# 3D CONCRETE PRINTING: VARIETY OF AGGREGATES, ADMIXTURES AND SUPPLEMENTARY MATERIALS


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*This review paper provides a report on the up-to-date research on the 3D printing technology for the concrete in terms of materials. It reviews the required characteristics of concrete rheology, printing process and discusses the challenges for reaching compatible mix proportions using eco-friendly binders, aggregate, and chemical admixtures. The recent research on the durability behaviour of 3D printed concrete needs future research and identification.*

**Keywords:** concrete 3D printing; extrusion; printable concrete; rheology; printing process parameters; durability

## 1. INTRODUCTION

3D concrete printing (3DCP) is a new emerging construction technique, and it has the capacity to revolutionize industrial building by enabling the use of construction automation. 3D printing is also known as additive manufacturing (AM), which gained its popularity in the construction field in recent years (Buswell et al., 2018; Lim et al., 2012; Mechtcherine et al., 2019). The process entails printing layers of materials product that are subsequently set up on top of each other. This technology was developed by Charles Hull in 1986 in a process known as stereolithography (SLA), then it was followed by other subsequent developments with different techniques and technology such as powder bed fusion, fused deposition modelling (FDM), inkjet printing and contour crafting (CC). 3D printing has involved various equipment, materials, and methods that gave it the ability to transform manufacturing and logistics processes. AM has been applied in different applications including construction, prototyping and biomechanical. However, the uptake of 3D printing in the field of construction industry was very slow and limited despite the advantages (Ngo et al., 2018). Compared with the existing construction methods, 3D printing can offer enormous advantages such as increased speed-related construction, architecture freedom, less work-related injuries and reduced waste material, less labour and fewer costs (Wangler et al., 2016). Therefore, such advantages have forced the construction industry to include this technique in some specific cases.

Generally, flowable cement paste contributed to increase strength particularly in the use of particle bed method. Meanwhile, it affects the shape accuracy. During the printing process, the accuracy of the printed shape relied on the size of the used particles in the bed. In which, particle with small size and layer thickness would provide high accuracy. Yet, it could also cause an increase in printing time during construction in large-scale application. Generally, the accuracy demand is not as high as in mechanical properties in the construction industry. Based on the reasons above, it is important to develop a new printing routine in order to use large particles for the expansion of the adoption of particle-bed 3DCP. Compared with other printing techniques, particle-bed printing is easier to adopt a large coarse aggregate volume.

Coarse aggregate is an important concrete part as it provides the highest strength, highest durability, less shrinkage, and cheapest cost among concrete components (Shen et al., 2010). Current research in 3DCP faced difficulty in using large aggregate size due to the requirement of extrudability. Ji et al. (2019) have made the first attempt in extrusion-based printing whereas, the design of 3DCP machine limited the size of the used coarse aggregate. In case of particle-bed printing method, coarse aggregate could be placed as the skeleton, then to be filled with cement paste.

At the moment, 3D printing technology, particularly concrete, is in its infancy. Consequently, the life-cycle behaviour is yet to be assessed. A limited number of studies on 3DCP structures have developed several methods and materials, some common of them are briefly discussed hereafter.

## 2. SUSTAINABILITY ADVANTAGES

Sustainability is a vast term that specifically goes beyond the decrease of the usage of raw material and decreasing environmental impact. Treatment of sustainability for environmental, economic, and societal effects has become worldwide accepted, with different procedures to quantify the impacts. The most feasible to quantify it are the economic consequences, especially in the context of construction, and the most complicated one are the societal implications. When 3DCP is compared with conventional construction, some advantages are stated such as savings in cost which is counted due to lower project durations, the non-use of formwork and labour. On the other hand, using unconventional ingredients and stricter control in 3DCP mixtures proportions may increase the cost of the concrete. The environmental impact would be decreased by the non-use of formwork and lowering in material wastage but may increase if the content of binder is high. The beneficial societal impact of using 3DCP in the construction site and prefabrication plant is predicted to be significant because of the decrease of manual labour for pouring and compaction of concrete, the lifting of formwork, and the decrease of errors and accident probabilities due to automation.

