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SUSTAINABLE 3D PRINTING CONCRETE MIXTURES, LITERATURE REVIEW

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Abstract. Some properties of 3D Printing Concrete Mixtures (3DPC) need to be developed in order to make them widespread in the construction industry. The amount of cement used to provide extrudability in 3DPC mixtures is quite high compared to conventional concrete mixtures. This situation negatively affects the sustainability of 3DPC mixtures as it is not ecological and economical. In this article, the development, advantages and production process of 3DPC mixtures from past to present are mentioned. In addition, the use of mineral additives such as fly ash, silica fume, blast furnace slag and other waste materials instead of cement for the production of sustainable 3DPC mixtures was investigated. Also, the possibilities of using other aggregates such as recycled concrete aggregate and desert sand in 3DPC mixtures were investigated. Within the scope of the study, the rheological properties of 3DPC mixtures were examined. In addition, the interlayer adhesion properties, which is another obstacle to the widespread use of 3DPC mixtures and the parameters affecting the interlayer adherence were investigated.

Keywords: 3DPC mixtures, sustainability, mineral additives, waste materials, recycled concrete aggregate.
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1 Introduction

3D printing technology is a technique in which a structure is produced layer by layer based on a three-dimensional CAD model. In recent years, it was understood that there has been a great increase in the use of 3D printing technology in construction applications (Rollakanti & Prasad, 2022). In a study Tay et al. (2017), the number of studies on 3D printing concrete mixtures (3DPC) between 1997 and 2017 was investigated (Figure 1).

The studies on 3DPC have increased especially after 2012 and continued to increase until 2017. It was also emphasized by Hou et al. (2021) that these studies continue to develop and increase today.

It is known that the use of 3D technology in the construction industry especially increases the production speed, reduces the cost of formwork due to the absence of use of formwork, provides freedom in design, and reduces labour and work accidents (Agustí-Juan & Habert, 2017; Zou et al., 2021; Khoshnevis, 2004; Nematollahi et al., 2017) (Figure 2).

The manufacturing process of 3DPC mixtures is (i) data preparation, (ii) concrete mixtures preparation, and (iii) object printing (Panda et al., 2017; Şahin & Mardani-Aghabaglou, 2022). During the data preparation phase, a CAD model is created as shown in Figure 3.a and G-Code is created with any slicing program as shown in Figure 3.b. Finally, the 3D Object is printed as shown in Figure 3.c.

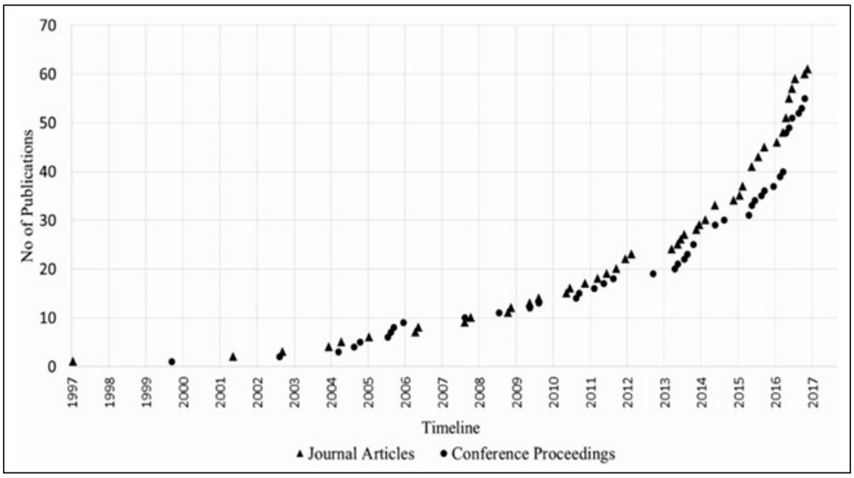

Figure 1: The increase of 3DPC studies over time (Tay et al., 2017)

