Paper No. 350

Introduction to 3D Concrete Printing Technology and its Possible Use In Pakistan

Rashid Hameed, Khalid Farooq and
Muhammad Rizwan Riaz

INTRODUCTION TO 3D CONCRETE PRINTING TECHNOLOGY AND ITS POSSIBLE USE IN PAKISTAN

By

Rashid Hameed, Khalid Farooq and Muhammad Rizwan Riaz[1]

Abstract

Deposition of material in layers without the need of formwork through computer based system to build structures is known as additive manufacturing or more commonly known as 3D concrete printing which is a promising technology in construction industry. In the recent past, research efforts have been made to design printing system, printable concrete mix with certain required early age properties such as yield stress and thixotropy, and also to find suitable printing process parameters such as printing speed and time interval between layers. Design flexibility, speedy construction, saving of materials due to process automation and less labor requirements are its main advantages over conventional methods of construction. Although initial cost of such construction method is high which mainly involves installation of 3D concrete printer on site and design of printable materials in laboratories, but overall construction cost of large number of small housing units could be expected less than that of traditional method of construction due to significantly less labor and no formwork requirements. Further, once the printing system is installed on site, the same could be used to print as many housing units as required. For the construction of small housing units in Pakistan on large scale, use of such advanced and innovative method of construction using clay or geopolymer concrete could be considered as a way forward towards sustainable and low-cost construction. Purpose of this contribution is to introduce 3D concrete printing process to our local construction industry and discuss research work being carried out in Civil Engineering Department of University of Engineering and Technology (UET) Lahore-Pakistan related to design of cement and earth based printable mixes.

Keywords: 3D Printing; concrete; clay; history; advantages; experimental study.

[1] Civil Engineering Department, University of Engineering and Technology Lahore, Pakistan

1. Introduction:

Concrete is the most widely used construction material all over the world. In conventional method of construction, the fresh concrete is poured into rigid mold under the effect of gravity to cast concrete elements of required shape. It is pertinent to mention here that mold/formwork not only dictates the shape of concrete element but also provides early-age protection against drying before it is removed 24h after casting and / or once the material has set-[1]. In many developed countries on the globe, it has been observed during the last two decades that pre-casting has significantly replaced conventional method of in-situ concrete mixing and casting [2]. In recent past, construction industry has benefited from automation technology and a new way of shaping the concrete has been introduced known as "3D Concrete Printing (3DCP)" which is also known as Additive Manufacturing (AM). 3DCP is an emerging technique of construction where unlike conventional construction technique, the material is extruded from a nozzle and deposited in layers without the need of formwork through a computer controlled system to build structures. Figure-1 (taken from ref. 3) presents scheme of 3DCP setup.

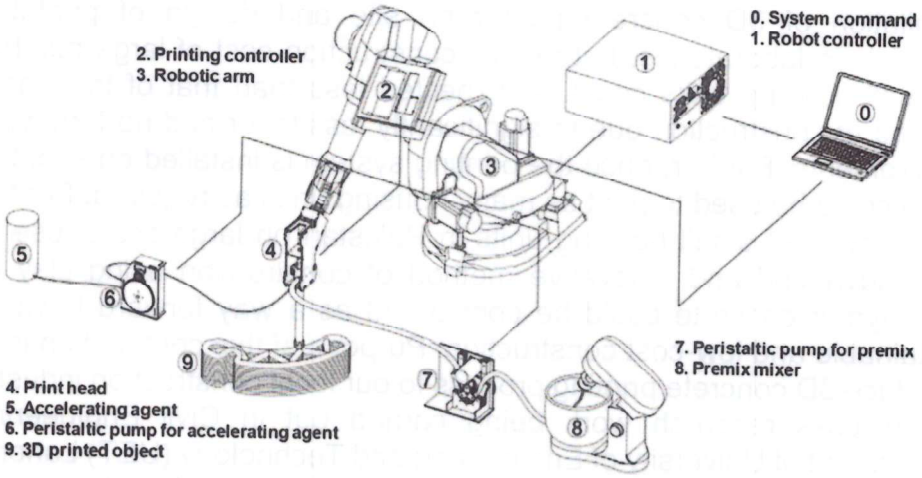


Figure 1: Setup of 3D printing process [3]

2. 3D Printing in Construction Industry: History

In 1997, first effort on cement-based Automatic Manufacturing (A.M) was made [4]. In order to print concrete elements, a thin layer of sand was first deposited which was followed by deposition of cement paste in a certain pattern to glue the sand particles together.

In 1998, a cement material based automatic manufacturing (AM) process called "Contour Crafting", was designed and developed at University of Southern California [5] which is a technique of layered manufacturing in which large scale 3D printer is used to print layer by layer any type of large scale objects having smooth surface finish. This technique made it possible to print real life housing units. Materials such as ceramic slurry, polymer and cement are generally used in this technique. Contour Crafting is also capable of using diverse materials with large aggregates and additives like fiber reinforcement [6]. An important aspect of this technique is to print object with accurate and smooth surfaces with the help of two side trowels which mainly act as two solid planar surfaces [7]. A simple design of the system used in Contour Crafting is shown in Figure-2 taken from reference [8]. Figure-3 represents the printing process of a housing unit through Contour Crafting technique [9].

