrudability. A larger diameter causes problems with the buildability because the layers could not support themselves while a smaller diameter posed problems with the separation of the concrete components [21]. In addition, lower flowability (such as low 192 mm spread diameter during flow table testing) could cause congestion and interruption of printing, poor printable material property can lead to an increase in concrete filament voids [14]. The sand-to-cement ratio (S / C) exceeding 1.5 significantly reduced the flowability that a nozzle cannot extrude.

2.3 Buildability
Buildability refers to the concrete layer's ability to hold the successive layers above it without subsiding. The concrete must also have a certain compressive strength [1]. Because of its relatively low stiffness and strength of the printed filament, concrete can pose buildability problems during its initial condition and another observation showed that the extruded filament temporarily suffers from
cavity [1]. With a time gap of 19 minutes, smaller deformations were measured as per layer settlement test results. Significant deformations (1.5 mm) occurred after second layer was deposited for Poly-Propylene mixture with no time gap [2].

2.4 Strength
Panda et al. [13] studied the role of printing parameters such as the time gap between two successive layers, height from which the layer is deposited and its impact on the tensile bond strength. The study concluded that the surface moisture content at the interface between the layers played a vital role in regard to bond strength [16]. Le et al. [12] demonstrated the possibility of anisotropic 3D printable concrete components. Compressive and flexural strengths were tested in different directions on the printed specimen in the experiment and compared to the mold cast samples. High compressive and flexural strengths in the mould cast specimens was observed when compared with specimens which were 3D printed.

3. Solutions to Various issued related to 3D Printable Concrete (3DPC)
A square nozzle is generally used which improves buildability which is generally programmed so that the nozzle's orientation is always tangible to the tool direction. If the process is ignored, the filament tends to get twisted. Therefore, a rectangular nozzle is chosen for better performance efficiency [1]. A proper mix design requires high cement content or, more precisely, high paste content for adequate pumpability [10]. Addition of more water and 1% to 2% of super plasticizer makes the mix more flowable and hence improves the extrudability [12], use of polypropylene fibers reduces formation of cracks [1, 11] reported higher buildup rate of internal structure after shear induced breakdown for Nano-clay incorporated cementitious mixtures, especially at early stages. This could be a likely reason for enhanced buildability of Nano clay mixture [18] resolved the issue pertaining to cold joints by printing hollow structures so that the rebars can be placed afterwards. Increase in contact surface of layers resulted in increase in bonding strength [20].

4. Case Study
Construction of a Power distribution substation using 3D printable concrete technology [22]. In this project, A mechanical column-type structure consisting of a four-column frame shown in figure 2 for 3D printing was set up. The 3D printer was divided into several structural parts in the frame: X-axis path, Y-axis path, Z-axis column path, print head, top stabilization system and ready-mixed concrete. This printer had a width of the X-axis and height of the Z-axis as 20 m. The Y-axis length could be extended indefinitely by increasing the column number of Z axis. The Y-axis length could be extended indefinitely by increasing the column number of Z axis.

![Figure 1. Double Aided Nozzle](image1)

![Figure 2. Four legged Column Frame](image2)

A double aided nozzle was used in this project as shown in figure 1 that can extrude concrete with 15 mm diameter aggregates. The upper end of the concrete feeding system was constructed with a V-
shaped vibrating sieve. This sieve had a 15 mm pore spacing and can filter out aggregates with a diameter of more than 15 mm. The dual-assisted print head's working principle was that feed containers A and B can work together at the same time. The printing effect was highest when the concrete slump in the feed bin was between 120 and 130 mm. This nozzle was equipped in the concrete performance test system with a torque test screw. This ensures that the rough aggregate in the concrete does not exceed 15 mm in diameter. The concrete used had a strength of 20 MPa during the printing process of the power distribution substation, which met the structural design requirements. The concrete wall was first printed horizontally and the location of the building columns during the printing process was reserved. After the concrete printing wall was completed, construction columns were then constructed by supporting shaping, tying steel bars and casting concrete, as shown in the figure 3. After each printing layer reinforcement was given to strengthen the bond strength as well as the building's compressive and flexural strength. It should be noted that for the printing of the lintel above the door and window openings, it is still important to use the conventional formwork type, i.e. the prefabricated wooden formwork to support the lintel. The 3D design model was first performed, and the 3D printing slice technology was then used to slice the construction model, creating a layer of digitized code. The overall construction time of the power distribution substation project using conventional cast-in-place concrete was 54 days, while the construction period using 3D printing was less than 35 days, the construction time being reduced by 30% with concrete printing reduced the work needed but lead to increase in the cost of materials as a comparatively higher-class concrete was used.
5. Conclusions
In the above paper, various challenges faced by 3D printing concrete technology such as problems encountered have been summarized below
- Pumping of concrete from the source to the nozzle such as choking, changes in structural properties, segregation of concrete, etc. to which possible solutions were studied which include addition of superplasticizers, viscosity modifying agents and use of retarders.
- Extrudability of concrete from the nozzle which had issues in improper printing, formation of cavities, poor finishing, etc. These issues were solved by changing the section of the nozzle, varying the size of the nozzle, modifying the water cement ratio, etc.
- Buildability of concrete after extrusion which resulted in problems such as collapse of lower layers, deformations with respect to time gap between layers, formation of cold joints between layers, etc. These issues were resolved by use of Attapulgite clay or nano clay, creating hollow structures to avoid cold joints, increasing the cement paste content, etc.
- Variation in strength of concrete of printed specimen and mould casted specimen, weak bond strength between layers of concrete, low flexural strength, etc. These issues were overcome by using polypropylene fibers, introduction of steel reinforcement between layers of concrete, etc.

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