3D Printing Concrete: A Review

A.R.Krishnaraja¹, K.V.Guru²

¹ Assistant Professor, Department of Civil Engineering, Kongu Engineering College, Perundurai, India- 638060.
² PG Scholar, Department of Civil Engineering, Kongu Engineering College, Perundurai, India - 638060.

*email: guruvenkateswaran97@gmail.com

Abstract: 3D Printing concrete is new developed technology with no reinforcement or by providing reinforcement as like cable in the year 1987. The printing concrete is printed with the printer in different shapes and sizes. Size of aggregate used is very minimum which passes through the nozzle of printer. The strength of 3DPC is tested by compression, flexural, tensile, shear tests for identifying durability, extrudability, workability of printing concrete. The slump flow is carried for finding the flowability of concrete that passes through the nozzle of the printer. Fibers such as polypropylene, PVA, GGBS, Steel were used in addition of mix to increase the strength of 3DPC. Superplasticizers, Fly ash Silica fume, Geopolymer are used in concrete with percentage addition into the mix for raising the strength of the printing concrete. Result shows the strength of PC in different mix proportions along with varying size of specimens. Pumpabality and Buildability of printing concrete is analysed by slump flow test. Reinforcement for this concrete is provided as in form of cables that passes freely through nozzle for printing the concrete.

Keywords: 3D Printing concrete, Engineering cementitious composites, Strain hardening.

1.0 Introduction:

In recent years, performance of concrete is improved by adding admixtures. Addition of admixtures in concrete tends to increase the strength of concrete. Increase in strength of concrete reduces the section size and durability of structures[1]. Engineering cementitious composites(ECC) is a type of HPC that was developed with admixtures such as Fly Ash, fine sand, Poly Vinyl Alcohol(PVA), is recommended for structural and pavement methods, if size of the aggregate increases strength of the concrete decreases[2]. The high strength concrete is tested with samples more than 20 and compressive strength is commonly gained as 150MPa.

In the year 1987, 3D printing technology is introduced as rapid prototyping[3]. Concrete which is built by printing technology said to be printing concrete. Printing concrete in construction makes construction easier, cost efficient. Printing concrete can be made in different shapes without reinforcements. Aggregates used in printing concrete is very much less in size than in normal conventional concrete. Size of aggregate used in printing concrete is taken in mm and µm.
Admixtures Fly Ash, Silica Fume, Geo-polymer are most probably used in printing concrete. Concrete is printed layer-by-layer, layer printed should not change its position.

3D Printing Concrete(3DPC) is new growing technique in construction world, however printing concrete is a new one only the basic two characteristics – workability and extrudability defines the printability flow of concrete. The printing flow of concrete should not block in nozzle and the stiffness of printed layer should not fall down while printing of next layer above printed layer. Ordinary Portland cement is used along with the admixtures to identify the behavior of 3DPC. The determination of slump is identified to get the measure of pumpability and the buildability of printing concrete mixtures. Factors such as water, fine aggregate, fly ash and silica fume are compared with binder ratio analyse the behavior of 3DPC.

External prestressing tendons is inserted to gain tensile capacity and ductility in printing concrete, small idea is being explored to develop system capable as reinforcement while printing. The development of a 3DPC permits flexible reinforcement into the printed concrete filament [5]. The structural behaviour of cables that provided as reinforcement is tested in four point bending tests by three variant types of system cables[4, 5].

The concrete based on geopolymer material is used for printing. Other than concrete based on cement, the use of solution based on highly viscous material such as sodium silicate ends in different extent while blending, creating it hard to see flowability and formability at the same instant. While using of concrete in base of geopolymer material, there is a need for laboratory tool able to test easily the character of the material. There are many trails and studies in geopolymer based concrete by 3D printing [6-8]. Only the fresh properties of a printing mixture are taken into account for frame work. While other required to identify the hardened printing mixture. Developing a small framework for laboratory testing of 3D printing concrete.

Behrokh Khoshnevis first developed Contour Crafting (CC) in 2003 through the use of cemented materials to enhance 3D artefacts on a wide scale[9]. The main task of 3D printing concrete materials is which obtain better flowability to assure continuous pumping and concrete flow through the nozzle. In addition, printing concrete should have good supporting capacity that, in critical terms, is extremely resistant to the load induced without major deformation, the correspondingly printed concrete layer. From the above, additive materials for concrete can be used to create items which vary smaller to larger to complete the buildings. In order to print bigger size of structural parts, common design concepts of printing concrete materials such as viscosity, elasticity, yield stress, plasticity and thixotropy have been developed according to Bingham fluid. The printing concrete is investigated for material behaviour requirements which improve concrete printability[2]. In addition, the 3D printing concrete is tested for compressive strength and flexural strength, and the drying shrinkage is also assessed for 4 months[10].

![Figure 1: a) 4-axis gantry printers, b) 6-axis robotic printers, and c) crane printers [3]](image-url)
This figure 1 shows in Contour crafting process is a small instrument developed for checking by building inner and outer walls. After good results, 3D printer developed in bigger size for practice. 3D printer consists of nozzles; in this nozzle concrete is printed. [11].

![Figure 2: Schematic configuration of 3D printing](image)

Figure 2: Schematic configuration of 3D printing

This figure 2 shows Schematic configuration of 3D printing, that are as follows: 0. Device command; 1. Controller Robot; 2. Controller Printing; 3. Arm Robotic; 4. Head to print; 5. Agent accelerating; 6. Peristaltic Accelerator Pump; 7. Peristaltic Premix Pump; 8. Mixer with Premix; 9. Printed 3D piece.[11]. Volume-The forming process uses a variable cross-section lump material instead of conventionally collecting filaments to achieve a target, meaning the distance, orientation and height.

The target geometry of crosssection of lump substance deposited must be same. In this scenario, the structure shall be printed by more shorter cycles of superpositions of materials, that tend to increase the efficiency of processing. The relation between the traditional 3D printing concrete process and the proposed Volume Forming 3D Concrete Printing(VF3DCP) system is shown in Figure 3.[9]

![Figure 3: (a) 3DCP process and (b) VF3DCP process](image)

Figure 3: (a) 3DCP process and (b) VF3DCP process.[9].

A patented extrusion kit prototype as shown in figure 4 is builted to execute VF3DCP operation. The package is seated on movable portal steel lifting beam, which consists of four types of modules such as Mixing, depositing, steering and nozzle variating with a specially made nozzle which was square in shape.[9].
Four isosceles triangular plates are needed to move centrifugally or centripetally through these plates to achieve precise nozzle of square shape dimension. The nozzle made of square shape will range in size between 0 mm and 25 mm while middle of nozzle stays constant. The variable-module nozzle style is shown in Figure 4a.