# 3. RHEOLOGY

The fresh printable concrete mix process requires contradicting rheological properties. It requires high workability at the pumping stage before extrusion, whereas after extrusion, it needs low workability and high thixotropy in terms of buildability of concrete (Perrot and Rangeard, 2019; Lu et al., 2019). During the process of printing, a balance is required between the rheological properties' requirements for pumping, extrusion, and buildability phases (Wangler, 2019; Papachristoforou et al., 2018). If the printable concrete has low yield stress used for helping the pumping and extrusion phases, then the extruded concrete will negatively affect the shape retention.

Workability is an essential parameter for the printable concrete, high dosages of superplasticizer are needed because of using low water to cement (w/c) ratios (Aïtcin, 2019). Phase separation as apart from workability is also essential for pumpability and extrudability of concrete. Evaluation of phase separation has been conducted by desorptivity parameter (Rahul et al., 2020), and a decrease in w/c ratio was observed to decrease desorptivity.

# 4. MAIN METHODS

## 4.1 Inkjet printing and contour crafting

Inkjet printing is a method used for printing complex geometries and advanced ceramic structures for applications such as scaffolds for tissue engineering. A similar printing technology to inkjet method, named contour crafting, is used for large building structures. This method has the capacity for extruding concrete paste by adopting large nozzles and with high pressure. Contour crafting technology has been prototyped to be applied for construction on the moon (Nerella et al., 2020).

The fresh properties of concrete used for contour crafting are the most important aspects for successful application. The 3D printing of complex geometries demands high workability for extrusion, shape retention, or printing open time, and requires high early strength for buildability (Le et al., 2012). A mix design that can achieve the requirement of workability for extrusion before setting and at the same time have high early strength to bear successive layers without collapse needs designed materials and supported equipment. Gosselin et al. (2016) developed a printing method that could pump the accelerator and the premix mortar in different pipes and then combines it before extrusion at the printhead. The rheology properties of the premix mortar can be controlled for a longer period without losing the early strength of the printed layers to successfully retain the stability of subsequent layers. This method builds complex and larger structures by using a robotic six-axis arm and governing the behaviour of material during and after the extrusion. *Fig. 1* shows a Contour Crafting machine used for concrete processing.

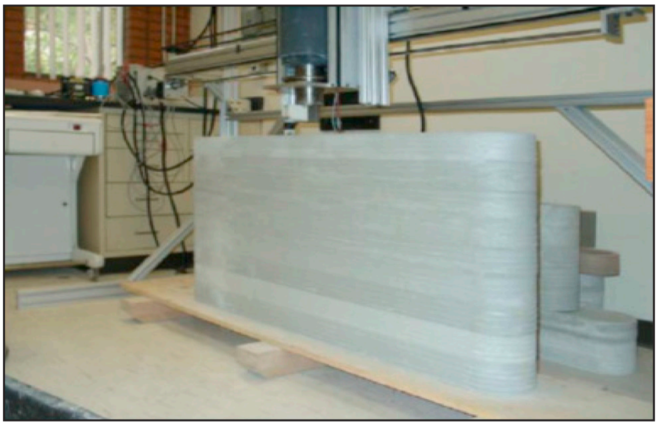

**Fig. 1:** Contour Crafting technology (Zareiyan and Khoshnevis, 2017)

## 4.2 Aggregate-bed 3D concrete printing

Particle-bed is one of the promised AM printing techniques, in which water-based binder is throwed pre-selected zones in order to bind the granular materials for each layer. A detailed research review of these studies was carried out by (Lowke et al., 2018). Rapid-hardening Portland cement (Gibbons et al., 2010), slag and fly ash-based geopolymer (Xia et al., 2019), a combination of OPC and calcium aluminate cement (Shakor et al., 2019) have been used to print components in ZPrinters, USA.