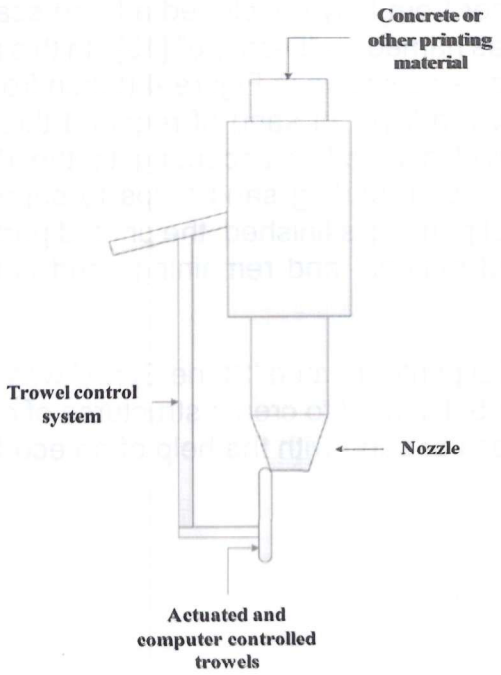


Figure 2: System in Contour Crafting [8]

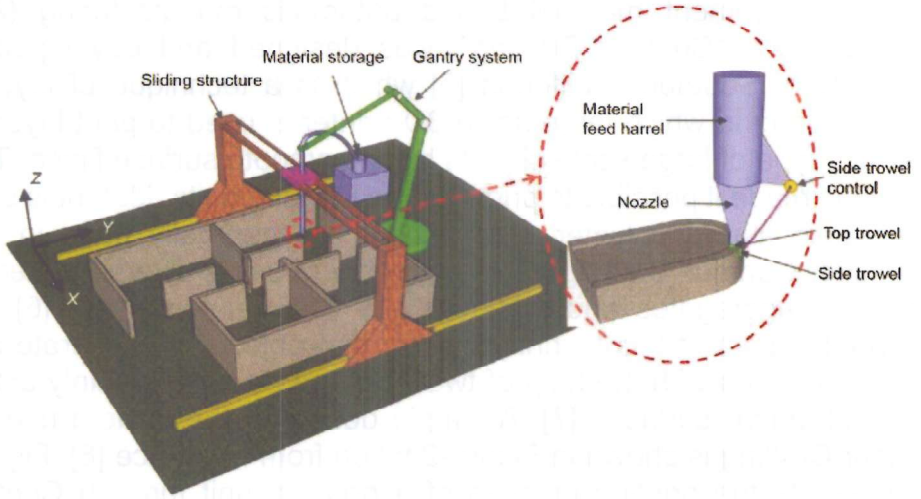


Figure 3: Printing of housing unit using Contour Crafting [9]

In 2007, an Engineer from Italy developed a large scale powder based 3D printer which was named as "D-shape" [10]. In this printer, print head equipped with nozzles as shown in Figure-4 (taken from ref. 9) deposits binding material over a layer of sand of required thickness in order to bind the sand particles together according to the digital prototypes. During this process, surrounding sand helps to support the structure. Once the process of printing is finished, the printed part is taken out from the un-consolidated material and remaining sand is re-used for other printing.

In 2012, a robotic 3D printer named 'Stone Spray' was built in Spain [11] as shown in Figure-5. It aimed to create structures of complex geometry by gluing a mix of soil or sand with the help of an eco-friendly binder.

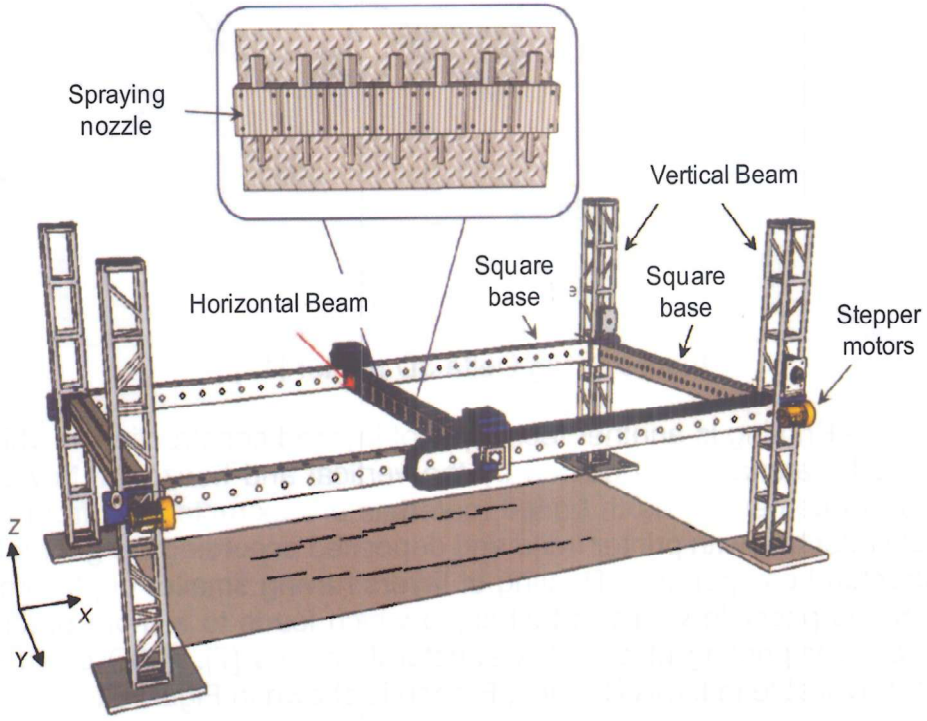


Figure-4 : D-shape printer [9]

