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3D Concrete Printing: A Road Map for future of Automated Construction in India

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Abstract - 3D concrete printing (3DCP) is the potential future of total automation in building and construction (B&C) industry. 3D concrete printing which works on the principle of additive manufacturing, has gained significant attention due to its promising benefits such as formwork free and efficient construction, high flexibility in architecture and customized design and minimized waste production etc. However, it is still at primitive stage due to lack of fundamental and comprehensive research on its various components such as printable materials, printed shape of structure, the forces acting on the structure and the printing methods itself. At first, this paper reviews the progress of 3DCP in B&C industry and academia across the world. The paper also highlights the current challenges in the path of use of 3DCP in Building & Construction sector particularly in India. Finally, the authors present their idea to accelerate the use of 3DCP in construction in India.

Keywords - 3D concrete printing; Automation; building & construction Industry, Additive manufacturing

INTRODUCTION

3D printing is a new technology that works on the principle of additive manufacturing. According to the American Society for Testing and Materials (ASTM) "Additive Manufacturing (AM) is a process of joining materials to make objects from 3D model data, usually layer upon layer" [1]. Thus, 3D printing can be defined as "*an additive manufacturing process where materials are deposited, usually layer upon layer, to create a 3D solid object from a predefined digital model*". 3D printing provides sufficient flexibility to customize an object with complex shape, it reduces the need of intensive labour and minimizes the waste generation. Many industries such as Medical, Aerospace and Manufacturing are quite successful today in terms of adoption of automation such as 3D printing. However, 3D printing in building and construction which is also known as 3D concrete printing (3DCP), has been under the novice stage till date. The potential cause of underdevelopment stage of 3DCP are lack of comprehensive research on printable material & mix design, complex shape of the structure and the complex loading etc. As a result, even though some buildings have been constructed through printing techniques, various challenges and possibilities need to be explored properly. Starting from the concepts of 3D printing process, this paper critically reviews the progress of 3D concrete printing across the world. Also, major challenges in adoption of 3DCP in India are discussed and finally, the authors present their own ideas to accelerate the process of 3DCP in the large-scale construction.

3D CONCRETE PRINTING

3D concrete printing can be defined as "*an additive manufacturing process where cementitious materials are deposited, usually layer upon layer, to create a 3D solid object from a predefined digital model*". The typical process of 3D concrete printing is shown in (Fig.1)

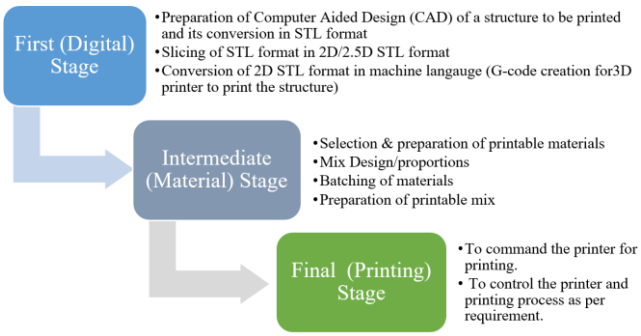

Fig. 1: Typical Process in 3DCP

In the past few years, many 3D concrete printing techniques have been developed to enhance the use of automation in construction. However, most of these techniques work on two principles i.e., extrusion-based and powder-based. The Extrusion-based printing is done layer by layer deposition of the printable mix, whereas Powder based printing is prepared by spreading the dry base materials first and binding it selectively by cementitious material. Though the first cement based additive process was suggested by J. Pegna in 1997 [2] in form of free form construction, the first popular 3DCP method was developed by Prof. B Khoshnevis and his team through a series of works at university of southern California and named as 'Contour Crafting (CC) method' [3, 4]. Contour Crafting method is, essentially, a layered-based printing technique which uses different materials such as cement, ceramic paste and polymer etc. to print a structure, providing it with a smooth surface finish. A relatively new printing technique known as 'Concrete Printing' [5-8] but

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similar to CC method was started by Dr. R. Buswell and his team at Loughborough University, United Kingdom. As compare to CC method, this technique has greater printing control in different geometrical shape of object to be printed but it provides poor surface finish. 'CONCPrint3D' is one of latest extrusion-based printing technique used for monolithic large-scale construction and it is being explored as a part of Project led by professor Günter Kunze at Technical University, Dresden, Germany [9]. D-shape printing technique which is based on powder-based printing, was developed by Enrico Dini [10]. This technique has potential to be very useful in large scale modular construction.

Since, materials and their compositions are one of the important elements of the 3D printed concrete, various researchers [6, 8] have defined four key characteristics of the printing materials and mix to predict the performance of 3DCP, as follows:

1. *Pumpability:* ability of material at wet mixed condition to pass through the delivery system at desired speed, pressure and discharge.
2. *Extrudability:* ability of material at fresh state to be extruded through a deposition device say from nozzle in continuous filament of desired shape and size.
3. *Buildability:* The ability of a printed layer to resist the weight of printed layers applied on it.
4. *Open time:* The time period for which these three properties are consistent within permissible tolerances.

