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State of the Art of Concrete 3D-printing: Materials and Processes

Review Paper

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Abstract:

A house is a place to live comfortably and one of the most important and expensive needs for humankind today. To meet this need, the construction industry is constantly looking for easier, cheaper, and safer ways. 3D-printing technology has been a significant advance and has been used daily in various fields for about last two decades. Moreover, 3D-printing can improve the process of building and providing housing. The purpose of this research is to examine and review the discussion of 3D-printers, methods of operation, materials, and effective approaches to the performance of this technology in the construction industry. The results of this research deal with the topics related to 3D-printed concrete, such as its special and general features, the mixing plan used in material printing, work safety challenges, how to use concrete in house construction with 3D-printing technology, and an overview of the research done in this field in the last few decades.

Keywords:

3D-printing of building, 3D-printed concrete, 3D-printer, Mix design, Concrete reinforcement.

1. Introduction:

The creation of objects with 3D printers was first done by Professor Charles (Chuck) Hull in 1986, employing various polymers and a powerful linear laser to harden liquid resin; This printing method is called SLA[1]. In 1988, when Scott Crump was looking for an easier way to create toy frogs for his daughter using heat gun adhesive —which melts plastic and deposits it in thin layers—he invented the FDM[2] printing method, which is common for printing concrete and making structural and architectural components. The aforementioned technique represents the most prevalent approach in the field of 3D printing, and its popularity is due to its ability to print a wide range of materials, such as thermoplastic polymers, ceramics, concrete, and even foodstuffs such as sugar and chocolate.

Design software limitations, void formation, low resolution of printed parts, and anisotropic behavior, after three decades of 3d printers emerging, are still among the remained challenges in construction and manufacturing processes. In addition, AM[3] technology still suffers from inflexible and stable parts. Therefore, there is a lot of ongoing research to remove the existing challenges (Lee et al., 2017).

The application of 3DPC[4] in construction and civil engineering, utilizing extrusion-based or particle bed printing techniques, has led to automated processes, increased reliability, safety, and quality in construction, reduced labor costs, and has proven to be more cost-effective compared to traditional concrete construction (Weng et al., 2020; Han et al., 2021). It should be mentioned that according to the OSHA[5] report, 20.7% of occupational accidents in the United States occur in construction sites (OSHA, 2022). Similarly, statistics from Iran's MCLS[6] indicate that 39% of fatal accidents occur in construction sites (MCLS, 2021).

3DPC technology is emerging and being automated in the construction industry, which operates without the need for formwork. This automated system consists of a nozzle attached to a robotic arm, capable of moving along digitally predetermined axial paths to extrude a rigid material like cement in layers (Ji et al., 2022).

Due to the use of unique and durable concrete mixtures, 3DPC eliminates the need for blocks and formwork during execution (Si et al., 2025). Typically, 50% of the cost and 70% of the construction time (in terms of structure, not the entire construction process) in conventional concrete projects are spent on formwork. However, 3DPC can reduce time and cost in construction projects (Batikha et al., 2022). Numerous research groups have successfully conducted experiments using 3DPC technology, resulting in the construction of prototype structures. Case in point, the WinSun engineering group in China has constructed 10 houses in less than a day (24 hours) at $5000 per house using 3D printing technology (Kira, 2015).

Among other applications of 3D-printing in architecture and industry, the production of 3D-printing formworks looks important. This act can increase the application of different geometric forms in formwork according to the capabilities of the field of 3D-printing. The Formwork system for production includes a 3D-printed body and the creation of a space (hole inside the formwork), which serves as a lost formwork for the production of reinforced concrete components (lost formwork) (Uhl, 2022).

A review of recent publications on 3DPC indicates a lack of comprehensive and unified information in this field. This article comprehensively reviews and discusses the major points in 3DPC from materials to construction methods. First, the various 3D printer components are introduced, and then materials, reinforcement, composite design, and implementation challenges are discussed, respectively.

2. Materials and Methods:

2.1. 3D-printing technology:

2.1.1. 3D-printer and its various components:

The best response to rapid population growth and the extensive need for infrastructure and affordable housing (Jindal & Sharma, 2020) is to adopt innovations in construction, such as digital construction technology. Digital construction, due to its characteristics, can provide an efficient response to the high demand for housing and infrastructure - unlike conventional construction, and simultaneously reduce environmental challenges by decreasing the consumption of cement as a common construction material (Jindal & Jangra, 2023; Lu et al., 2024).

