Additive Manufacturing through Digital Concrete by Extrusion and Non-extrusion method

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Abstract. The phase of construction industries is very weak to adapt new technologies. We faced plenty of problems related to our construction industries because of old conventional method. Digital Concreting (DC) is the techniques from Additive Manufacturing (AM), the concrete is laying like layers to build a whole structure. DC could to overcome the problems faced by conventional construction. Furthermore, the DC will open the windows that allow the new innovative technologies enter in to construction industries. Generally, the usage of concrete is more than enough so it leads to increase the waste in site and harmful to environment. In DC technique uses of the concrete is only for need and no excess use. The properties of concrete are different for printing compared to conventional method. In this paper, we discussed about the general view on DC, properties of concrete and the methods used to print.

1. Introduction
Additive manufacturing (AM) is widely used in manufacturing industries and is now processed to become a vital factor in building construction industries. Construction industries are ordinarily considered less developed than other industries due to the less utilization of innovative technological ideas. Moreover, nowadays constructions are processed with the help of earlier primitive techniques. Now the use of advanced computer drawing software and Building Information Modelling (BIM) leads to adopt new technique in construction sector. Obviously, we will witness a considerable rise of additive manufacturing process in construction industries as well as there is a chance to further adopt innovation in construction sector [1]. Concrete is the major construction material in construction universal. This is because of the efficient and appropriate specification of concrete in construction industries. The easy availability of raw materials, comparatively unchallenging managing as well as handling, load carrying properties. However, the concrete is inevitable and extremely threat to environment. 10% of evolution of universal CO₂ emission is took place due the manufacturing of Portland cement. Digital concreting (DC) is possible to define as implementation of digital modeling and technologies to the generation of custom structure. 3D printing (3DP) technology has verified that it is suitable in terms of most effective use of construction time, design feasibility and reduction in field error as well as environmentally friendly. 3DP does not require any formwork as well as vibration. The major concept is that of Additive Manufacturing process (AM). It means adding of
material layer by layer. Usually AM process utilize Computer Aided Design (CAD) modal as blue print to make up complicated 3D design in a layer manner [2]. Digital concreting technique was started at 1980s, eventually popularized in the construction field at 1990s only. The studies are functioning to enhance the efficiency of 3d printing technology. The ‘NASA’ developed a competition program to encouraging the students from various university towards 3D printing structures. The topic was provided 3D printing structures in extraterrestrial habitat for humans [3]. Additionally, enhancement of concrete properties should increase the efficiency of printing ink. Addition of Nano clay and Silica fume, magnesium potassium phosphate cement with waste materials and introduction of silica particle in to gypsum powder was developed leads to enhance the properties of printing concrete [4, 5, 6, 7]. The mechanical properties also should we take in to account compressive strength, direct tensile bond strength is also important to DC. The increase in the mechanical properties of 3D printing concrete compared to traditional method [8, 9]. The application of recycled glass in concrete can overcome the severe environmental problems as well as provide good building properties to concrete [10]. Utilization of geopolymer cement mixture also provide same advantages as well as plenty of chemical composition that are used to improve the properties of concrete and reduce the effect on the environmental [11, 12]. The interlayer bonding is one of the important aspects in DC. The bond between layer must be adequate and bear the load acting on the joint by holding two layers together. There are lot of researches are already done to improves the bonding. The sulphur-based binder introduces and achieved remarkable improve in bond strength [13]. In some studies, they provide interlocking to increase the interlayer bond strength [14]

The aim of the study to validate about the characteristics of concrete used in 3D printing and various methods to printing the concrete. Moreover, discussed about the major 3D printed structure as well as implementation strategies. The major significance of this paper to give an idea about how much our technologies are changing in construction sector. Ultimately, the results from this paper make people to aware of the general importance of DC