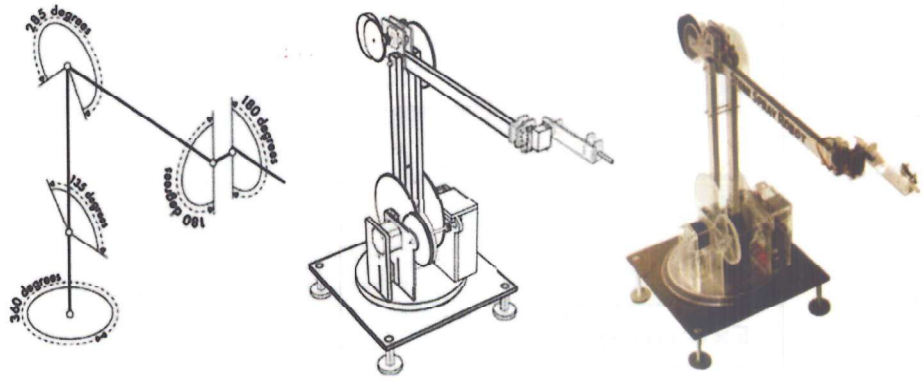


Figure 5: Robotic 3D printer [11]

In 2015, the world advanced saving project (WASP) introduced a huge 3D printer, named Big Delta as shown in Figure-6, which measures 12 m tall and 6 m wide.



Figure 6: Big Delta 3D printer [12]

Concrete Printing is another technique of layered construction in which extruded material is not guided by the vertical and horizontal trowels. Layers of cement or earth based materials are extracted out from the nozzle attached with printer head and deposited according the geometry of structural components. Printing of layers having smaller depth like 4 to 6mm is possible with this technique which leads to a more precise control over printing of complex structural shapes [7]. A 3D concrete printer available in INSA Rennes, France is shown in Figure-7.