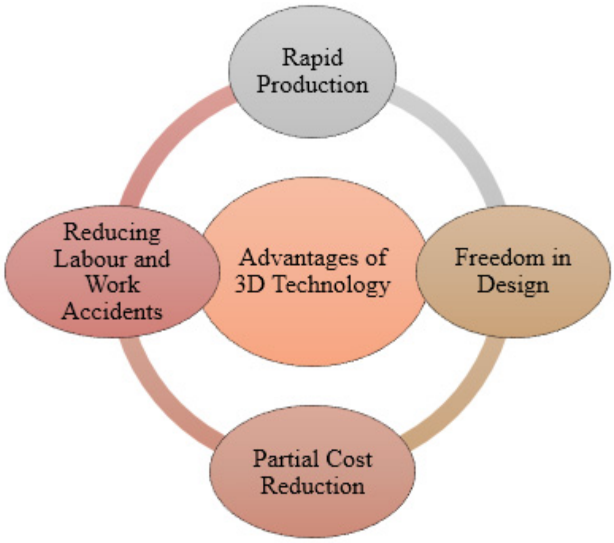

Figure 2: Advantages of 3D printing technology

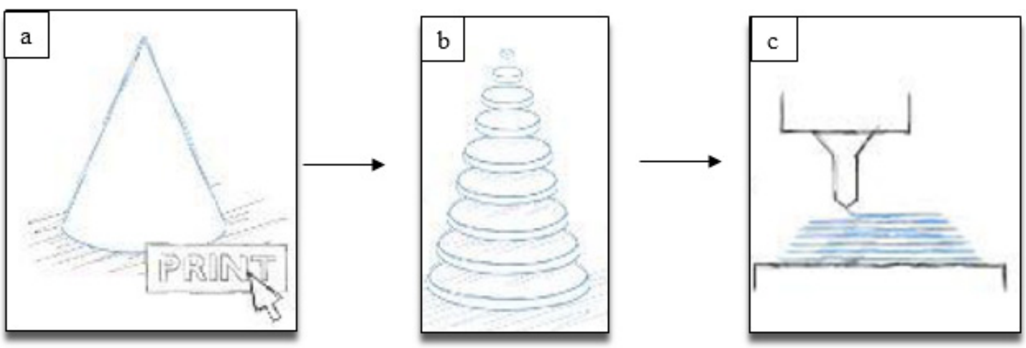

Figure 3: 3D Object printing phase (Bos et al., 2016)

2 Development of 3D Concrete Mixtures from Past to Present

3D Technology, which is widely used in sectors such as medicine, automotive and aviation, has also influenced construction applications today (Sanjayan et al., 2018). The most common of the 3D Concrete printing technologies used to adopt the additive manufacturing technique in concrete applications are Contour Crafting (Zareiyan & Khoshnevis, 2017), Concrete Printing (Bai et al., 2021) and D-shape technology (Feng et al., 2015). The developments in the structures produced using 3D Technology over the years are shown in Figure 4.

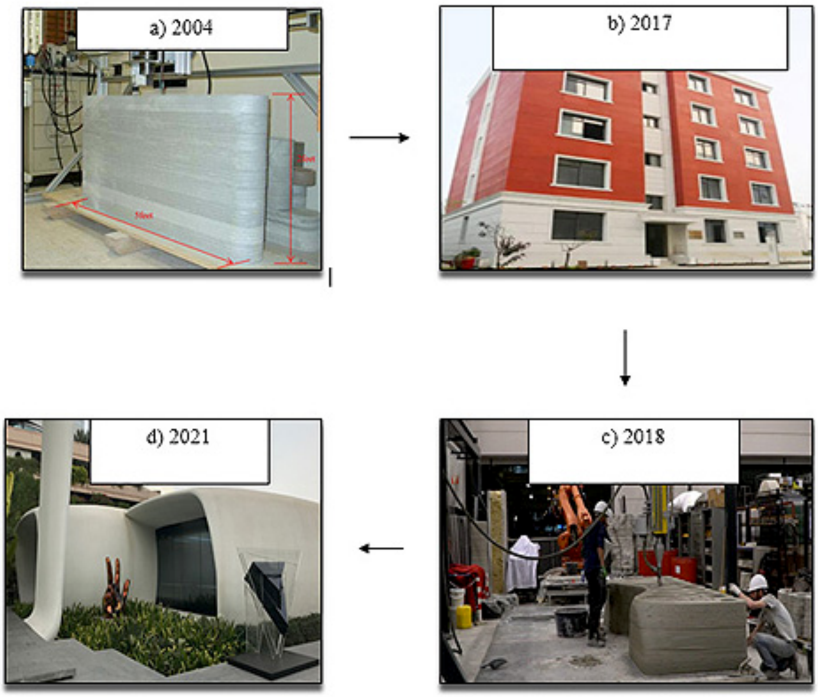

Figure 4: Structures produced using 3D Technology a. (Hwang et al., 2004) b. (3D Printed Office Dubai, 2021) c. (3D Printing Concrete Bridge, 2018) d. (3D Printed Office Dubai, 2021)