### 4.2.1 Aggregate-bed 3DCP process

A schematic of the proposed technique showed the printing process is shown in *Fig. 2*. The system contains three main key components: (1) aggregate feeder, (2) paste feeder, and (3) blade. The aggregate feeder serves to store and spread aggregate to each layer. Not similar to powder-based printers, it is impractical to govern the volume of aggregate for each layer due to the increased uncertainties of aggregate, such as particle shape, and size distribution. Therefore, an additional blade could be utilized to control the aggregate and height of each layer. The paste feeder should have the capacity to extrude the paste at a regular and accurate flowability rate. More discussion for the extrudability details can be referred to (Nerella et al., 2019).

# 5. INFLUENCING PARAMETERS ON 3D PRINTABLE MIXTURES

3D concrete printing process needs concrete with special properties and characteristics. Mixtures are designed based on three important material parameters, i.e., pumpability, extrudability, and buildability (Panda and Tan, 2018; Nerella et al., 2020). The pumpability and extrudability are controlled by the fresh properties such as consistency, stability, cohesiveness, and probability of separation under pressure (ACI 304.2R-96, 2008; Vanhove and Khayat, 2016). The extrudability and pumpability of concrete are further controlled by the rheological properties of the lubricating layer (Kim et al., 2017; Roussel, 2018). The main parameters governing the rheology of fresh concrete are yield stress, viscosity, and thixotropy (Roussel, 2006; Perrot et al., 2016). The buildability of the 3D printable concrete is affected by the static and dynamic shear yield stress (Kruger et al., 2020; Jeong et al., 2019), green strength and early age elastic modulus (Wolfs and Suiker, 2018; Panda et al., 2019). These properties further evolve with time as a result of hydration of cement and are affected by the conditions of curing (Diggs-McGee et al., 2019; Suiker, 2018). The other affecting parameters for the printing process of concrete are the workability open time, thixotropy open time, printability window, bond strength of layer and printing time gap (Panda, 2018; Zhang  et al., 2018). The

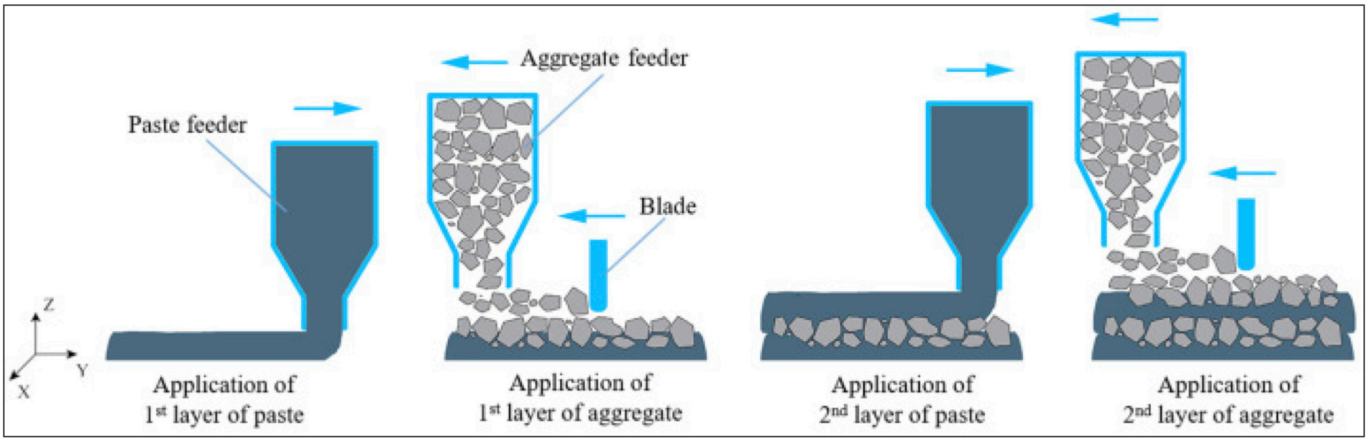

**Fig. 2:** Aggregated-bed 3D concrete printing process (Yu et al., 2020)

bond strength of layer is depended on the time gap of printing process, geometry of layer and environmental conditions affecting the properties of the surface (e.g., drying of surface) (Marchment et al., 2017; Keita et al., 2019).