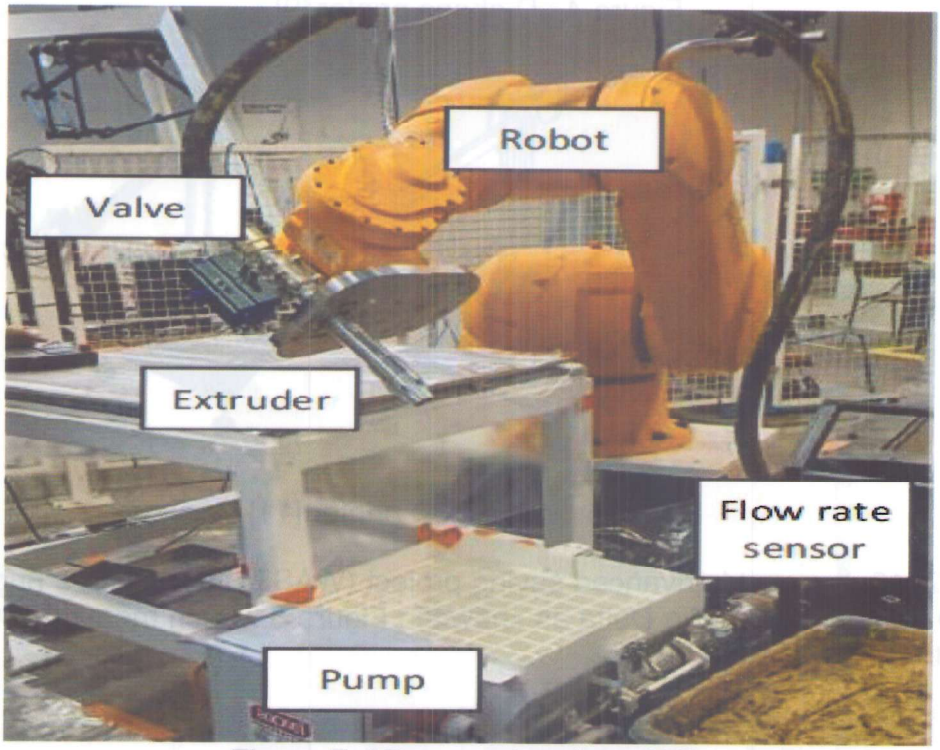


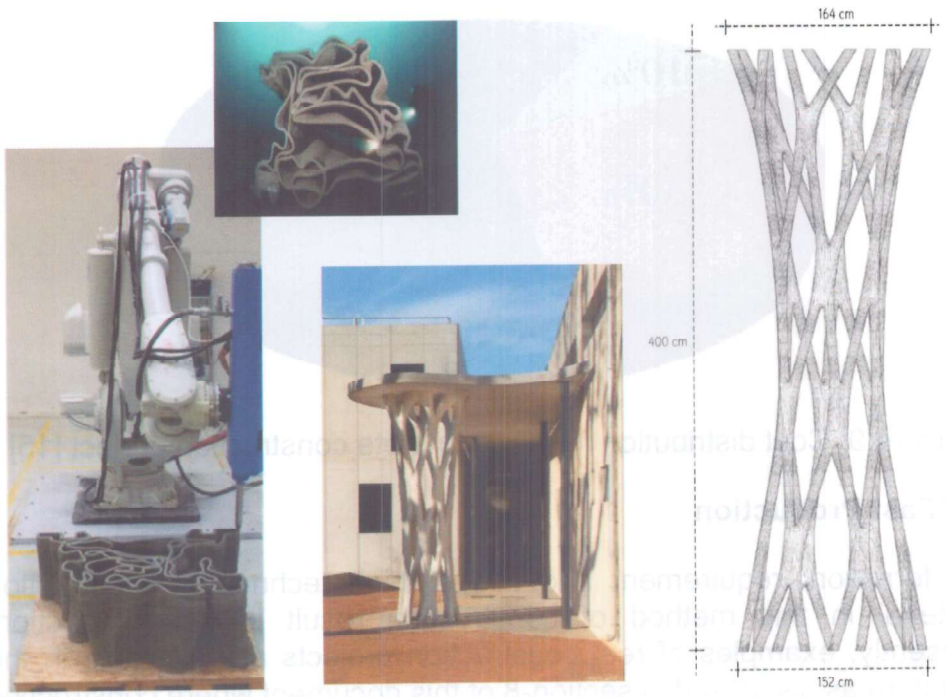
Figure 7: 3D concrete printer [13]

3. Advantages of 3D Concrete Printing (3DCP)

The potential advantages of 3DCP include the following:

3.1 Architectural Freedom

3DCP has made it possible today to build objects of any required complex shape as shown in Figure-8, where it can be observed that artificial coral reefs of complex geometry were printed to restore coral ecosystem. Similarly building columns of complex geometry have also been printed using this technology.



Artificiel Coral Reefs Building Column

Figure 8: Printing of objects of complex geometry [14]

3.2 Cost Reduction

Cost distribution of a new concrete construction project [15] is shown in Figure-9, where it is clear that more than 60% of the project cost is for formwork. Since no formwork is required in 3DCP, it is possible to significantly reduce the total cost of the construction project through this technology.

3.3 Replace Human Labor by Robots

Contrary to other construction methods, main operations involved in construction through 3DCP are performed by the robots and as a result, very less labor is required. Due to this fact, reduction in overall cost of the project is achieved.

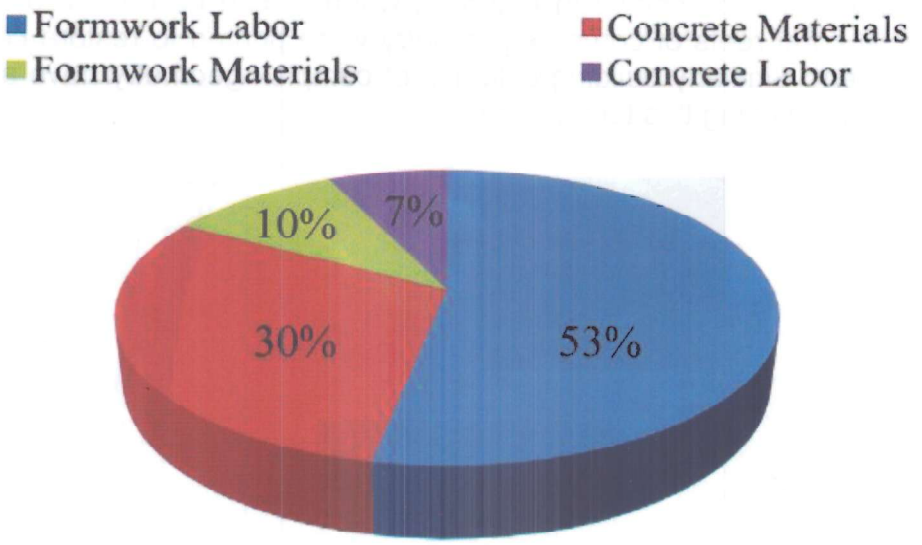


Figure 9: Cost distribution for new concrete construction project [15]

3.4 Fast Production

No formwork requirement and use of high technology construction material in this method of construction result in fast production. Presently, examples of real construction projects are available in the literature as discussed in section-8 of this document where construction work had been completed in days instead of months through the use of 3DCP technology.

3.5 Improved Efficiency and Safety

Since most of the activities in this technology are computer controlled, efficiency of the work and safety on site are very much improved compared to other conventional construction methods currently in practice.

Note: Although above mentioned advantages of 3DCP are obvious but the difficulty in providing required reinforcement in layers of printed

structures has limited the benefits that this innovative construction technique could have been able to offer construction industry [16].

4. Basic Concept of Printable Material Design

For 3DCP, an extrudable concrete having no slump is generally required. Properties of such concrete in fresh and hardened states are affected by following factors [17]:

- Environment (Temperature)
- Print path
- Printing speed
- Shape of nozzle
- Layer thickness
- Geometry

According to [18], following two steps are most essential for 3D printing of cement based materials:

- Conveying step: to convey mixed materials to the nozzle through a delivery system, and this step requires cementitious materials having good pumpability, which indicates how easily mixed materials can be conveyed.
- Deposition step: to deposit materials to print a solid object in layers, and this step requires cementitious materials having good buildability, which indicates how well the printable materials can be stacked stably.