Digital construction technology, also known as 3D printing or AM, is a rapidly emerging technology that is used in various sectors, including agriculture, healthcare, automotive, locomotive, and aerospace, and is able to produce a digital model of an object based on its geometry. In fact, 3D printing can print the desired object as a layer of material directly from the CAD[7] model, but the process of layering could be various in 3DP technologies like jet binder, direct energy deposition, material extrusion, material jet, powder bed fusion, sheet lamination, and VAT photopolymerization (Shahrubudin et al., 2019).

Since the first 3D printers' creation, various materials, including plastic, ceramics, concrete, and clay, have been printed. The printers themselves are of different types and dimensions (mobile robots, robotic arms, crane-like printers, Cartesian frame printers, etc.) that are classified according to the scale, application, and materials they print (Weng et al., 2020). The process of concrete 3D printing involves four stages: printer preparation, material mixing and preparation, pumping, and finally printing. The printing process consists of converting a 3D CAD model into an STL file, creating a G-code file, and printing the material (printing schematic, Fig.1) (Guangchao et al., 2019).

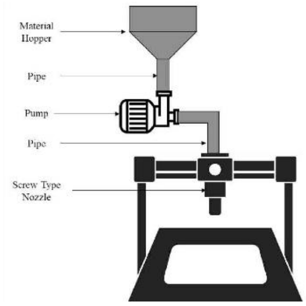

Fig.1. A diagrammatic view of the printing process for 3D printers (Shahrubudin et al., 2019)

A group of researchers has developed a 3DPC device that includes multiple independent print nozzles with separate motion and functional structures (Fig.2). This method solves the problems of high cost and poor performance of 3D printing and existing materials, and enables rapid printing of multi-meter composite building structures. In the designed prototype, to achieve the desired result, for each nozzle, the material for each nozzle should be placed in the nozzle tank with the following mass percentage ratios: nozzle A (42-39% cement, 40-45% standard sand, 11-13% water, 0.02-0.05% water reducing agent, 5-3% silica fume, 0.02-04% retarder) and nozzle B (37-40% slag, 40-45% standard sand, 12-14 % water, 3–5% silica fume, 0.02–0.05% retarder, 2–4% alkali activator, and 0.03–0.05% defoamer) (Dong et al., 2022).

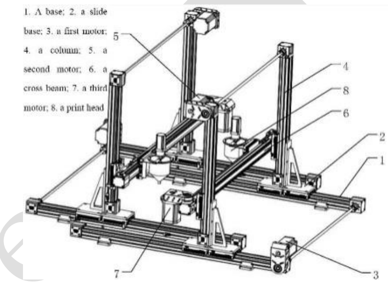

Fig.2. A diagrammatic view of a 3D-printer with several independent nozzles (Dong et al., 2022)

2.1.2. 3D-printing techniques:

According to the features of 3DP, replacing it with conventional construction methods can significantly reduce costs, time, and energy consumption and increase the quality of structures (Lim et al., 2012; Hassan et al., 2024). The use of 3DPC in construction increases reliability, reduces manpower, mitigates the potential for injuries, and minimizes work interruptions by addressing weather-related challenges (OSHA, 2022). Penga (Penga, 1997) was among the pioneers who proposed the first attempt at 3DPC structures. He revealed the benefits of 3DP for reducing the reliance on human labor within the construction industry, thereby reducing the risk of related injuries and work stoppages due to weather-related issues.

The three foundational methodologies underpinning large-scale 3D printing are named 1. Contour Crafting (CC) (Khoshnevis, 2004), 2. D-Shape (Colla & Dini, 2013), and 3. Concrete Printing (Lim et al., 2011). The diverse research has indicated that the aforementioned three techniques can, in their own way, produce large urban structures (Hamidi & Aslani, 2019). Contour crafting is an on-site, rail-mounted arm approach, while D-Shape and Concrete printing are gantry-based off-site processes (Buswell et al., 2018).

2.1.2.1. Contour crafting (CC):

CC is a large-scale layered fabrication process that constructs 3D parts by sequentially depositing paste-like materials in layers at unprecedented speed, and with superior surface quality (Khoshnevis et al., 2006). This allows for the incorporation of structural components, piping, wiring, utilities, and even consumer devices (Chaitanya et al., 2023). Also, the use of two trowels is a distinguishing feature of CC, which creates smooth and precise complex surfaces (Khoshnevis, 2004). CC is fully automated, making it an ideal method for constructing affordable housing, emergency shelter housing, and complex architectural structures (Khoshnevis, 2003). A schematic representation of the CC extrusion setup is shown in Fig. 3.