2. Additive Manufacturing of Concrete

Additive manufacturing (AM) of concrete as we all know the laying of concrete layer by layer. The primitive method of additive manufacturing (AM) was masonry the laying of brick layer by layer. Eventually, AM gained new specifications and converted in to modern AM techniques. Currently, the concrete is depositing layer by layer and form a whole structure. The modern AM technique has lot of advantages like less time consuming as well as cost effective. Implementation of robotics providing suitable solutions for errors caused in conventional method. Now, AM process achieved widely and providing new innovative ideas. In general concrete is most universally used building material. Concrete has plenty of disadvantages like influence the environment inadequately, time consumption, waste formation. Introduction of proper measures should implement to vanquish them very effectively. Analysis of the relationship between stress, shear rate and time is done by rheology. Compared with conventional cementitious materials, the properties such as viscosity and stress are various in digital concreting, it demonstrates that the materials present low yield stress and well-flowability from the concrete tank to printer nozzle and the fresh paste after printing should get high viscosity and short setting time [15]. Time gap between extrusion of layers is unavoidable, the concrete is time dependent. So, the concrete has to change with time and that is unpredictable. This lead to reduce the strength on the structure and cause fail [16]. The robot used to print the concrete has some specification and conditions. The printing system consist of the concrete tank and pumping mechanism, the printing nozzle, and the motion control system [17]. The concrete is loaded inside the tank and is pumped to reach the nozzle, which is responsible for depositing it. The robotic arm consists of nozzle and can move x, y and z direction. The machine should overcome the difficulty to printing as well as the machine must be efficient. The major characteristics of 3D printing concrete (3DPC) depends on the machine. Printability, extrudability, buildability and open time are the major characteristics [18, 19, 20]. The nozzle size, speed of pumping and speed of robotic arm movement are the prime conditions to effective printing. The 3D printing technology and Powder based 3D printing are the two techniques we prepare to discuss.
The Digital concreting (DC) has developed a tremendous futuristic way to construction sector. DC has faced plenty of difficulties in construction sector. Later introduced so many ways to burying the difficulties. DC offers the capability to manufacture complex and modified structures to people needs. The concrete wall can be made without formwork is the crucial step. DC developed a wall without formwork, the Polyurethane foam. The wall is manufactured in the manner of two Polyurethane foam walls and between they provided self-compacting concrete [21]. 3D printing of curved structure was done with the help of adaptable membrane. Introduced adaptable membrane formwork to print the curved structure as well as self-reinforced cementations components [22, 23]. Printing of support-less shells is one of the significant challenges and DC could achieve that [24]. Until now plenty of residential and public buildings have been constructed with DC. Introduced some project related to DC and demonstrated the ideas about the diamond model. The major challenges and difficulties faced by the company and how the overcame the situations [25] should take in to account.

3. Demonstration of Digital Concreting in Construction

3.1. HuaShang Tengda: Mansion

HuaShang Tengda, a construction company based in china manufactured a mansion of area 4305.5 ft² using digital concreting technology and the completion period is in 45 days [26]. The mansion is can withstand earthquake up to magnitudes of 8 on the Richter scale. The thickness of the wall is 25cm and used 20 tons of C30 grade concrete. This mansion is located in an earthquake zone, so manufacturing earthquake resistance structure is vital. This mansion considered as the first fully printed structure. They completed pre-cast foundation and another MEP services before printing process [27]

![Figure 1. HuaShang tengda mansion](image)

3.2. Winsun houses and offices

Winsun a construction company was the first to start Additive manufacturing. They designed a project constructed with Additive manufacturing in 2013. Later they constructed their office with Additive manufacturing process in 2016. This office was initially manufactured within China and later delivered to Dubai. During this construction it is calculated that 80% lower building expense, 60% reduced cost of workers and 60% reduced waste than a traditional building [28]. The company designed a double-storied, 1,100-square-meter house that consumed more time to construct in the factory in an unspecified time and couple of days to install at site by 3 labours. The internal structures are placed before the installation. Their strategy has advantages supplying up to 1/2 the manufacturing materials from the waste of building, simpler implementation of insulation, cabling and piping and a pollution
free building procedure at site. Winsun managed to sell more than 100 house and general house cost about $30,000

![Winsun dubai building office](image)

**Figure 2.** Winsun dubai building office

### 3.3. 3D bridge in Castilla La Mancha

3D printed bridge in Castilla La Mancha is considered as the initially constructed printed bridge. It has a span of 12m length, 1.75m width [1]. This was manufactured in 2016, is build-up of eight sections, each with extreme horizontal measurements of 2x2m and manufactured with blended powdered concrete and polypropylene reinforcement. In the time of construction procedure, there are no raw materials used and the construction procedure that use creative algorithms to extreme efficiency in raw-material deposition.