Both terms "*pumpability & buildability*" are usually represented by a single term called *printability* which defines the capacity of a cementitious material to be successfully processed through 3D printing technique. Followings are four key attributes of printability:

1. Extrudability
2. Buildability
3. Interlayer bonding
4. Segregation prevention

4.1 Extrudability

It is the ability of cement based material in the fresh state to be pumped or pass through small nozzles and finally be deposited in a continuous and even filament [16]. To evaluate extrudability, Le *et al* [19] employed a method in which 9-mm wide filaments of 300 mm length are printed as shown in Figure-10. The test result is evaluated as "OK" when the

complete length of 4500 mm (five groups from one to five filaments) is deposited successfully without any problem of blockage or fracture.

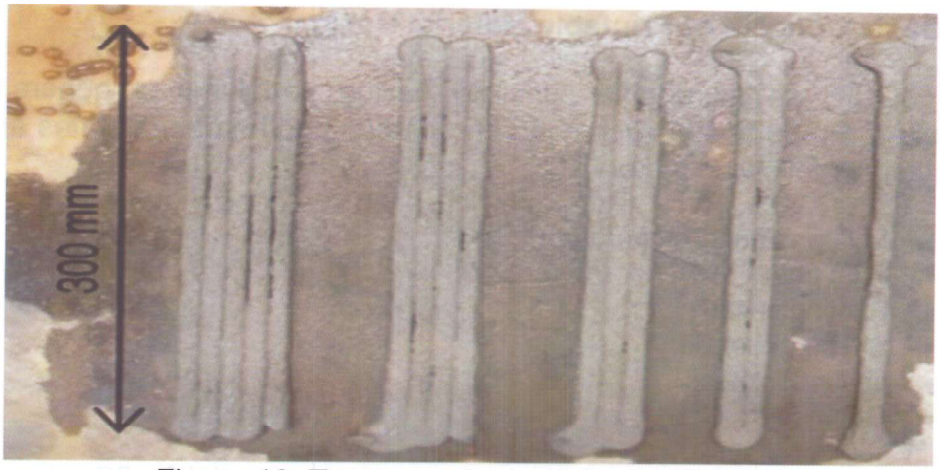


Figure 10: Test to evaluate Extrudability [19]

4.2 Buildability

It consists of quantifying the number of filament layers that may be printed without noticeable deformation in the lower layers due to load from upper layers [20]. It enables the extruded material to be laid down accurately without any change in the filament form, to be hard enough to take the load of further layers without failure (refer to Figure-11) and yet still be appropriate to provide a good bond between layers [9].

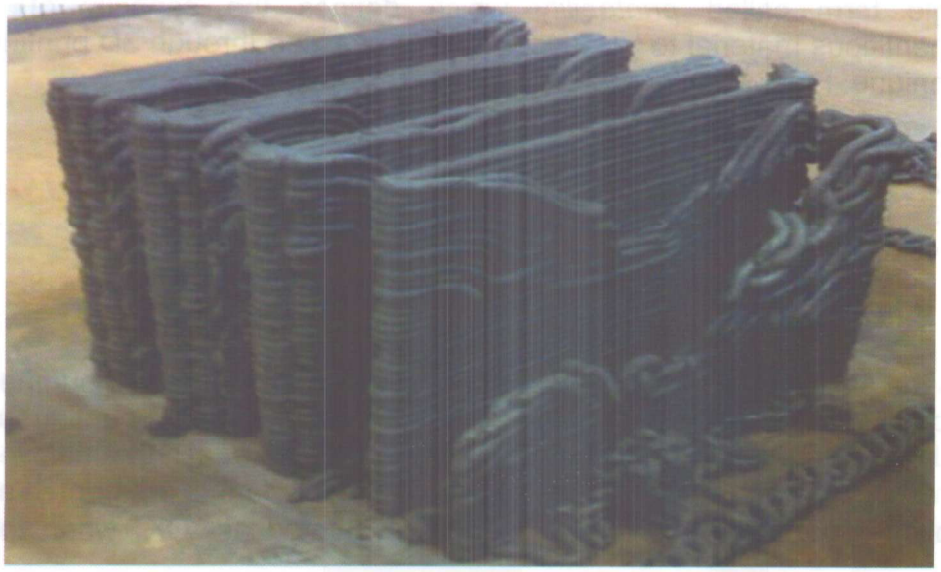


Figure 11: Buildability of concrete mix [19]

Note: It is important to mention here that Extrudability and Buildability are competing factors [16]; High workability supports extrudability while low workability supports buildability. Low workability can have detrimental effect on interlayer bonding and excessively high flow-ability can result in segregation of constituents.

4.3 Inter Layer Bonding

The bond strength between layers is considered as a major weakness of printed concrete. During the extrusion process, creation of micro-flaws in layers may cause stress concentration [19] which ultimately affects the inter-layer bonding. Adhesion between extruded layers is also one of the main factors which controls the inter-layer strength in printed elements and it is a function of time interval between deposited layers, referred to as delay time. In order to make sure that the printed layers gain adequate green strength to support the upper layers, the delay time should be long enough. Also, it should be short enough to guarantee sufficient bond strength between printed layers [21]. Poorly controlled delay time may result in cold joints as shown in Figure-12 at the interface layers [22]. A study carried out by Zareiyan and Khoshnevis [23] showed that interlocking of layers as shown in Figure-13 with key depth of 12 mm and width of 25 mm can improve bond strength between deposited layers.