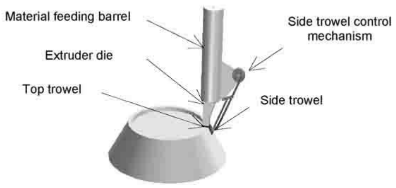

Fig.3. Schematic view of CC extrusion assembly (Khoshnevis et al., 2006)

2.1.2.2. D-shape:

D-Shape is a large-scale 3D printing technology specifically developed for the construction of architectural structures, similar to Stereolithography, developed by Dini, founder of Monolite UK Ltd (Dini, 2017; Cesaretti et al., 2014). He used epoxy resin as a binder, which was later changed to a magnesium-based binder and re-patented in 2008 (Dini, 2013). This was the world's first large-scale construction printer, similar to Yoo et al. 1993 (Yoo et al., 1993) at MIT[8], 3D powder bed printing technique for conglomerate building blocks or entire structures.

Powder bed 3D printing techniques offer several advantages in building construction, including high production resolution for large-scale objects and independence of production time from geometric complexity, which makes them a superior choice for structural design (Lowke et al., 2018). Despite the limitation of printing space in D-Shape, it can print objects up to 6 meters wide using existing powder bed 3D printing technology (Colla & Dini, 2013; Cesaretti et al., 2014). Fig. 4 shows the mechanism of the D-shaped process (Cesaretti et al., 2014).

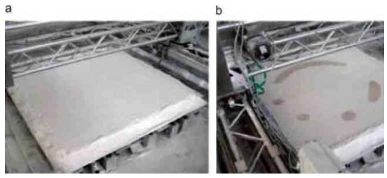

Fig.4. (a) A layer of deposited material is prepared for binder application. (b) A sectional view of the printed model (Cesaretti et al., 2014)

2.1.2.3. Concrete printing:

Loughborough University’s method is a layered fabrication process, like contour crafting, called concrete printing (Le et al., 2012a). The main advantage of this method is the potential to incorporate functional cavities into structures (Lim et al., 2012). It offers lower-resolution printing despite better control of internal and external geometries. The difference between concrete printing and contour crafting is evident in the final result because concrete printing creates smoother walls with fewer sharp edges (Fig. 5). To achieve a more uniform surface, the wet paste can be troweled during printing or the printed coating can be manually ground on a flat surface (Lim et al., 2009). Low shrinkage is crucial for the construction of free-form components to prevent cracking in concrete (Le et al., 2012b). To address this issue, a high-performance cement with high compressive strength—about 100–110 MPa—has been developed to counterbalance the weaker structure of printed components (Lim et al., 2011).

Fig.5. A concrete printed object, highlighting the ribbing on the side resulting from the layered construction technique (Le et al., 2012b)

From the comparison and analysis of the three main technologies in 3DPC, the following diagram can be obtained. Fig. 6 shows examples of components fabricated through the main structural 3D printing technology, as well as the similarities and differences between them (Fig. 6) (Lim et al., 2012).

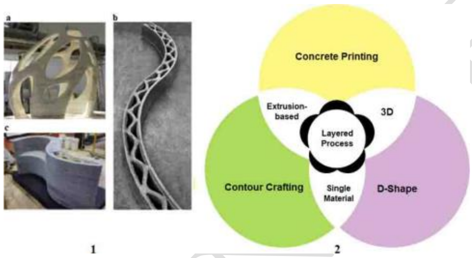

Fig.6. (1) Examples of full-scale constructions utilizing (a) D-shape, (b) Contour Crafting, and (c) Concrete printing/ Diagram 1: (2) Provides a comparative analysis of the primary similarities and differences among these three 3D structural printing methods (Lim et al., 2012)

2.2. Specifications and characteristics of materials required for 3D printing:

This section examines the 3DP process and printed materials, including construction, transfer, and printing time, and also focuses on standard tests for evaluating and classifying materials. These cases will be discussed in the order of examining the important properties of 3DPC, material for 3DPC, influencing factors and limitations, the initiation, and then the properties post-processing and achieving the final strength.

3DPC is a unique and emerging technology, based on concrete printing, which, to achieve a satisfactory result, has several characteristics, including rheology, extrudability, printability, pumpability, open time, anisotropy, thixotropy, and buildability. The concept of rheology in the discussion of concrete affects the pumpability and shape retention of the layers, which is essential for supporting the weight of the subsequent printed layers (Si et al., 2025; Paul et al., 2018; Ma & Wang, 2018). To reach a high-quality 3DPC, it's important to keep the balance between yield strength and viscosity. This balance shows itself in concrete flow during pumping and extrusion, which requires a low yield strength and viscosity, while a high yield strength is required throughout the construction to minimize deformation and collapse (Muthukrishnan et al., 2020).