**Figure 4a:** (a) Longitudinal section; (b) Bottom view of variable size of square nozzle.

TU / e defines the method of 3D concrete printing (Bos et al. 2016). This machine includes M-Tec Duomix two thousand mixer pump along with linear displacement pump which lays 25 mm hose concrete with 9.0m x 4.5m x 2.8m diameter. 4-DOF gantry robot is shown in figure 5. Printer head has a clear nozzle printed in stainless steel[5].
2. Materials and Mix proportions:

2.1 Materials:

2.1.1. Fly Ash:
Fly ash contains concentrations of silicon dioxide (amorphous as well as crystalline) aluminium oxide and calcium oxide, the main mineral compounds of rock strata containing coal. Fly ash particles are typically spherical in shape and vary between 0.5 μm and 300 μm in scale. ASTM specifies two types of fly ash they are class F and class C. The biggest distinction among these two classes is the quantity of silica, alumina, iron and calcium in ashes. Class F contains less than 7% lime content and Class C contains higher than 20% of lime content. Class F Ash may form a Geopolymer and an activator such as Sodium Silicate may be added, whereas Class C does not add an activator and contains more of Alkali and Silicate materials[12].

2.1.2. Silica Fume:
Silica smoke is a pozzolanic substance that is incredibly strong. ASTM C1240, EN 13263 is a common specification for silica smoke used in cement mixtures. Silica smoke is the ultrafine substance with less than 0.15 μm. SF volumes are around 100 times smaller than that of average scale of cement particles. A bulk density of silica fumes tends to the degree of densification, which varies between 130 and 600 kg/m³. The specific gravity for silica smoke ranges between 2.2 and 2.3. The total area of the silica smoke is determined using the BET system or the nitrogen adsorption system. The surface area varies from 15,000 m² per kg to 30,000 m².

2.1.3. Geopolymer:
In 1978 this term was examined by Joseph Davidovits, Commercially manufactured geopolymers are used for fire and temperature resistant coatings and as additives, high temperature ceramics, new fire resistant fibre composite binders and hazardous waste[13]. The features and purpose of geopolymers are studied more areas of medicine and business as contemporary inorganic, physical, colloid, mineralogy, geology, and in various forms of technology[6]. This is a part of polymer research, chemistry and generation whose administration is one of the key fields of material production. Polymers are normal fabric that is Carbon based polymer[7]. Real polymers contains directions of medicinal polymers as rubber, cellulose, synthetic organic polymers as fabric fabrics, plastics, film, elastomers and real biopolymers are biology, medicine, pharmacy. Raw substances used of silicon based polymers are primarily rock forming minerals such as geological origin[14]. For this cause, geo-polymer and the development of a French research non-profit[15].

2.1.4 Superplasticizers:
Superplasticizers is a high-quality water reducer used as a mixer to produce high-strength concrete. Superplasticizers are chemical compounds capable of creating 15 per cent less water content of concrete[4]. Superplasticizers cause the water content to be decreased by 30% or more. Superplasticizers are slowing down the curing of concrete[16]. Superplasticizers are used in distributed particles needed to enhance the properties of the flow of concrete. Their contribution to concrete makes it possible to minimise the water cement ratio in need of compromising workability of mixture and allows manufacture of self consolidating concrete and high performance concrete[17].

Figure 5: 3D Concrete Printing system at TU/e[5].
increases the efficiency of fresh paste hardening. The strength of the concrete increases by reducing
the water to the cement ratio. Admixtures applied to the concrete slump flow procedure [18].

2.1.5 Sand:
Adding sand to concrete increases sturdiness and reduces time dependent deformations which
include shrinkage and creep[19]. As concrete sets, moisture content will evaporate leaving a few
voids at the back of. If you do not have a positive part of sand on your concrete, the dimensions of the
voids may be big, so is the poor impact to the shape. However, which include excess quantity of sand
in concrete decreases strength. Thus, you need to have superior sand proportion to your design[12].
For the concrete to have the most power in line with the code it must have maximum density or
minimum voids so if we consider the above cases a concrete blend may be organized with the aid of
blending graded metallic, sand, cement and water wherein the metallic is solely answerable for power,
sand fills the distance interior steel packing by using which the voids are reduced and density is
expanded. The cement with the help of water binds the aggregate[20]. So the sand which is non-
reacting is used only for filling the voids. The sand quality fits the gap in gradation.

2.1.6 Fibers:
2.1.6.1 Polypropylene fiber:
Polypropylene is a thermoplastic polymer applied as a part of wide assortment of uses
 together with bundling, substances (e.g., ropes, heat apparel and covers). Polymer cement is a chunk
of amassing of cements that utilizes polymers to supplement bond as a cowl[21]. The types include
polymer-impregnated stable, polymer cement, and Polymer-Portland-bond concrete. The aim of the
examine become to reap maximum power of concrete via the usage of greatest weight of
polypropylene fibers[22]. Fiber reinforced concrete is utilized in a variety of engineering programs
because of its nice and high-quality performance within the industry and production discipline[23].
Polypropylene fiber in concrete blend layout is used for more than one purpose that includes rigid
pavement, self-compacting concrete and other programs. Forty cylinders of polypropylene concrete
had been casted and tested for 7 and 28 days electricity for each compressive and cut up tenstile
power[24]. It was concluded that the widespread development turned into determined in ultimate
compressive electricity after 7 and 28 days. The ideal percentage of Polypropylene fiber turned into
acquired to be 1.5 percent of cement with the aid of quantity[18]. The addition of small amount of
polypropylene advances the mechanical properties of concrete[25].

![Figure 6: Effect Polyporpylene fiber over split tensile strength after 28 days curing.](image)

2.1.6.2 Polyvinyl alcohol (PVA) fiber:
Polyvinyl alcohol is an artificial water soluble polymer. It has the perfect solution
\[ \text{CH}_2\text{CH(OH)} \]. This is used for textiles, and coating branching, papermaking. These are colourless
may be white and odourless. It is rarely supplied as beads[26].

2.1.6.3 Ground granulated blast furnace slag (GGBS):
Ground-granulated blast-furnace slag is generated by the use of quenching cast iron slag (derived
from iron and metal production) from a blast furnace in water or steam to create a glassy, granular
substance which is then dried and ground into the best[7]. The most important additives for blast
furnace slag are CaO (30% to 50%), Al₂O₃ (8% to 24%) SiO₂ (28% to 38%) and MgO (1% to 18%). In the trendy growth of the CaO content of the slag impact material, increased slag basic and increased compressive strength[27]. The contents of MgO and Al₂O₃ demonstrate the pattern as 10% to 12% and 14% respectively, above which no comparable growth can be accomplished[28]. Several compositional ratios or so called hydraulic indexes have been used to compare the structure of the slag with hydraulic pastime; these are often expressed because of the compressive power of the binder[29].