3 Sustainable 3DPC Mixtures

It has been emphasized before that not using molds in 3DPC is beneficial both economically and ecologically (Yu et al., 2021a; Ting et al., 2022; Khajavi et al., 2021; Jipa & Dillenburger, 2021). In addition, it was reported that the materials used in the mixture must also be sustainable in order for 3DPC mixtures to become widespread in construction applications (Bhattacherjee et al., 2021; Luhar et al., 2020). The cement types and amounts used in 3DPC mixtures are shown in Table 1. In order to ensure extrusion and shape stability in 3DPC mixtures, it is understood from the table that the cement dosage used is quite high compared to conventional concrete considering the 1.2 tons of raw material and 130 kWh of energy required during the production of 1 ton of cement, plus approximately 1 ton of CO2 (Mardani-Aghabaglou et al., 2017), it is clearly understood that reducing cement consumption will ensure the sustainability of 3DPC, both economically and ecologically.

It was noted that the use of no molds, no curing processes and the use of high cement dosage increase the risk of shrinkage and cracking of 3DPC mixtures (Ye et al., 2021; Yu et al., 2021b). It has been stated that the use of pozzolan and waste materials in 3DPC mixtures should be widespread in order to eliminate these negative effects and ensure sustainability.

Table 1: Cement type and dosage used in 3DPC Mixtures

Reference	Cement Type	Cement Dosage
(Schröfl et al., 2018)	CEM I 52.5 R	704.9 kg/m^3
(Van Der Putten et al., 2019)	CEM I 52.5 N	675 g
(Khalil et al., 2017)	OPC 42.5	1000 g

3.1 Use of Waste Materials as Binders and/or Aggregates in 3DPC Mixtures

One method of reducing cement dosage used in 3DPC mixes is fly ash substitution. As it is known, fly ash obtained from thermal power plants that produce electricity is widely used in conventional concrete production (Özen et al., 2022; Bayqra et al., 2022; Mardani-Aghabaglou & Ramyar, 2013). It has been reported that fly ash, which has a spherical structure, reduces the

Table 2: Use of Waste Materials in 3DPC Mixtures

Reference	Cement Type	Waste Type	Utilization percentage*	Highlights
(Zhang et al., 2018)	Type II Portland Cement	Silica Fume	2	A small amount of Silica fume showed that 3DPC mixtures increased the buildability by 117 percent and significantly increased the thixotropy and green strength.
(Panda & Tan, 2019)	CEM I	Class F Fly Ash	50, 65 and 80	The 65 and 80 replacement percentages of fly ash reduced the yield stress and viscosity of the 3DPC mixtures. It was emphasized that the spherical shape of the fly ash caused the ball-bearing effect.
(Weng et al., 2019)	Magnesium potassium phosphate cement	Fly Ash	40,50 and 60	10 percent of silica fume was used to regulate the rheological properties of 3DPC mixtures. The mixture containing 60 percent by weight fly ash and 10 percent by weight silica fume was chosen for a small-scale printing demonstration in accordance with its rheological and mechanical properties, and a 20-layer structure could be printed in 5 minutes.
(Rahul et al., 2020)	Portland Cement	Slag	50	As a result of the study, the positive effect of the use of blast furnace slag in minimizing the phase separation was reported.