LITERATURE REVIEW

A. Material and Mix Design

T.T. Le, S.A. Austin., S. Lim and R.A. Buswell, [7], and Le et al. [8], used cement binder ratio of 3:2 with sand of a maximum size of 2 mm and binder comprising of 70% cement, 20% fly ash and 10% silica fume to prepare optimum mix of high-performance printing concrete. V. Mechtcherinea, et al. [9], used mix design of concrete for the maximum aggregate size 8 mm. The concrete was printed in large rectangular filament of size 150 mm × 50 mm. Z. Malaeb, [11], et.al. used maximum aggregate size 2 for the size of printer nozzle 2 cm. Other dry constituents include cement type I and sand. The optimum ratio of sand to cement is 1.28 and minimum w/c ratio 0.48 for extrudability. C. Gosselin et.al., [12] presented a novel premix that includes original Portland cement CEM I 52.5N, silica fume, crystalline silica and limestone filler for high-performance printing concrete paste. Rushing et al. [13] investigated the ability of conventional mix with various type of additive and fibres for 3DCP. This study demonstrated that Coarse Aggregate can be used for 3DCP but with very low amount as compared to Fine Aggregate. Rahul et al. [14] used Portland cement, fly ash (Class F) and silica fume as the binders, PCE based superplasticizer and methyl cellulose based VMA for mix design. Panda et al. [15] also used fly-ash (class F), micro silica, ground granulated blast-furnace slag, chemical admixtures, sand with maximum 1.18 mm in size and tap water to prepare the printable mix of a fiber reinforced geopolymer mortar.

It is clear from the literature that printable mix are not a conventional mix, rather, a customized mix prepared on the basis of performance for a particular printer and printing process.

B. Mechanical Properties and Structural Behavior

Lim et al. [6] found that the compressive strengths of high performance printed concrete samples are 80% to 100% of the ordinary cast specimen, whereas the flexural strength of extruded samples shows insignificant variation from the standard cast specimen, however, orientation of printed layers in the sample and direction of loading at the time of testing plays vital role. Le et al. [8] observed from their experimental studies that compressive strength and flexural strength of 3D printed sample are 75–102 MPa and 6–17 MPa respectively depending on testing direction. Malaeb et al. [11] found that the compressive strength of 3D printed cubes of optimum mix was approximately 42 MPa. Gosselin et al. [12] found from their experimental study that average flexural strength of samples of 40×40×160 mm size cut from 3D printed specimen is 14.3 MPa. They also suggested to employ fibres to strengthen the printed structures. Feng et al. [16] found from their study on the mechanical properties of the powder-based 3D printed structure that printing direction has significant effect on the mechanical properties such as compressive strength, flexural strength and bond strength. Rahul et al. [14] studied on the mechanical characterization of the 3D printed structure and they found that the porosity was high at the layer interface and bond strength were significantly low (22-30%) at these areas compare to the bulk. On the basis of the mechanical characterization of the unreinforced concrete masonry, the authors presented the structural design procedure for 3D printed concrete wall.

PROGRESS AND CHALLENGES OF 3DCP IN INDIA

A. Current Progress of 3DCP in India

only a handful of construction companies are working towards 3DCP either independently or with collaboration with academia. There are only two residential houses constructed using this methodology in India so far.

1) Single story structure: Tvasta Manufacturing Solutions, a start-up founded by alumni of IIT Madras, has made India's first single storey 3D-printed house of 600 square feet area (Fig. 2). The team has printed the structure in collaboration with Habitat for Humanity's Terwilliger Centre for Innovation in Shelter. The concrete mix is based on ordinary Portland cement, having a lower water-cement ratio which is an extrudable concrete consisting of cement, sand, geopolymers, and fibres.

2) Double story structure: Larsen & Toubro Construction (L&T), has built a two-storey building (Fig. 3) of a floor area 65 m², situated at L&T's Kanchipuram facility near Chennai [22]. The building is claimed to be fabricated using 3D printing technology. The building is made of a locally obtainable materials and the 3D printable concrete mix are developed by L&T's team.

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B. Key challenges for use of 3DCP in India

There are certain challenges before the Indian construction industry while adopting the 3DCP. Some of them are:

Fig. 2: One story house 3D printed house by Tsvasta [21]

Fig. 3: Two story house 3D printed house by L&T [22]

1) Printer setting: When a particular set of printing material and design methodology is used to print an object, 3DCP is proven to be quite efficient as compare to conventional construction techniques. However, in case of changes in material composition and design methods, the printer settings require significant changes and it consumes a significant time also. Thus, the printing process may not be as efficient as it should be.