2.2 Mix proportions:
The mix proportions are made in different mixes with different percentage of mixing of admixtures along with normal Portland cement and river sand as well as water to binder ratio. Admixtures such as Silica fume, Superplasticizers, Polypropylene fibers, Ground Granulated Blast Steel Furnace, Poly vinyl alcholol fiber, etc.[24, 28, 30] The percentage of fibers, Portland cement, sand, fly ash, silica fume are mixed in different proportions to conduct test such as compressive strength, young modulus, tensile strength, flexural strength, slump cone, shear strength, triaxial strength, etc., Size of the aggregate varies for each mix, varying size of aggregate plays in changing the strength of the printing concrete[31]. The mix proportion should be in easy flow of concrete in the nozzles of printer, flowability of concrete in printer may resist the gaps forming during the printing process. The size of the aggregate ranges from 1 to 5mm. Diameter of the specimen varies for testing the strength of the printing concrete[8]. The tests are carried out define the mechanical properties.

**Table 1: Mix proportion, Size of aggregate and Materials used**

| S.No. | Mix | Aggregate Size | Ingredients                        | References |
|-------|-----|----------------|------------------------------------|------------|
| 1.    | CEM I, FA, SF | 2mm to 3 mm | Geo-polymer, Fly ash, Calcium sulfaluminate, Silica fume | [13]       |
| 2.    | CEM, FA, Aggregate | 2mm | Fly Ash | [33]       |
| 3.    | CEM I, FA, SF | 4.75mm | Superplasticiser, Flyash, Silica Fume | [4]        |
| 4.    | Portland cement- 5-50% Sand- 5-50% Fly ash- 0.1-30% Silica fume- 0.1-50% Activators - 0.1-15% | 4mm | Portland cement, River sand, Fly ash, Silica fume, Activators | [34]       |
| 5.    | Portland cement- 5-50% Sand- 5-50% Fly ash- 0.1-30% Silica fume- 0.1-50% Activators - 0.1-15% | 5mm | Dia of 0.35 mm and Dia of 0.4 mm steel wire as reinforcement. | [5]        |
| 6.    | Portland cement- 5-50% Sand- 5-50% Fly ash- 0.1-30% Silica fume- 0.1-50% Activators - 0.1-5% | 4mm | Polyurethane (PU) foam | [2]        |
| 7.    | Water/cement ratio of 0.39. Maximum diameter of aggregates is 4 mm. 0.5% in weight of polypropylene short fibres. | 4mm | Polystyrene moulds, Steel rebar reinforcement | [35]       |
| 8 | Geopolymer mortar, Light weight mortar and Fibre-reinforced mortar for concrete printing. In addition to this, recycled glass aggregates and crushed rock dust are added. | [6] |
| 9 | Total cementitious materials content is 600 kg/m³ and water/cement ratio is 0.43. | 2.36mm | Nano-clay, silica fume and fiber | [36] |
| 10 | 21.10%(FA), 42.20%(S), 11.70%(W/C), 17.80%(FA), 49.30%(S), 11.90(W/C), 32.80%(FA), 32.80%(S), 14.90(W/C), 33.30%(FA), 33.30%(S), 13.70(W/C). | Coarse aggregate with size up to 10 mm, straight steel fibres of diameter 0.16 mm | Geopolymer, Blast Furnace Slag, Fly Ash quartz sand, Silica Fume (SF), water glass, water and AE agents. | [7] |
| 11 | Water to cement ratios in the range 0.23 - 0.41. Sand ratios in the range 0.63-0.73. | | | [21] |
| 12 | 54% sand, 36% reactive cementitious compounds and 10% water. | 1mm | Portland cements, Polypropylene fibres. | [22] |
| 13 | OPC (90%) and silica fume (10%), OPC (70%), fly ash (20%) and silica fume (10%), OPC (55%), fly ash (22%) and silica fume (23%), OPC (60–67%), limestone filler (17–20%) and silica fume (17–20%). | | Ordinary portland cement, Fly ash, Silica fume, Limestone filler. | [37] |
| 14 | Fly-ash (class F) 23%, Slag (Ground granulated blast-furnace slag) 5%, Micro silica 3%, Fine (river) sand with maximum 1.18 mm in size 47%, Liquid potassium silicate 15%, Hydroxypropyl methylcellulose (HPMC) 2%. | | Fly ash, Silica fume, River sand, Liquid potassium silicate, Hydroxypropyl methycellulose, Tap water. | [19] |
| 15 | Concrete mixes - C25/30, Cement - 23.69%, Silica Fumes - 21.05%, Sibleco CV32 Sand - 45.31%, Water - 9.30%, Superplasticizer - 0.39%, Accelerator - 0.26% | Silica Fumes, Sibleco Sand, Superplasticiser, Accelerator |
| 16 | Portland cement - 40%, Calclined Clay - 40%, Limestone Filler - 20%, Cement to sand ratio - 1:1.5, W/C ratio - 0.3%, Superplasticiser - 2%, Limestone to Calclined clay ratio - 1:2. | Portland cement, Calclined Clay, Limestone Filler, Superplasticiser. |
| 17 | Silica Fume - 60%, Fibre - 1.18%, Nano Clay - 0.30%, HRWRA - Upto 0.16%, VMA - Upto 0.11%, W/C ratio - 0.43. | Silica Fumes, Polypropylene fibre, Nano Clay |
| 18 | Heat of hydration at 20 °C, Materials at 20 °C for 24 h before using, Crushed Sand - 63μm | Calcium Sulfoaluminate Cement and Ordinary Portland Cement, Crushed sand, Superplasticiser. |
| 19 | Mortar size - 1mm | |
| 20 | C3S - 57.59%, C2S - 14.87%, C3A - 4.10%, C4AF - 13.94% along with portland cements. | Silica sand - 184μm Portland cement of sizes - 39.43 μm, 0.69 μm. |
| 21 | Fly Ash - 19.27%, Slag - 2.14%, Silica Fume - 4.28% | Fly Ash, Slag, Silica Fume |
| 22 | Silica Fume - 0.11% | River sand of size 600μm, Coarse aggregate of size - 1.18mm | Silica Fume |
| 23 | Class (F) fly ash 22.42%, (GGBS) 3.27%, Silica fume 6.54%, River sand 49.0%, Thixotropic additives 0.50%. | Fine aggregate - 0.1mm to 0.6mm, 2mm, Fibres - 3mm, Limestone filler - 0.1μ to 100μ. | Fibres, Limestone filler, Geopolymer, Fly ash, |
| 24 | Fly Ash - 5%, SF - 10%, W/C ratio - 0.4 | River Sand - 1mm | Fly Ash, Silica Fume |
| Table | Composition | Properties | References |
|-------|-------------|------------|------------|
| 25    | Fly Ash - 19.27%, Slag - 2.14%, Silica Fume - 4.28%, K2SiO3 - 10.70%, Water - 4.28%, Sand - 58.88%, Additives - 0.42%. | Max.size < 2mm | Geopolymer, Fly Ash (FA), GGBS, Silica Fume | [27] |
| 26    | Cement - 0.7%, Flyash - 0.2%, Silicafume - 0.1%, Sand - 1.7%, W/C ratio - 0.495%. | River sand - 2.36mm | silica fume, Fly ash (Class F), River sand | [12] |
| 27    | Homogeneous mixes | Cement - 20.29μm, Glass powder - 80.63μm, Gypsum - 30.42μm, Sand - 691.17μm. | Cement, Glass powder, Gypsum | [42] |
| 28    | OPC - 40%, CSA - 60% | Sand - Max.size of 4.75mm | CSA, OPC, River sand | [43] |
| 29    | Portland cement - 55%, Flyash - 30%, Silica Fume - 15%. | Quartz - 0.2mm, Sand - 1mm to 2mm. | Portland cement, Flyash, Silica Fume | [44] |
| 30    | Fly Ash - 5%, LFS - 20%, SF - 10%, River Sand - 100%, Limestone - 100%, W/C ratio - 0.4 | River Sand - 1mm | Fly Ash, Ladle Furnace steel Slag, Silica Fume, Superplasticiser | [17] |
| 31    | Every mix is mixed with by increasing 5% of materials used | River sand - 2mm, Glass fibre - 4mm, Clay - 1.75mm(Length), 3mm(Diameter) | Fly Ash, Ground Granulated Blast Furnace, Silica Fume | [28] |
| 32    | 2% Nano Caly, 2% Silica Fume | | Portland cement, Retarded clay, polycarboxylate based high range water reducer | [45] |
| 33    | Dry mortar is mixed for 2min, after adding water and superplasticiser mixed for 3min | Silica Sand - 120 μm to 212 μm | Portland cement, Fly Ash, Silica Sand, PVA Fibre, Hydroxypropyl Methylcellulose (HPMC) | [26] |
| 34    | Portland cement - (30-40%), Siica Fume - (40-50%), Crystalline silica - 10%, Limestone filler - 10% | Coarse aggregate - less than 4mm dia | Portland cement, Siica Fume, Crystalline silica, Limestone filler | [46] |
| 35    | W/C ratio - 0.51% | Sand - Upto 2mm, Gravel - Upto 8mm | Super plasticizer, Fly ash, Micro Silica fume | [30] |
| 36    | PC - 50%, Clay - 30%, Limestone - 15%, Gypsum - 5% | Fine aggregate - Upto 2mm | Portland cement, Calined Caly, Limestone filler | [47] |
37  Optimal mix | Max - 2mm | Sand, Portland cement, Gravel, Retarders | [48]
38  50% - Cement, 50%- (Limestone Powder, Quartz Powder, Kaolin, Fine aggregate, Superplasticiser) | Max - 4mm | Limestone Powder, Quartz Powder, Kaolin, Fine aggregate, Super plasticizer, Cement | [49]
39  100 - F, 100 - FA, SH- 26, SS- 26, AA- 52 | Sand - 0.3mm | Fly Ash, Fine aggregate, Activators | [14]
40  All together for 2min | | Super plasticizer, Polyproylene fibre | [18]
41  C -1:FA -1:CA -0.5 | CA - 700 μm, FA - 300 μm | Retarder, VMA | [50]
42  70 % Cement, 20% Fly Ash, 10% Silica Fumes, Super plasticizer 1 %, Retarder 0.5%, Micro polypropylene fibers (Length/diameter) 120/0.18, W/C ratio 0.26 | Silica Fume, Fly Ash, Polypropylene fibre, Super plasticizer, Retarders | [24]
43  Optimal mix | River sand - Upto 5mm | Cement, Fine aggregate, Coarse aggregate | [51]
44  Optimal mix | Max. - 5mm | Fly Ash, Silica Fume, Sand, Cement | [52]
45  Nano clay - 2%, Silica Fume - 2% | 2mm Sand | Nano-clay, silica fume | [10]
46  Fly Ash and GGBS with activator 5%, 10%, 15% | | Fly Ash, GGBS | [29]
47  C:S- 1,1:1,2:2,3, Retarders - 1-1.5% | | Retarders | [53]
48  | Siliceous aggregate - Max. size 1mm | Portland cement, Siliceous aggregate, Limestone filler, Polypropylene fibre | [53]
49  C-0.7%, FA- 0.2%, SF- 0.1%, Agg-1.2, W/C ratio-0.46% | Aggregate - Medium 1000μm – 1700μm, Fine 500μm – 1000μm, Super fine 150μm – 710μm | Fly Ash, Silica Fume | [54]