*By the weight of cement

yield stress and viscosity values of conventional concrete mixtures. It is known similar effects were observed in 3DPC mixtures (Alghamdi et al., 2019). There are also researchers who state that these effects depend on the dosage, specific gravity, fineness and surface properties of fly ash (Laskar & Talukdar, 2008). Another pozzolan used to ensure sustainability in 3DPC mixtures is silica fume, a very fine material, which is a by-product of silica alloys in electric arc furnaces (Mardani-Aghabaglou et al., 2014). In many studies, it was observed that 3DPC mixtures increase both yield and viscosity due to the high fineness of silica fume (Zhang et al., 2018). In a study by Rehman et al. (2020), the use of two different municipal solid waste ash was investigated to ensure the sustainability of 3DPC mixtures. As a result of the study, it was determined that solid waste ashes used in 3DPC mixtures increased the setting time and yield stress of the mixtures, and this increased the printability of 3DPC mixtures. Also, it was reported that waste ash can be used in 3DPC mixtures due to its positive effects on the rheological properties of the mixtures. In another study by Bai et al. (2021), a way of obtaining environmental and economic benefits was investigated by using waste solids as aggregates in 3DPC mixtures. Desert sand, river sediment keramsite sand and recycled concrete aggregate were used in the study. As a result, it was determined that the 3DPC mixtures of the aggregates used increased the structural build-up. In addition, it was emphasized that the interlayer bonding performance of the mixtures was positively affected. A study by Ting et al. (2019), investigated the use of recycled glass as fine aggregate in 3DPC mixtures. As a result, it was determined that the use of recycled glass concrete aggregate in 3DPC mixtures decreased the compressive strength but increased the flow properties. In a study by Xiao et al. (2020), the effect on the performance of 3DPC mixtures containing recycled aggregates was investigated. In conclusion, it was emphasized that replacing natural sand with 25 percent recycled sand increased the green strength of 3DPC mixtures, and also did not significantly decrease the hardened mechanical properties. Similar studies are summarized in Table 2.

4 Special Requirements of 3DPC Mixtures

It is known that 3DPC mixes require different rheological properties compared to conventional concrete mixtures (Guo et al., 2020; Liu et al., 2021). The main reason for this difference is that 3DPC mixtures are produced by extruding layer by layer. In addition to the rheological parameters such as yield stress and viscosity (Mardani-Aghabaglou et al., 2021), which are important for conventional concrete mixtures, it was understood from the literature that rheological parameters such as static yield stress development (structural build-up) and dynamic yield stress development (reflocculation) of 3DPC mixtures are widely used (Leal da Silva et al., 2019; Zhang et al., 2021; Chen et al., 2020). 3DPC mixtures should have low yield stress and viscosity during extrusion. Plasticizers are generally used for concrete mixtures to have low yield stress and viscosity values (Mardani-Aghabaglou, 2016; Altun et al., 2020). However, as explained before, the spherical shaped fly ash used in the mixture was also found to be suitable for use, since it has the ability to reduce the yield stress and viscosity values. On the other hand, 3DPC layers need to have relatively high yield stress and viscosity after extrusion in order to resist deformations caused by the top layers and their own weight. It was understood that in order to provide these rheological properties, researchers generally use fine supplementary cementitious materials such as viscosity-controlling admixtures, nanomaterials and silica fume (Yalçınkaya, 2022). Another property of 3DPC mixtures that differs from conventional concrete is the 'weak interlayer bond strength'. It has been reported that poor adherence between layers as a result of the layer-by-layer fabrication technique causes the 'cold joint' (Panda et al., 2018). It has been reported that cold joint regions are the weak link of 3DPC structures and generally have lower compressive strength. It is noted that the interlayer adhesion properties of 3DPC mixtures are generally determined by flexural test, direct tensile test and microstructure analysis (Kruger et al., 2021; Cicione et al., 2021). However, the adhesion between layers is affected by the materials used in the composition of 3DPC mixtures, the printing speed, and the layer printing time interval (Wolfs et al., 2019). By determining the optimum properties of the mentioned parameters, it was determined that 3DPC mixtures could have high interlayer adherence properties. However, the surface moisture properties of the substrate affect the interlayer adhesion. Decrease in the surface moisture of the layers adversely affects the interlayer adhesion (Marchment et al., 2019).

5 Conclusion

In this article, the concrete production technique with 3D technology, the advantages of this technique and the use of sustainable materials in 3DPC mixtures have been investigated and the following results were reached. o It was understood that the use of 3D Concrete technology in construction applications has become widespread due to the advantages it provides. o Generally, it was understood that high doses of cement are used in 3DPC mixtures and this situation negatively affects the drying-shrinkage performance of the mixtures. It was observed that fly ash, silica fume, slag and waste materials can be used in 3DPC mixtures in order to eliminate these negative effects and ensure sustainability. o It was found that 3DPC mixtures have different rheological requirements during and after extrusion. o It was stated that in order to make the use of 3D technology widespread in construction applications, it is necessary to develop the adhesion properties between layers and this property depends on many parameters.

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