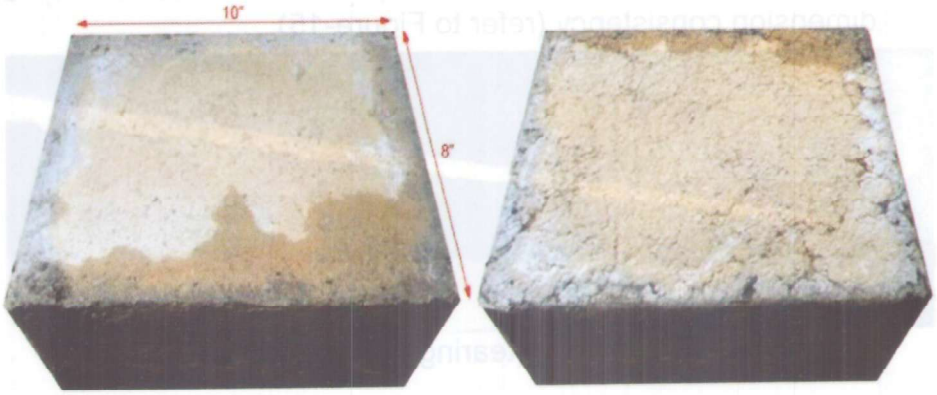


Figure 12: Cold joint formation [22]

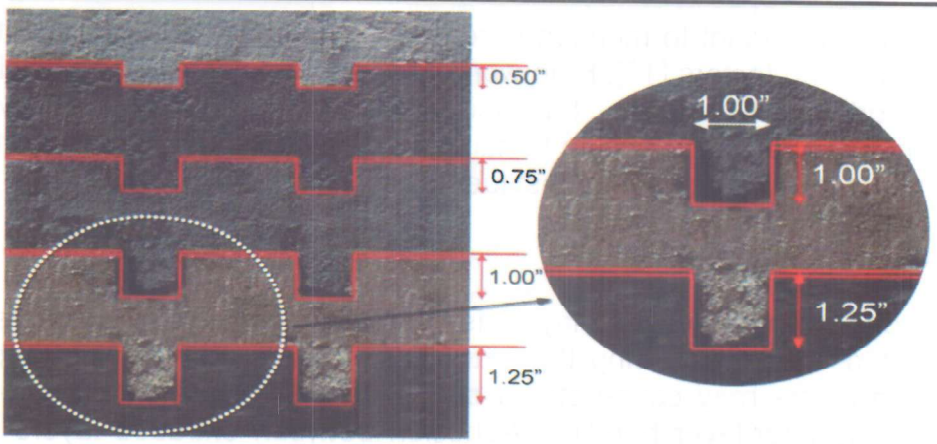


Figure 13: Interlocking of layers [23]

5. Print Quality

For an acceptable printing mixture, following three requirements are to be satisfied [24]:

- ✓ The printed layer must be free of surface defects, including any discontinuity (refer to Figure-14) due to excessive stiffness and inadequate cohesion.
- ✓ The edges of printed layer must be visible and squared versus round edges.
- ✓ The printed layers should satisfy dimension conformity and dimension consistency (refer to Figure-15).

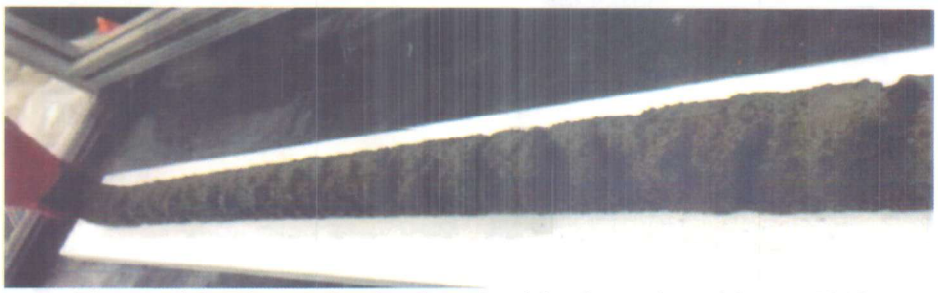


Figure 14: Discontinuity (tearing) in the printed layer [24]



Figure-15 : Variations in width of a single layer [24]

6. Requirement of Yield Stress

During printing of objects, the yield stress of material should increase at least according to the additional weight of each layer placed on top in order to avoid flow out of the lower layers [25]. For an admixed system, the initial yield stress required for good workability depends on the type of super-plasticizer, its dosage and structure. Initial yield stress of material generally ranges from 0.15 k Pa to 0.9 k Pa [25,26].

After extrusion and deposition stages in Figure-16, the structural build-up is controlled by the use of flocculation and / or thixotropic agents, which allows a lower yield stress at the very beginning and a rapid structural build-up right after deposition [27]. Green strength (stage-2 in Figure-16) is the open time during which concretes can still be easily placed and shaped. The duration of the open time is adjusted with the combination of retarders and accelerators [28]. The rapid increase of the yield stress shown as stage-3 in Figure-16 characterizes a crucial point for the 3D printing of structures. For this reason, it is obviously very necessary to investigate the properties of the concrete system particularly shear stress in this time frame [27].