2) Properties of printed structure: During the printing process, it is quite challenging to make the structure isotropic as the literature suggests that 3D printed layered structure shows anisotropic behavior, moreover, bond strength at the interface is the one of those areas that needs to be explored in much details.

3) Cost Benefit Ratio: In spite of being a promising technology, 3DCP is not a first choice of the construction companies in India and it may be attributed to cost associated with equipment, software and skilled workers. Since, there is no comprehensive study available on the cost benefit analysis on the use of 3DCP and Indian market, it become the need of an hour to explore the cost benefits of the technology.

4) Lack of standards/codes: There are numerous researches being carried out for the development of 3DCP. But unfortunately, there is no standard or the code available to construction industry. As construction involves a number of variables at the site, Indian construction companies are not ready to take the risk of new technology.

PROPOSAL

A. Utilization of Waste Paper Sludge

Literature on the properties of the waste paper sludge [17-19] suggests that waste paper has high potential to be substituted specially as a binder for concrete production. Waste paper also shows pozzolanic behavior after the treatment at higher temperature. At one end, it will solve the problem of wastage, on the other hand, it will be used in concrete production.

B. Investigation on the properties of fibers

Inclusion of fiber improves the hardened properties of the concrete in significant amount in case of conventional method of concreting. So, it may be useful in the printing techniques [20] also. Concrete production through printing process depends on the fresh properties such as extrudability and pumpability. Inclusion of fiber may degrade the desired fresh property of printable mix. So, a comprehensive study is needed to fix the role of various fibers

C. Investigation on locally available material

3D concrete printing uses specially customized material. Generally, the 3D printing companies offer the mix proportion needed for the particular work, thus most of the time a common user has to rely on the specific market. It is one of the reasons why 3DCP is not as much popular as it should be. Therefore, broad and comprehensive study on the properties and applicability of the locally available construction material needs to be done.

D. Approach towards Actual Construction

One of the impediments in concrete 3D printing is the usage of present design codes for the design of structures. Many approaches depending on the importance, size and utility can be adopted to print a structure. To explain it, Water Closet of size (1200mm x 1000mm x 2400mm) taken from IS 2064 [23] as a part of the structure and it is shown in (Fig 4).

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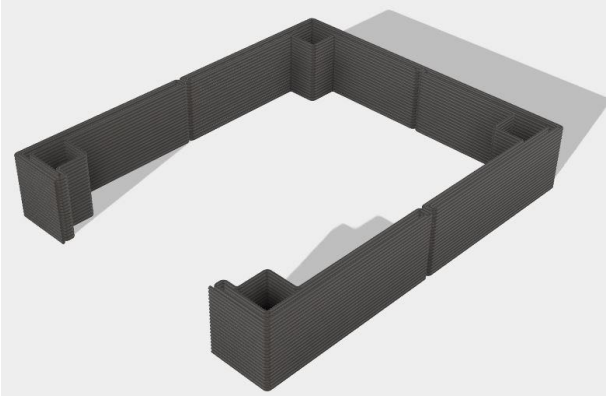

Fig.4 Assembly of 4 modules for the base of the structure

Also, (Fig 5) shows a single module which would be printed in one go. The structure will be printed in different modules and later on the different modules will be assemble, this process is known as off-shore 3D printing.

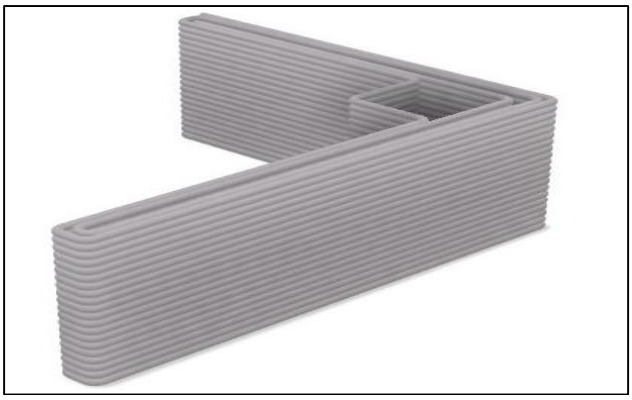

Fig.5 Single module for the base of the structure

CONCLUSION

3D concrete printing is the need of an hour in the age of technological advancement, however, there are many areas that requires detailed study for any further decision as construction at site is more difficult if all the variables involved in the printing process are not defined and known clearly. The research on the applicability of the locally available material is equally important especially for the developing big economies like India. To make the 3D concrete printing more sustainable, possibilities of use of various wastes like paper sludge also needs to be investigated thoroughly. To improve the structural performance of the 3D printed structure, inclusion of different types of fiber is another area of research.

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