### 3.0 Mechanical properties:

#### 3.1 Pumpability:

Pumpability in concrete maintaining initial properties under pressure refers to stability and mobility. For printing the concrete only the soft materials are preferred, where the soft materials are easy to pump into the nozzles[6]. The soft materials should contain minimum stiffness to maintain its shape, size and densities of concrete[38]. To measure the pumpability of concrete rehometer is used, also the consistency of material should be measured by using Vicat apparatus with the help of needle[33].
3.2 Extrudability:
The extrudability is tested only in fresh properties of cement mortar to quantitatively characterize the material[35]. The squeeze flow method and penetration resistance method are also used to characterize the extrudability of printing concrete. Extrudability is purely based on flowability of printing concrete[28].

3.3 Buildability:
The buildability in printing concrete refers to the quality of the material used for printing the concrete[4]. Buildability of concrete is improved by increasing the layers in concrete and also by creating a cellular type structures[45]. The buildability is measured by the yield stress of concrete. Shapes and size of concrete are also comes under buildability to identify the quality In-order to maximize the life cycle of the concrete [30].

3.4 Workability:
Concrete workability is the assets of freshly mixed concrete that decide the profit and homogeneity with which it can be combined, found, consolidated and completed, as defined in ACI Norm 116R-90 (ACI 1990b)[36]. ASTM describes it as “the resource deciding the effort to manage a newly merged volume of concrete with a limited homogeneity failure.” The workability of concrete depends on several elements that can be described as factors influencing the workability of concrete[12]. Water to cement ratio have a lot of impact on workability[47]. Workability was directly proportional to the ratio between water cement[49]. The rise in the water to cement ratio would enhance concrete’s workability.

3.5 Flowability:
Flowability allows the intercouse of natural foam and formation of even coating at pore wall, and the thixotropy may endorse the molding method through decreasing viscosity, increasing flowability with shear motion all through the intercouse, and ejecting immoderate foam[50].