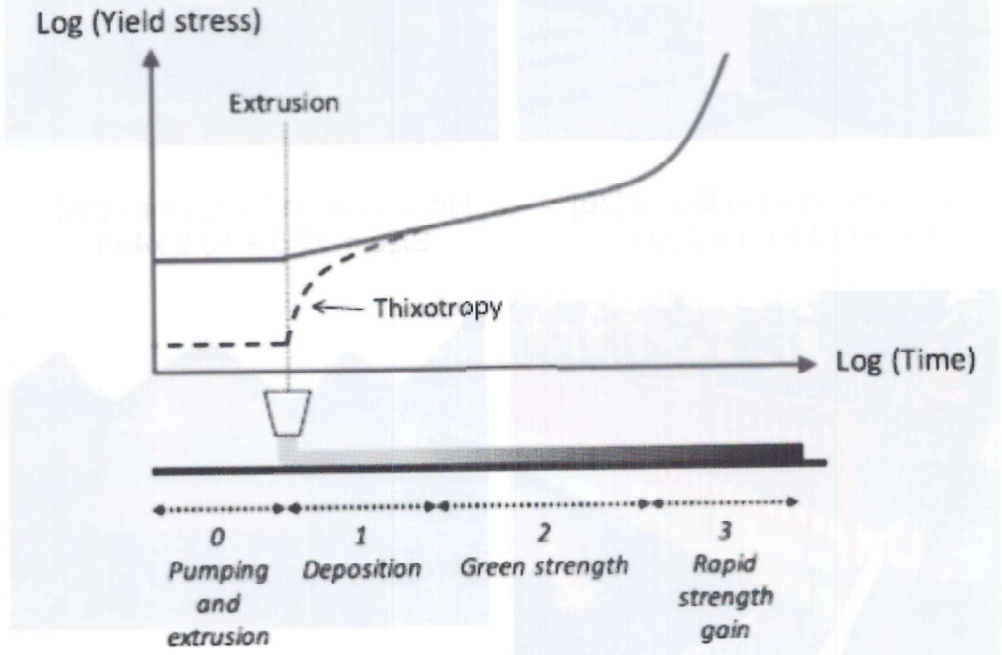


Figure 16: Evolution of yield stress [27]

7. Reinforcement

Although structures are being printed today in many countries as shown in section-8 of this paper but lack of conventional reinforcement in printed concrete and unavailability of certified standards for this construction technique are the two major reasons of underutilization of this innovative technology in real life construction. Few researchers have recently tried to use micro fibers in the mix before extrusion as well as adding fiber reinforcement during the extrusion to enhance the structural performance of printed elements [16,29].

8. Real Projects – Examples



Office building in Dubai [30]
Covered area = 250 m^2



Hotel Suite in Philippines [31]
Size = 12.5 x 10.5 x4 m



3D printed bridge [32]
Netherlands, 2018



Two story house in China [31]
Covered area = 400 m^2



Villa in Suzhou, China [30]
Covered area = 1100 m^2



Five-story apartment, China [30]





Printing of columns and perforated wall panels [33]

9. 3DCP Technology in Pakistan

Current government is planning to build large number of houses for poor families. Time of construction for such projects is generally very important. For the execution of this kind of construction project in short time, innovative technologies like 3DCP could be a good option. Since our local construction industry is not aware of this technology, one of the objectives of this contribution is to introduce construction industry of Pakistan with 3DCP and its advantages. With respect to its application in real projects in Pakistan, research work will be definitely required to be carried out in the public and private academic institutes to formulate the mix design of printable cement based mixes containing local materials. Further, for low cost housing, earth based printable material could be of great importance. A recently carried out research study by A. Perrot *et al* [13] has shown positive results with respective to 3D printing using earth based materials.

Research work on the design and characterization of printable cement and earth materials has already been started in Civil Engineering Department UET Lahore as a part of undergraduate final year project and Master research thesis. Up till now main focus of this work has been to carry out mix design of printable mixes. Second phase will focus on the characterization of printable mixes through different tests such as direct shear test, vane shear test, unconfined compression and tri-axial compression tests. It is important to mention here that under the scope of this work, it is being tried to design and develop a controlled system on small scale to print linear elements for print quality studies.

9.1 Cement Based Mix

Although important information is presently available in the literature regarding different mix designs, but the materials used for such mix designs are generally not available in Pakistan, or if available their characteristics are not same. Therefore, it is required to work for mix design of cement based printable mixes using local available materials. As a pilot research study on this innovative technology in Pakistan, mix design is being carried out using Ordinary Portland Cement (OPC), Chenab sand with maximum particle size of 2mm, limestone powder, silica fume, fly ash obtained from Sahiwal power plant, marble powder, water and high range water reducing admixture. Pictorial presentation of this work is given in Figure-17.

9.2 Earth Based Material

For the mix design of earth based printable mixture, clayey soil, clay mixed with bentonite, cement, rice husk, water and some chemical additions are being used. Pictorial presentation of the initial work regarding the mix design of earth based materials is given in Figure-18. Extrusion of the material was done using silicone gun.