![Castilla La Mancha 3D bridge](image)

**Figure 3.** Castilla La Mancha 3D bridge
3.4. Gemert bicycle bridge
BAM Infrastructure and TU Eindhoven companies are combined to build an 8m length, 3.5m width bicycle bridge with concrete located in Gemert, Netherlands [1]. It is narrated as the prestressed bridge with digital concreting. During the printing operation, 1cm concrete mix layer was poured with an extruder, as well as the concrete has the ability to withstand its structure after extrusion with no extra formwork. This bridge was constructed in different parts and later combined each other at site. This bridge was opened on late 2017.

4. Characteristics of Digital Concrete

4.1. Pumpability
Pumpability is the simplicity with which the concrete mix is carried from the storage tank to the extrusion nozzle. Pumping of concrete is the major technique in DC and is an unavoidable part. The pumping of concrete is different from the pumping of other fluids like water, oil, and other liquids. The predominant reason behind this is fresh cement-based material are yield stress fluids. So, consideration of pipe pressure in to account is very significant. Moreover, the inadequate mixing preceding to pumping and the particle segregation due to pumping of concrete from tank. Furthermore, concrete has time-dependent property so very hard to predict the behaviour of concrete mixture. Mixing of concrete in traditional manner will not work properly so we need to modify the concrete for printing. The utilize of lubricant can reduce the segregation, the lubricant provide a layer in between the aggregates and the layer decrease the friction between aggregate. Workability could increase with the help of lubricant, the 3DPC need high workability [29]

4.2. Buildability
Buildability is defined as the ability to retain the shape stability after the extrusion. Buildability is inevitable in DC and the property of concrete mix depends the buildability as well as the nozzle. On the other hand, successful printing of layer without any collapse. Moreover, pumping parameter is predominant, if the printing speed is more than structural build-up the structure will fail. Introduction of admixtures can increase the material structural build-up. The shape retention ability after extrusion is very important in 3DPC. Printing of concrete without formwork may leads to collapse, so the internal bond strength between materials and significantly the bond between the layer. The extruded
layer must be able to bear the load of following layer. The structure strength and serviceability depend on buildability.

4.3. Extrudability
Extrudability is potentiality of the concrete to be flowed out of the nozzle. It is evaluated based on the concrete paste that can be printed without blocking the nozzle. As well, the printed concrete paste should be free from cracks and separations. Extrudability depends on properties of concrete mix and the calibration of nozzle. If the nozzle is not well calibrated will affect on the printing of concrete and concrete may stick inside the pumping pipe. The concrete is time-dependent so it will affect the whole mix. The structure will fail if the concrete is not extruded properly and it will affect the interlayer bonding between layers. Moreover, we should investigate the extrudable distance from various experiments. Pouring of concrete with high efficiency will provide structure proper strength.

4.4. Open time
This is defined as the time period in which the workability of fresh concrete was that perpetuate extrudability. With open time we can identify the relation between cementitious materials and setting time. Open time can be calculated with help of slump and slump flow test [17]. The concrete must not change from liquid state to solid form before pouring. The workability must high in the DC. Addition of proper admixtures can overcome the concrete hardening problem.

4.5. Workability
The workability is defined as the ease with which a concrete can be transported, placed and compacted without any bleeding or segregation. In DC the other parameters are depend on workability. The 3D printing concrete must be flowable, transportable and stability after printing etc. is controlled by workability. The tests like flow table, ICAR rheometer, slump, slump flow and Vicat’s apparatus are used to find workability [30]

5. Methods of Digital Concreting
5.1. Extrusion method
As we all know this is the most general method used in DC. The concrete is poured through the nozzle. The DC system consist of Computer for designing the toolpath and generating the G code, Robotic controller for reading the programmed code and controlling the robot. The nozzle is mounted on the robot and moving along the generated toolpath. The Mixer for material preparation. The pump controller is used for running the code and controlling the pump speed. The heat guns are used for heating the material during printing. The strength of the structure is increased by printing precisely and give high serviceability to structure. Printing of concrete is a complicated procedure we must accurately aware of the procedure. Principally, the develop the 2D drawing and generate the path in computer. Then generate the code for the robot to printing the path. Generation of code must be accurate otherwise lead to problem in printing. After the entire nozzle must be well calibrated and the proper design of nozzle is required. Before constructing the original structure, the scaled structures are constructed to investigate the significant parameters and later it changes to large scale structure [31]. The mode of construction changed now and the problems faced by the traditional construction reduced up to certain limit. On many occasions the printing is done with large-gantry machines. Unfortunately, this need lot of time to manufacture so to avoid this robotic arm was introduced [21]. For large-scale and on-site applications, this technique seems more satisfactory.
The large printed structures with ultra-high performance concrete is introduced and the tangential printing technique was introduced [32]. To attain the dominant necessity of Digital concreting with extrusion, printing materials should be thixotropic, sudden setting, sudden hydrating, closely packed and should require well controlled properties such as yield stress as well as plastic viscosity. The extrusion method achieved the formwork free wall printing and this was happened due to modify the concrete mix in to correct proposition. DC not being print the overhanging part, the overhanging part need reinforcement and because of the low green strength properties of printing material after printed. The printing of complex structures is very difficult but the lot of experiments done to overcome this and achieved. Furthermore, there are different parameters in digital concreting such as “concerning scale, environment, support, and assembly strategies” and a method for classifications are introduced [33]. The extrusion method is most used method used in DC and this method gained popularity, many of construction companies are using.