4.0 Calculation of Yield stress with respect to time:
The time dependent material resistance can be expressed as:[4]

\[
\begin{align*}
\tau_s(t) &= \tau_{D,i} + R_{thix} \times t \\
trf &= \frac{(\tau_s,i - \tau_{D,i})}{R_{thix}} \\
\tau_S(t) &= \tau_S,i + A_{thix} (t - trf)
\end{align*}
\]

parameters as follows:
\(\tau_s(t)\) - Static or apparent yield shear stress of the material attime t after agitation (Pa)
\(\tau_{D,i}\) - Initial dynamic yield shear stress of the material,measured from first rheological test (Pa)
\(\tau_S,i\) - Initial static yield shear stress of the material, measured from first rheological test (Pa)
\(trf\) - Time period over which re-flocculation occurs anddominates shear stress increase (s)
\(R_{thix}\) - Short term re-flocculation rate (Pa/s)
\(A_{thix}\) - Structuration rate (Pa/s)
\(t\) - Time since cessation of agitation (s)
Note: prerequisite \([t\geq trf]\) for Eqn. (1)[4].
5.0 Test and Results:

5.1 Test conducted for printing concrete:

5.1.1 Compressive strength test:

The compressive strength test is done to identify the maximum load taken by the member of the structure [20]. It depends mainly on durability of the structure to witheld the load in the structure. The compressive strength of the printing concrete ranges between 75 and 102MPa. Optimum anisotropic compressive strength of printing concrete with geopolymer ranges between 18.4 to 27.7MPa [27]. Compressive energy values have been measured on mould-cast specimens. The mould-forged specimens were healed and preserved in the fog room (20 ± 2 °C, above ninety-nine percent RH) and studied for day1, day7 and day28 days to control the progress compressive electricity over the period [48]. At the same age, six samples were prepared for each mix pattern. Both samples were tested according to the NEN-EN 196-1 criteria. The loading price has improved to 2.4 kN / s for each trial.

Figure 8: Compressive strength of printing concrete
5.1.2 Flexural strength and Tensile strength test:

Flexural strength test describes the tensile strength of printing concrete, test done by point load test[32, 55]. The prism is used for flexural strength testing of concrete[22]. Modulus of rupture ranges from 10 to 15 % of compressive strength[56]. Flexural strength ranges between 6 to 17MPa and tensile strength ranges from 2.3 to 0.7MPa, reduces due to increase in time of printing adjacent layers[14]. The anisotropic flexural strength with geopolymer ranges between 7.7 to 8.2MPa.
5.1.3 Slump cone test:

Slump test is conducted to measure concrete workability by the measurement of slump. The value of slump should not be in collapse[33]. If water cement ratio is high in concrete the slump value leads to collapse, the slump should be in true slump whereas to maintain the workability of concrete throughout the structure[2]. The slump is tested by compaction of concrete in three layers with 25 blows in the cone, each layer of concrete is tested[7].
5.1.4 Direct shear test:

A direct scissor test is carried out to calculate the shearing properties of soil or rock material, the discontinuity of soil or rock density. The measures are ASTM D 3080 as shown in figure 10i, AASHTO T236 and BS 1377-7:1990, respectively. For rock, the measure is usually constrained due to low shear strength. The scissor examination is performed on a group of three to four specimens. The sample shall be placed in the scissor case, the specimen shall have two supported rings to carry the sample. Stress is added longitudinally to the specimen, and upper ring is steadily drawn until the sample fails, or by an unique pressure. The applied load and strain caused by the sample are reported at time intervals to calculate the stress-stress curve for each constrained stress. 3 to 4 samples are tested under different pressures to assess the shear strength. Direct shear experiments can be conducted under a variety of conditions. The sample is usually saturated before the measurement, as well as the in-situ moisture content of the measurement. The degree of strain can be varied in order to obtain a test of undrained or drained conditions. The examination using a direct shear system measures the consolidated shear strength of the soil content under direct shear[41].

The features of a direct shear test than other shear tests are the consistency of the set-up. Advantages must be measured against the difficulties of calculating pore-water pressure while operating under undrained conditions, potentially high outcomes from pressuring the malfunction plane to occur at a particular spot.
Figure 10i: Schematic diagram for a typical direct shear test (ASTM D3080/D3080M-11)

Figure 10j: Direct shear stress apparatus

Figure 10k: Shear box used in direct shear test

Figure 10l: Direct shear test
5.1.5 Ultra sonic pulse velocity method:

This test emerges as finished based mostly on NEN-EN 12504-4. A Pundit ultrasonic pulse rate research equipment that could relay and get conserve of longitudinal wave (P-wave) appear as used. In order to preserve the normal test period of the green energy check, the simple mortar specimen was checked within 30mins to 4hrs. As seen in Figure 10m, the ultrasonic pulse speed test system is fitted with a transmitter, receiver and steel rectangular mould with inner length (250 mm), width (50 mm) and height (one hundred and sixty mm). The transmitter and receiver were placed and mounted on either side of the mould at a distance between 50 mm. While pouring the clean mortar into the mould, it was compacted by jolting 5 instances to the homogeneous country. The thin plastic layer that has been adjusted to cover the sample to avoid water loss to a degree inside the test. Within the length of the test (four h), one P-wave is sent in line with 2d. With the hardening of mortar, the transmitting time of P-wave have become getting shorter. For every mix layout, three instances of repeated ultrasonic pulse tempo test had been performed to get the common give up result[47]. All assessments were carried out in similar environmental conditions with phase 2.

5.1.6 Penetration test:

Automated Vicat equipment was used to assess the improvement of stiffness and to set time for different mixing designs. To check the structural actions of the cementitious compounds. A penetration tolerance take a look at by Ma et al. In this article, the complete check was carried out below the NEN-EN 196-3 criteria. Until initial set (penetration strength > 36.5 mm), the Vicat needle dropped every 10 minutes. When the depth was equivalent or less than 36.5 mm, the next time is shortened to five minutes. Overall, there were forty-four declines for each specimen.[47].
5.1.7 Extrusion test:

The objective of this check is to measure alternative extrusion tension with the assistance of the use of various mixtures at one time. As seen in Figure 2, 4 stainless steel parts are used in the ram extruder: a stand, a prolonged spherical die and the piston. The Instron customary testing unit that can apply the extrusion pressure and file the test results is based on the ram extruder. 1 L of sparkling mortar that was changed to prepared for each test.

The appropriate quantity (about 0.16 L) of fresh content changed to stuffed into the barrel after the mixing process and expired. The closing fabric was collected into a lined plastic bag right away. Before acting the extrusion check, a Fluon ring was inserted inside the piston to decrease the pressure between the piston and the barrel, the floor of the piston. Using the actuator, the check was controlled at a predefined speed for a given displacement. The pre-test begins with a 0 mm to 56.5 mm displacement. Subsequently, special speeds (2, 1 and 0.5 mm / s) were continuously completed to allow adequate shear pressure to be exerted within the fabric. Record readings were taken from a displacement of 56.5 mm to 70 mm at a loading charge of 0.25 mm / s. 13.5 mm has been found to be long enough to bring a constant-country extrusion regime below the velocity of zero.25 mm / s.