Figure 17: Study of print quality of trial mix (extrusion through silicone gun)

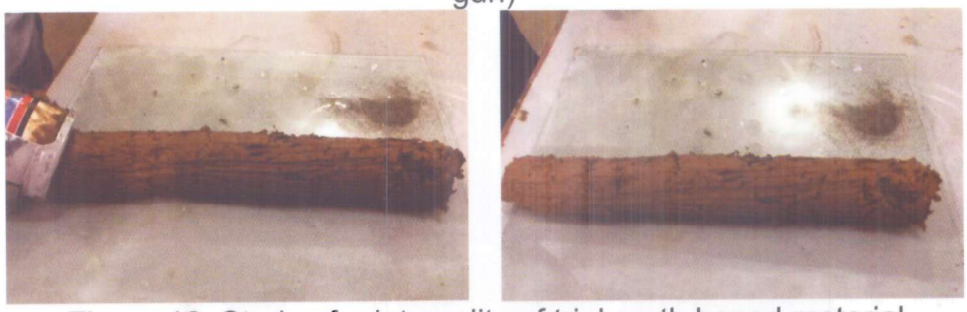


Figure 18: Study of print quality of trial earth based material

10. Concluding Remarks

In this contribution, introduction of an innovative construction methodology known as "3D concrete printing" is presented for the interest of our local construction industry. Basic concept of design of printable material is discussed. Examples of some real structures have been given for the interest of the readers. Although initial cost of such construction method will be high for Pakistan but various advantages of 3DCP discussed in this document over other conventional construction methods may attract the attention of public and private sector

organizations planning to work on project launched by Government of Pakistan to build homes for poor families. Finally, information about the initiative taken by the faculty of Civil Engineering Department UET Lahore regarding the design and development of 3D concrete printing is unveiled. Findings of such research works will help material engineers to design printable mix of required properties for specific projects in Pakistan.

Acknowledgment

Authors are thankful to Dr. Wajahat Hussain Mirza, General Manager, Imporient Chemicals (Pvt.) Ltd. Lahore for providing materials for the experimental work presently being carried out in Civil Engineering Department UET Lahore.

References :

[1]. N. Roussel: *Cement and Concrete Research*, 112 (2018), pp. 76-85

[2]. S. C. Paul, *et al*: *Archives of Civil and Mechanical Engineering*, 18 (2018), pp. 311-319

[3]. C. Gosselin, *et al*: *Materials and Design*, 100 (2016), pp. 102-109

[4]. J. Pegna: *Automation in Construction*, 5(1997) 427-437

[5]. Khoshnevis and Dutton: *Material Technology*, 13 (1998), 53–56

[6]. B. Khoshnevis, *et al*: *Int. J. Industrial and Systems Eng., 1* (2006), 301-320

[7]. S. H. Ghaffar, *et al*: *Automation in Construction*, 93(2018) 1-11

[8]. P. Wu, *et al*: *Automation in Construction*, 68 (2016), pp. 21-31

[9]. M. GuoWei, *et al* : *Science China Technological Sciences*, 61(4) (2018), pp.475-495

[10]. Dini E. D-shape printers. (2007), http://d-shape.com/d-shape-printers

[11]. Designboom: (2012) http://www.designboom.com

[12]. https://www.3dwasp.com/en/giant-3d-printer-bigdelta-wasp-12mt

[13]. A. Perrot, *et al*: *Construction and Building Materials,* 172 (2018), 670-676

[14]. https://www.xtreee.eu

[15]. K. N. Jha: *Tata McGraw Hill, India, 2012*

[16]. Soltan & Li: *Cement and Concrete Composites*, 90 (2018), 1-13

[17]. B. Panda, *et al*: *Materials Letters*, 209 (2017), 146-149

[18]. Y. Weng, *et al*: *Construction and Building Materials*, 163(2018), 600-610

[19]. T. T. Le, *et al: Materials and Structures,* 45 (2012), 1221-1232

[20]. A. Perrot, *et al*: *Materials and Structures,* 49 (2016), 1213–1220

[21]. J. G. Sanjayan, *et a l*: *Construction and Building Materials,* 172 (2018), 468–475

[22]. Zareiyan and Khoshnevis: Automation in Construction, 81 (2017), 112-121

[23]. Zareiyan and Khoshnevis: Automation in Construction, 83 (2017), 212-221

[24]. A. Kazemian, *et al*: *Construction and Building Materials,* 145 (2017), 639–647

[25]. L. Reiter, *et al*: *Cement and Concrete Research,* 112 (2018), 86-95

[26]. R.A. Buswell, *et al*: *Cement and Concrete Research,* 112 (2018), 37-49

[27]. D. Marchon, *et al*: *Cement and Concrete Research,* 112 (2018), 96-110

[28]. E. Lloret, *et al*: *Computer Aided Design*, 60 (2015), 40-49

[29]. Hambach and Volkmer: *Cement and Concrete Composites,* 79 (2017), 62-70

[30]. http://www.winsun3d.com, China

[31]. https://3dprint.com

[32]. T.A.M. Salet, et al: *Virtual and Physical Prototyping*, 13:3, 222-236

[33]. https://www.maisons-france-confort.fr/ (in French)