5.2. Non extrusion method
The non-extrusion method is also known as “powder-based 3D printing or particle bed 3D printing”, is another Additive manufacturing process that produce perfect components by extrusion of binder liquid specifically into to powder-bed. Then it binds the powder where it impacts on the bed [34]. The thickness of bottom layer is 3mm. A new thin layer of powder ‘approximately 0.1mm’ is applied and made smooth by the roller on the bed surface. At a time, a layer is completed, the binder feeder delivers binder solution to head of printer and extruded through nozzle. The process of operating the binder solution is drop-on-demand (DoD) technique. Eventually, the excess waste powders are cleared in a de-powdering process. The durability as well as strength can be increased by heat treatment or infiltration process [35]. Non-extrusion method technically an ex-situ procedure developed to construct prefabricated components. Non-extrusion 3D printing techniques is appropriate for small-scale elements like panels, permanent formworks and interior structures that then can be joined together at site. The cement-based or non-cement based materials are used to make formwork. The binder is extruded through a nozzle in to the powder causing powder particle bind each other. After certain appropriate steps the completion of build part and can be remove after some drying. The unbonded powder can be remove by air blower. Furthermore, the component transport to site and assemble.

**Figure 5.** Diagrammatic representation of 3D printing setup: (0) Operating system. (1) Robotic controller. (2). Print controller. (3). Arm. (4). Nozzle head. (5). Accelerator. (6). Pump for accelerating agent. (7). Premix pump. (8). Mixer. (9). Sample
Figure 6. Diagrammatic representation of the Non-extrusion printing process: (a) binder jet print system, (b) interaction of binder/ material between adjacent layers.

There are some limitations that mostly effect to powder-based 3D printing. Printer and printing materials are the limitations. The size of the printer is small or medium compared to extrusion method. So, the requirements of larger size components may be difficult. The speed of printing is effect by several factors. The velocity of binder jetting and the speed of powder laying are the major factors so, is must be parallel to improve the printing speed. The availability of printing material limitation is the next problem. Till now, Rapid Harden Portland Cement (RHPC), Magnesium Oxychloride Cement (also known as Sorel cement), Calcium Aluminate Cement (CAC), Ultra-High Performance concrete (UHPC) and Fibre Reinforced Cement Polymer [36] are the few materials that are used for this process.

6. Conclusions
Digital Concrete (DC) is the innovative step in construction industries. The popularity of this technique is comparatively low but on other hand the major studies are going on to make this technique more popular. This paper reviewed about the general view on DC and the properties of printing concrete. The detailed about the method of extrusion also evaluated in this paper. The popular successfully completed projects also detailed in this study. The characteristics and properties of printable concrete is different from ordinary concrete, the general study on these properties are implemented in this study. Pumpability, Buildability, Extrudability, Open time and workability these are studied. These properties are inevitable and make sure there should be no way to reduce these properties. For high strength of the structure, the printable concretes should have these prosperities as well as to print efficiently. The two methods are introduced in this study are Extrusion and Non extrusion deposit method. The extrusion method or printing through machine is very popular and accepted method in DC the material is deposited through the nozzle. The structure gained more strength and serviceability when using the extrusion method with controlled printing. The non-extrusion method or powder-based 3D printing is used for small-scale printing especially components of structure and later is assembled on site. There is limitation for this method that already discussed. Generally, for efficient printing the extrusion method is very useful. There are some limitations in non-extrusion and that makes the extrusion method so popular.
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