Finally, the test stopped at 2 mm / s with a gross displacement of 83.5 mm. Overall, the length of the evaluation was about 2 minutes. The review can be terminated in advance if the mixture has a limited initial set time. In order to achieve typical outcomes, three repetitive evaluations have been carried out for each mix layout. This measure is completely below the same environmental situation. An high clarity camera is kept to make pictures of the very last extrusion exam. These filaments were used to test the first class printing of the tested combos[39].
5.1.8 Point bending test:

The 4-factor bending flexural test offers values of elastic modulus in bending, flexural pressure and the flexural strain-strain reaction of the fabric. This test may be very much like the 3-factor bending flexural test. The fundamental distinction is the addition to fourth bearing of the beam among 2 loading points, which were kept below most strain, in place of most effective the cloth right beneath the relevant bearing in the case of 3 point bending. The difference in high importance whilst reading materials, in which the number and seriousness of flaws uncovered to the maximum stress was straightly related to flexural electricity[5]. Comparing with three point bending flexural check, there are not any shear forces within the 4-point bending flexural check inside the area among the two loading pins. The 4-factor bending check is therefore in particular appropriate substances that can't face up to shear stresses thoroughly. It is one of the maximum extensively used apparatus to characterize fatigue and flexural stiffness of asphalt mixtures[5].

![Figure 10q: Extrusion test](image)

![Figure 10r: 4-Point bending test](image)
5.2 Results:

The strength of Printing concrete is varies with proportion of mix, size of the aggregate used, percentage of mixing of concrete with different admixtures in different percentage. Mechanical properties of concrete changes with respect to the strength attained by the printing concrete are described in the table 2.

Table 2: This table shows the test conducted to the printing concrete, size of the specimen

| S.No | References | Tests                      | Specimens                                      |
|------|------------|----------------------------|------------------------------------------------|
| 1    | [2]        | Tensile strength           | Ø 0.35 mm fishing line and Ø 0.4 mm steel wire |
|      |            | 4- point bending test      |                                                |
| 2    | [13]       | Flexural strength          | 100mm x 100mm x 400mm                          |
|      |            | Tensile strength           | 100mm x 100mm x 400mm                          |
| 3    | [33]       | Slump flow                 | Slump cone (100 x 200 x 300mm)                 |
| 4    | [4]        | Tensile strength           |                                                  |
|      |            | 4-Point bending LVDT       |                                                |
| 5    | [34]       | Slump cone test            | 30cm x 20cm x 10cm                             |
| 6    | [5]        | Slump flow                 | 100 x 200 x 300mm                              |
|      |            | Compression strength       |                                                |
| 7    | [35]       | Compression strength       |                                                  |
|      |            | Flexural strength          |                                                |
|      |            | Tensile strength           |                                                |
| 8    | [36]       | Workability                | 38.1mm x 25.4mm                                |
| 9    | [7]        | Slump flow                 | 100 x 200 x 300mm                              |
| 10   | [21]       | Flexural strength          |                                                  |
|      |            | Compression strength       |                                                |
|   |   |   |
|---|---|---|
|11 | [22] | Compression strength  
Flexural strength |
|12 | [37] | Fresh properties |
|13 | [19] | Compression strength  
Flexural strength  
Tensile strength |
|14 | [38] | Extrudability |
|15 | [16] | Shape stability |
|16 | [39] | Compression strength  
25 x 25 x 25mm |
|17 | [20] | Compression strength  
20 x 20 x 20mm |
|18 | [23] | Shape stability |
|19 | [8] | Compression strength  
Tensile strength  
50 x 50 x 50mm  
50 x 50 x 100mm |
|20 | [40] | Compression strength  
Tensile strength  
1m x 1.40m x 20mm  
1m x 1.40m x 20mm |
|21 | [41] | Shear stress |
|22 | [27] | Compression strength |
|23 | [12] | Shrinkage  
Durability  
Each layer is of 15mm thick  
Each layer is of 15mm thick |
|24 | [42] | Compression strength  
Flexural strength  
Density  
40 x 40 x 40mm  
40 x 40 x 160mm  
40 x 40 x 160mm |
|25 | [43] | Shear strength  
Torsion bond strength |
|26 | [44] | Compression strength  
Flexural strength  
25 x 25 x 25mm  
25 x 25 x 40mm |
|27 | [17] | Compression strength  
Slump flow  
40 x 40 x 40mm  
100 x 200 x 300mm |
|28 | [28] | Fresh property |
|29 | [45] | Slump flow  
Rheometer  
Green strength  
100 x 200 x 300mm  
100 x 100mm  
100 x 100mm |
| No. | Ref. | Property                                | Specification                                      |
|-----|------|-----------------------------------------|---------------------------------------------------|
| 30  | [26] | Tensile strength                        | 40 x 40 x 160mm                                    |
|     |      | Fresh property                          |                                                   |
|     |      | Cone - Bottom-100mm dia, Top-70mm dia, Height - 60mm |
| 31  | [46] | Contour crafting                        | 40 x 40 x 160mm                                    |
| 32  | [30] | Yield stress                            | 150mm width, 50mm height                          |
|     |      | Slump flow                              | 100 x 200 x 300mm                                 |
| 33  | [47] | Compression strength                    | 100 x 100 x 100mm                                 |
|     |      | Penetration strength                    | 125 x 34mm                                        |
|     |      | Green strength                          | 125 x 34mm                                        |
|     |      | Extrusion                               | 125 x 34mm                                        |
|     |      | Ultra sonic pulse velocity              | 125 x 34mm                                        |
| 34  | [48] | Compression strength                    | 50 x 50 x 50mm                                    |
| 35  | [49] | Compression strength                    | 40 x 40 x 40mm                                    |
| 36  | [14] | Flexural strength                       | 160 x 40 x 13.33mm                                |
|     |      | 3-Point bending stress                  | 160 x 40 x 13.33mm                                |
| 37  | [18] | Flexural strength                       | 30 x 30 x 120mm                                   |
| 38  | [50] | Slump flow                              | 100 x 200 x 300mm                                 |
|     |      | Interlayer bond strength                | 400 x 50mm                                        |
| 39  | [24] | Compression strength                    | 35 x 35 x 35mm                                    |
|     |      | Flexural strength                       | 35 x 35 x 120mm                                   |
|     |      | Tensile bond strength                   | 35 x 35 x 120mm                                   |
|     |      | Density                                 | 35 x 35 x 120mm                                   |
|     |      | Shrinkage                               | 35 x 35 x 120mm                                   |
| 40  | [51] | Uniaxial compression strength           | 100 x 100 x 100mm                                 |
| 41  | [52] | Compression strength                    | 50 x 50 x 50mm                                    |
| 42  | [10] | Compression strength                    | 50 x 50 x 50mm                                    |
|     |      | Flexural strength                       | 500 x 500 x 110mm                                 |
| 43  | [29] | Yield stress                            | 150 x 50mm                                        |
|     |      | Slump flow                              | 100 x 200 x 300mm                                 |
| 44  | [53] | Plasticity                              |                                                   |
|     |      | Viscosity                               |                                                   |
| 45  | [25] | Triaxial compression strength           | 140 x 70mm                                        |
| 46  | [29] | Compression strength                    | 30 x 30 x 30mm                                    |
|     |      | Flexural strength                       | 150 x 30 x 60mm                                   |
5.3 Discussions:
The strength of printing concrete is discussed to get a general idea about the load. The strength of concrete should ranges between the values as shown in the table 3.