*Fig. 3* shows an illustrative comparison of concrete mix proportions for all of the 3D-printable concrete, self-compacting concrete (SCC), and conventional concrete. 3D printable mixes were designed with higher fine aggregate and binder content than SCC and conventional concrete mixes to increase their properties, such as yield stress and shape retention capability. Based on previous research, the design of a 3D printable mix is an iterative process.

## 5.1. Influence of different types of Supplementary cementitious materials (SCM)

The inclusion of SCM in 3D printable concrete could have significant consequences for its properties. For instance, the early age strength is presented to be low, whereas the usage of a low dosage of metakaolin (MK) would enhance it. In addition, the presence of SCM provide a less porous microstructure, leading to an increase in durability properties such as using fly ash (FA) and silica fume (SF) can be used to improve resistance against chloride penetration.

3D printed concrete with binary and ternary blended mixtures have the capacity of resisting phase separation under pressure, providing optimized plastic viscosity and yield strength, and therefore improve the stability of the concrete. FA is suitable material in terms of workability (Long et al., 2017), while SF is beneficial to resist phase separation, it improves yield stress and plastic viscosity (Yazici, 2008; Meng et al., 2019; Vikan and Justnes, 2007); additionally, it improves the mechanical properties and impermeability of 3D printed concrete at hardened state (Kazemian et al., 2017). The volumetric stability and robustness of fresh concrete are also improved by the incorporation of SF (Kazemian et al., 2017; Rahul et al., 2019). Adding ultra-fine FA was found to be beneficial for the workability of printing mixture in terms of reducing yield stress and viscosity at fresh mix early stage. The combination of ordinary Portland cement (OPC), SF, FA, and fine sands achieve a high packing density, better rheological behaviour, and improved the strength (Nerella and Mechtcherine, 2019; Ma and Wang, 2018).

From environmental aspects, FA or ground granulated blast-furnace slag (GGBS) are ecofriendly materials. The estimation of sustainability for printable concrete with SCM should emphasize functional parameters such as pumpability, extrudability, and buildability, which are eased by the adoption of SF and FA. From this section could be concluded that the judicious use of SCM is essential for the design of sustainable 3D printable concrete.

## 5.2. Influence of aggregate content and type

Researchers have studied the effect of aggregate on the behaviour of 3D printable concrete. Zhang et al. (2019) investigated the influence of increasing the aggregate content on the rheology of concrete mix with a high thixotropy. Using