| S.No. | Tests            | Strength | Units |
|-------|------------------|----------|-------|
| 1.    | Compressive strength | 72 to 102 | MPa   |
| 2.    | Flexural strength  | 6 to 17   | MPa   |
| 3.    | Tensile strength  | 2.3 to 0.7 | MPa   |

6.0 Conclusion:
From this study, Printing concrete can be come into practice as high performance concrete. The Flexural strength, Compressive strength, Shear strength, Tensile strength varies among mix ratio of concrete. The strength of concrete increases with addition of fibers and activators in the concrete, the flowability of concrete should be maintained till the completion of design. Printing concrete can be printed in different shapes and designs.

- Maximum size of nozzle is 25mm, maximum size of aggregate is 5mm and generally 2 to 4mm size is used for mixing of concrete.
- Fibers are used in 1 to 15% to increase the strength of concrete, raise in percentage of flyash in concrete reduces the compressive strength in concrete.
- The printing concrete tested commonly with mix of portland cement and sand of minimum size as well as fibers and super plasticizers as activators in 3DPC.
- Printing concrete reduces the time period of construction of new building.
- The particle size of aggregate is taken in mm and μm.
- Maximum height of each layer is 35 mm.

7.0 Summary:
The review says, Strength of 3D Printing concrete is analysed with ECC, fibres is analysed. Use of 3DPC is explained in detail. Up to date there is no more work is made with 3DPC in India. This review gives a clear idea for use of 3D Printing concrete in India.

References:
[1] Costa F B P d, Righi D P, Graeff A G and Silva Filho L C P d 2019 Experimental study of some durability properties of ECC with a more environmentally sustainable rice husk ash and high tenacity polypropylene fibers Construction and Building Materials 213 505-13
[2] Furet B, Poullain P and Garnier S 2019 3D printing for construction based on a complex wall of polymer-foam and concrete Additive Manufacturing
[3] Paul S C, van Zijl G P A G, Tan M J, Gibson I, Campbell R I and Campbell R I 2018 A review of 3D concrete printing systems and materials properties: current status and future research prospects Rapid Prototyping Journal 00-
[4] Kruger J, Zeranka S and van Zijl G 2019 3D concrete printing: a lower bound analytical model for buildability performance quantification Automation in Construction 106 102904
[5] Bos F P, Ahmed Z Y, Wolf s R J and Salet T A 2018 High Tech Concrete: Where Technology and Engineering Meet: Springer) pp 2484-93
[6] Tay Y W D, Panda B, Paul S C, Noor Mohamed N A, Tan M J and Leong K F 2017 3D printing trends in building and construction industry: a review Virtual and Physical Prototyping 12 261-76
[7] Hirayama Y, Zhang J and Kawahara Y 2019 A method to evaluate the formability and fluidity of concrete based materials for 3D printing. In: Proceedings of the ACM Symposium on Computational Fabrication: ACM) p 7
[8] Panda B, Tay Y W D, Paul S C and Tan M J 2018 Current challenges and future potential of 3D concrete printing: Aktuelle Herausforderungen und Zukunftspotenziale des 3D Druckens bei Beton Materialwissenschaft und Werkstofftechnik 49 666-73

[9] Xu J, Ding L, Cai L, Zhang L, Luo H and Qin W 2019 Volume-forming 3D concrete printing using a variable-size square nozzle Automation in Construction 104 95-106

[10] Zhang Y, Zhang Y, She W, Yang L, Liu G and Yang Y 2019 Rheological and harden properties of the high-thixotropy 3D printing concrete Construction and Building Materials 201 278-85

[11] Gosselin C, Duballet R, Roux P, Gaudilliére N, Dirrenberger J and Morel P 2016 Large-scale 3D printing of ultra-high performance concrete – a new processing route for architects and builders Materials & Design 100 102-9

[12] Tay Y W D, Li M Y and Tan M J 2019 Effect of printing parameters in 3D concrete printing: Printing region and support structures Journal of Materials Processing Technology 271 261-70

[13] Buswell R A, de Silva W L, Jones S Z and Dirrenberger J 2018 3D printing using concrete extrusion: A roadmap for research Cement and Concrete Research 112 37-49

[14] Al-Qutaifi S, Nazari A and Bagheri A 2018 Mechanical properties of layered geopolymer structures applicable in concrete 3D-printing Construction and Building Materials 176 690-9

[15] <IJCIET_09_04_149.pdf>

[16] Khalil N, Rémond S, Baz B and Aouad G 2018 Characterization of 3D Printing Mortars Made with OPC/CSA Mixes. In: RILEM International Conference on Concrete and Digital Fabrication: Springer) pp 53-60

[17] Papachristoforou M, Mitsopoulos V and Stefanidou M 2018 Evaluation of workability parameters in 3D printing concrete Procedia Structural Integrity 10 155-62

[18] Li Z, Wang L and Ma G 2018 Method for the enhancement of buildability and bending resistance of 3D printable tailing mortar International Journal of Concrete Structures and Materials 12 37

[19] Panda B, Paul S C and Tan M J 2017 Anisotropic mechanical performance of 3D printed fiber reinforced sustainable construction material Materials Letters 209 146-9

[20] Xia M, Nematollahi B and Sanjayan J 2018 Compressive strength and dimensional accuracy of portland cement mortar made using powder-based 3D printing for construction applications. In: RILEM International Conference on Concrete and Digital Fabrication: Springer) pp 245-54

[21] Paul S C, van Zijl G P, Tan M J and Gibson I 2018 A review of 3D concrete printing systems and materials properties: Current status and future research prospects Rapid Prototyping Journal 24 784-98

[22] Bos F, Wolfs R, Ahmed Z and Salet T 2016 Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing Virtual and Physical Prototyping 11 209-25

[23] Kazemian A, Yuan X, Meier R, Cochran E and Khoshnevis B 2017 Construction-scale 3D printing: shape stability of fresh printing concrete. In: ASME 2017 12th International Manufacturing Science and Engineering Conference collocated with the JSME/ASME 2017 6th International Conference on Materials and Processing: American Society of Mechanical Engineers) pp V002T01A11-VT01A11

[24] Lediga R and Kruger D 2017 Optimizing concrete mix design for application in 3D printing technology for the construction industry. In: Solid State Phenomena: Trans Tech Publ) pp 24-9

[25] Wolfs R, Bos F and Salet T 2019 Triaxial compression testing on early age concrete for numerical analysis of 3D concrete printing Cement and Concrete Composites 103344

[26] Yu J and Leung C K 2018 Impact of 3D Printing Direction on Mechanical Performance of Strain-Hardening Cementitious Composite (SHCC). In: RILEM International Conference on Concrete and Digital Fabrication: Springer) pp 255-65

[27] Panda B, Mohamed N A N and Tan M J 2018 Effect of 3D printing on mechanical properties of fly ash-based inorganic geopolymer. In: International Congress on Polymers in Concrete: Springer) pp 509-15
[28] Panda B and Tan M J 2018 Experimental study on mix proportion and fresh properties of fly ash based geopolymer for 3D concrete printing Ceramics International 44 10258-65

[29] Panda B, Singh G B, Unluer C and Tan M J 2019 Synthesis and characterization of one-part geopolymers for extrusion based 3D concrete printing Journal of Cleaner Production 220 610-9

[30] Mechtcherine V, Nerella V N, Will F, Näther M, Otto J and Krause M 2019 Large-scale digital concrete construction–CONPrint3D concept for on-site, monolithic 3D-printing Automation in Construction 107 102933

[31] Chen Y, Chaves Figueiredo S, Yalçinkaya Ç, Çopuroğlu O, Veer F and Schlangen E 2019 The effect of viscosity-modifying admixture on the extrudability of limestone and calcined clay-based cementitious material for extrusion-based 3D concrete printing Materials 12 1374

[32] <Flexural performance of hybrid fiber reinforced concrete beams using textile and steel fiber.pdf>

[33] Tay Y W D, Qian Y and Tan M J 2019 Printability region for 3D concrete printing using slump and slump flow test Composites Part B: Engineering 106968

[34] Costanzi C B, Ahmed Z, Schipper H, Bos F, Knaack U and Wolfs R 2018 3D Printing concrete on temporary surfaces: The design and fabrication of a concrete shell structure Automation in Construction 94 395-404

[35] Asprone D, Auricchio F, Menna C and Mercuri V 2018 3D printing of reinforced concrete elements: Technology and design approach Construction and Building Materials 165 218-31

[36] Kazemian A, Yuan X, Meier R and Khoshnevis B 2018 A framework for performance-based testing of fresh mixtures for construction-scale 3D printing. In: RILEM International Conference on Concrete and Digital Fabrication: Springer) pp 39-52

[37] Chen Y, Veer F, Çopuroğlu O and Schlangen E 2018 Feasibility of Using Low CO 2 Concrete Alternatives in Extrusion-Based 3D Concrete Printing. In: RILEM International Conference on Concrete and Digital Fabrication: Springer) pp 269-76

[38] Kuzmenko K, Gaudilliè re N, Feraillé A, Dirrenberger J and Bavero L 2019 Assessing the Environmental Viability of 3D Concrete Printing Technology. In: Design Modelling Symposium Berlin: Springer) pp 517-28

[39] Duballet R, Bavero L and Dirrenberger J 2017 Classification of building systems for concrete 3D printing Automation in Construction 83 247-58

[40] Lindemann H, Gerbers R, Ibrahim S, Dietrich F, Herrmann E, Dröder K, Raatz A and Kloft H 2018 Development of a Shotcrete 3D-Printing (SC3DP) Technology for Additive Manufacturing of Reinforced Freeform Concrete Structures. In: RILEM International Conference on Concrete and Digital Fabrication: Springer) pp 287-98

[41] Jayathilakage R, Sanjayan J and Rajeev P 2019 Direct shear test for the assessment of rheological parameters of concrete for 3D printing applications Materials and Structures 52 12

[42] Vaitkevičius V, Serelis E and Kersvičius V 2018 Effect of ultra-sonic activation on early hydration process in 3D concrete printing technology Construction and Building Materials 169 354-63

[43] Zareiyan B and Khoshnevis B 2017 Effects of interlocking on interlayer adhesion and strength of structures in 3D printing of concrete Automation in Construction 83 212-21

[44] Nerella V N, Hempel S and Mechtcherine V 2019 Effects of layer-interface properties on mechanical performance of concrete elements produced by extrusion-based 3D-printing Construction and Building Materials 205 586-601

[45] Zhang Y, Zhang Y, Liu G, Yang Y, Wu M and Pang B 2018 Fresh properties of a novel 3D printing concrete ink Construction and building materials 174 263-71

[46] Gosselin C, Duballet R, Roux P, Gaudilliè re N, Dirrenberger J and Morel P 2016 Large-scale 3D printing of ultra-high performance concrete—a new processing route for architects and builders Materials & Design 100 102-9

[47] Chen Y, Li Z, Chaves Figueiredo S, Çopuroğlu O, Veer F and Schlangen E 2019 Limestone and Calcined Clay-Based Sustainable Cementitious Materials for 3D Concrete Printing: A Fundamental Study of Extrudability and Early-Age Strength Development Applied Sciences 9 1809

[48] Malaeb Z, Hachem H, Tourbah A, Maalouf T, El Zarwi N and Hamzeh F 2015 3D concrete printing: machine and mix design International Journal of Civil Engineering 6 14-22
[49] Skibicki S, Kaszyński M and Techman M 2018 Maturity testing of 3D printing concrete with inert microfiller. In: MATEC Web of Conferences: EDP Sciences) p 03008

[50] Marchment T and Sanjayan J 2018 Method of Enhancing Interlayer Bond Strength in 3D Concrete Printing. In: RILEM International Conference on Concrete and Digital Fabrication: Springer) pp 148-56

[51] Tian W and Han N 2018 Pore characteristics (> 0.1 mm) of non-air entrained concrete destroyed by freeze-thaw cycles based on CT scanning and 3D printing Cold Regions Science and Technology 151 314-22

[52] Tay Y W, Panda B, Paul S C, Tan M J, Qian S Z, Leong K F and Chua C K 2016 Processing and properties of construction materials for 3D printing. In: Materials Science Forum: Trans Tech Publ) pp 177-81

[53] Zhu Y, Wen C K, Xu G D, Liu D and Chen J 2018 The Preparation and Performance of the Cement-Based Concrete 3D Printing Materials. In: Materials Science Forum: Trans Tech Publ) pp 131-5

[54] Ting G H A, Tay Y W D, Qian Y and Tan M J 2019 Utilization of recycled glass for 3D concrete printing: rheological and mechanical properties Journal of Material Cycles and Waste Management 1-10