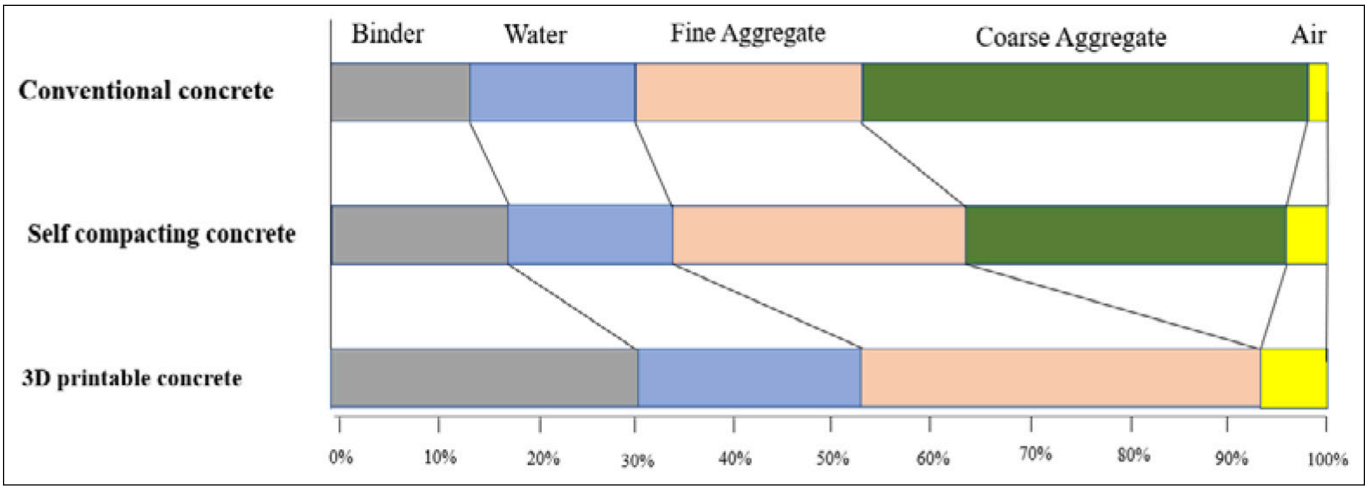

**Fig. 3:** An illustrative of volumetric comparison of percentage materials used in 3D-printable concrete, self-compacting concrete, and conventional concrete (Rehman and Kim, 2021)

different sand to binder ratio i.e., 0.6, 0.8, 1.0, 1.2, and 1.5. Results showed an increase in plastic viscosity and yield stress by 16.4% and 129.8%, where the sand to binder ratio increased from 0.6 to 1.2, while the thixotropy is reduced by 18%. Mohan et al. (2020) have noticed that increasing the sand to binder ratio from 1.0 to 1.4 increases yield stress and viscosity from 0.67 to 0.82 kPa and from 17.1 to 43.1 Pa·s, respectively.

Researchers have studied the use of recycled aggregate in 3D concrete printing, positive results have been observed in terms of buildability (Bai et al., 2021). Mine tailings residue was experimentally studied as a substitution for sand in the printable concrete (Álvarez-Fernández et al., 2021). The test results showed that using 30% of sand as mine tailings replacement produces optimum buildability and mechanical properties (Ma et al., 2018). Ding et al. (2020) investigated replacing natural sand with 25% and 50% recycled sand for printable concrete in terms of green strength and modulus of elasticity. Results showed that using recycled sand had an insignificant effect on mechanical properties up to the age of 90 min, whereas after 90 min, compressive strength and modulus of elasticity increased.

A few attempts to use printable concrete mixtures containing coarse aggregate have been reported: Rahul and Santhanam (2020) have printed mixtures containing lightweight coarse aggregate with sizes up to 8 mm (by using 30% of total aggregate content). Mechtcherine et al. (2019) used coarse aggregate up to 8 mm and printed ten layers (height of 500 mm).

While the experimental studies for 3D printing of cement-based materials generally focus on the printing process and on the mechanical properties of mortars (Roussel et al., 2020; Li et al., 2020), there are serious deficiencies such as early shrinkage cracking, long-term durability, weak interlayers, etc. Thus, this shortage of this technology seriously restrict its practical applications (Ma et al., 2020; Menna et al., 2020) and increases sustainability issues. The inclusion of coarse aggregate decreases the hydration heat and shrinkage, and it improves the volumetric stability of concrete (Shen et al., 2010). Therefore, incorporating coarse aggregate in printable mixtures is one of the important directions for researchers (Souza et al., 2020).

One of the challenges is that the use of coarse aggregate demands a nozzle with a larger cross-section to accommodate larger particles. The increase in the cross-section layer results in an increase in rate of concrete deposition, which is the product of cross-section layer and printhead speed, being a major parameter concerning productivity and thereby for economic sustainability. For instance, for a 0.4 m/s printhead speed, there is an increase of deposition rate from 0.58 $m^3/h$ to 10.8 $m^3/h$ for an increase of cross-section layer from 20 mm × 20 mm–150 mm × 50 mm (Storch et al., 2020). In this direction, using coarse aggregate provide additional values of static yield stress, helping obtain better shape stability and buildability for the print element.

However, Mechtcherine et al. (2019) stated that the presence of coarse aggregate in 3D-printing concrete, become more challenging compared to paste or mortar, especially at the printhead and on the rheological properties. 3D Printing of concrete having coarse aggregate requires more ambitious on the concrete conveyor in addition to the shaping tools of the printhead in terms of robustness, delivery rates, and resistance to wear (Mechtcherine et al., 2019). Yu et al. (2020) have proposed a solution for incorporating coarse aggregate by using particle bed printing method in which gravels with particle size range of 1.18–7 mm were spread over paste or mortar layers. The content of aggregate could reach 40%.

Several authors have used particle packing to minimize the binder content, to optimize the w/b ratio, and to mitigate the drying shrinkage (Kwan and Mora, 2002; Rozière et al., 2007). For a given paste volume, the increase in aggregate packing density could improve workability as a result of the increase in the paste excess thickness surrounding the particles of aggregate (Goltermann et al., 1997; Kwan and Li, 2012).

## 5.3 Chemical Admixtures

Concrete designed for printing purposes such as extrusion and buildability requires a high dosage of chemical admixtures. Dorn et al. (2020) studied the effect of admixtures on the setting time of printing concrete, results showed that the setting time can be controlled by accelerators such as sodium carbonate ($Na_2CO_3$), potassium carbonate ($K_2CO_3$), triethanolamine (TEA), and calcium nitrate ($Ca(NO_3)_2$). The proper use of these accelerators can judiciously regulate the setting time of printed mixtures within 5–150 min. However, the above admixtures affect the binder hydration and the crystallinity of a few hydration products. Khalil et al. (2017) investigate the effect of calcium sulfoaluminate (CSA) as a potential accelerator to control the concrete printability. A mixture containing 7% of CSA cement and 93% of OPC showed better extrudability and buildability and it improved the yield stress by 17 and 30 times compared to the reference mixture at the age of 20 and 25 min, respectively.

## 5.4 Nanomaterials

Researchers incorporated nanomaterials to concrete in order to modify the fresh performance in favour of 3D concrete printing (Song and Li, 2021; Sikora et al, 2021). Zhang et al. (2018) reported that cement containing 2% of nano-clay increases the concrete buildability by about 150% compared with the reference mixture. Moreover, presence of nano-clay in the concrete mix increases its shape stability (Kazemian et al., 2017). Kruger et al. (2019) concluded that using 1% nano-silica increased the concrete thixotropy. Chen et al. (2020) reported that the addition of bentonite improves the thixotropic behaviour of the printable concrete. Szostak and Golewski (2020) results showed that adding nano-calcium silicate hydrate (CSH) seeds to concrete mix reduces the setting time and shows a rapid increase in the earlier strength. Using nano-graphite platelets improve the thermal conductivity of the cementitious materials as well as provide self-sensing capability in concrete.

Incorporating nanoparticles to printable concrete increased the buildability, shape retention, mechanical properties, and interlayer bond strength. Several studies suggest that nanomaterials are beneficial for regulating concrete rheology and for optimizing the printability, but still the cost of nanomaterials is higher compared to the other ingredients of concrete.

# 6. DURABILITY

Several researchers have been performed different studies on the durability of 3D printed concrete. The properties of concrete constructed by layers is affected by the printing time gap and environmental conditions and therefore limit the durability. Formation of microcracks at the layer as a result of shrinkage during the printing time gap could permit the ingress of water, chloride penetration. Meanwhile, the freeze-thaw cycling could make the interlayer joints vulnerable and weaken the bond strength (Van Der Putten et al., 2020a; Van Der Putten et al., 2020b).

# 7. CONCLUSIONS

This paper reviews the latest research on 3D concrete from the standpoint of materials. Rheological properties, compatible design mix, and the effect of SCM, aggregate, chemical admixtures on the 3D concrete mix are discussed to help researchers and engineers recognize the procedures for reaching their own mix. The following co points are concluded from this review work:

- SCM binders such as silica fume, metakaolin, fly ash, nanoparticles, and chemical additives are very useful for governing the rheology of printable concrete according to the requirements of the process.
- The effect of rheology, printing process, porosity, and shrinkage cracks on the durability behaviour of printed concrete require investigation.
- Special attention should be applied to the mechanical properties of 3D-printed concrete.
- Incorporating coarse aggregate into printable concrete is an important future direction for researchers. The presence of coarse aggregate decrease the hydration heat and shrinkage of concrete and improves volumetric stability, in addition to its low cost.

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