The following sections will explain printability, rheology, and yield stress, extrudability, buildability, pumpability, anisotropy, thixotropy, and open time. After all these cases, a comprehensive discussion about fresh and hardened concrete and types of reinforcement in 3DPC will be done.

2.2.1. Printability:

Printability factor in 3DPC is about the potential of materials and nozzles to produce a controlled filament (Wangler et al., 2019), and evaluate the deformation of newly printed components with specific layers (Buswell et al., 2018). Similarly, Nerella and colleagues have described printability as a combination of factors such as pumpability, extrudability, and buildability (Nerella & Mechtcherine, 2019). Given these points, it is essential to examine the characteristics of 3DPC to determine the evolution process and further optimization of its printability (Hou et al., 2021; Gao et al., 2024).

Rheological properties can describe the printability in concrete and define it using experimental programs such as shear rate versus shear stress, both of which are subcomponents of thixotropy. To achieve smooth printing in 3DPC, the principle of effective printing must be considered, which is facilitated by adequate flow and time to meet the demands of pumping and extrusion (Wang et al., 2024). Buildability should also be regarded as an influential factor with low flowability, high strength, and rapid setting speed after extrusion (Riaz et al., 2023). Among other parameters that affect printability, it can be nozzle size, print size, pumping distance, concrete mix design, extrusion rate, amount of printed concrete, setting rate of concrete (Sambucci et al., 2020), and pumping pressure, also mentioned (Hamedanimojarrad et al., 2012).

As discussed above, printability is a complex concept encompassing several essential characteristics required for 3DPC. For efficient printing, the rheological properties of 3DPC must be finely tuned, and for optimal printability, attention should be paid to concrete mix properties, printing parameters, and rheological properties of 3DPC are crucial.

2.2.2. Rheology and yield stress:

2.2.2.1. Rheology:

Rheology and its properties significantly impact the printing process, which is constantly changing due to ongoing hydration. Therefore, it should be stated that rheology is the science of studying deformation or flow behavior (Jindal & Jangra, 2023). In additive manufacturing, there is a trade-off between process viability and structural performance. While removing the cement matrix stiffening may make the product less printable, it can also increase the mechanical strength of the first layers. Rheological measurements aid in adjusting the concrete casting properties, including workability, flowability, and printability (Souza et al., 2020).

By utilizing the advantage of the rheological properties of yield stress, thixotropy, and plastic viscosity, the rheology of concrete can be examined with greater precision compared to the slump test, especially when dealing with low-flow mixtures (Taylor et al., 2006).

2.2.2.2. Yield stress:

Yield stress determines the range of deformation of a sample so that below the designated threshold, the sample undergoes plastic deformation, and above the yield stress range, the sample flows like a liquid, which has two types of dynamics (is the minimum stress required to maintain flow) and static (stress required to start flow) (Qian & Kawashima, 2016). Although both static and dynamic yield stress are essential for maintaining flow and preventing plastic deformation, static stress is particularly crucial for determining the stability, shape, and size of the printed filament for 3D printing (Souza et al., 2020).

2.2.3. Extrudability:

Despite advances in 3DPC, challenges remain in enhancing printability due to an insufficient understanding of nozzle-related parameters and a lack of standardization in testing methods. Parameters such as movement speed, shape, size, and nozzle-to-building distance have the greatest potential impact on printability (Yang et al., 2023).

Extrudability indicates the ability of fresh concrete to be extruded from the nozzle as a continuous strand with the desired thickness and width. In cement-based 3D printing, the principles of SCC[9] and shotcrete can be used to transfer pressure without compaction or formwork (Li et al., 2020). Research has shown that in concrete mix design, the quantity and size of aggregates affect the rheology, viscosity, stress characteristics, and durability of concrete. It should also be known that increasing cement and reducing sand in the mixing design leads to better material output and printing (Malaeb et al., 2015; Le et al., 2012b). Also, the high content of coarse aggregates causes aggregates to interlock, printer clogging, and paste segregation (Rushing et al., 2017). Therefore, instead of using cement, fine and coarse aggregates should be used in a ratio of 1:3:1 (El Cheikh et al., 2017).

Granulation and (Lyu et al., 2021) nozzle diameter is directly related and important for better consistency during printing (El Cheikh et al., 2017). Notably, if the ratio of the nozzle diameter to maximum aggregate size is greater than 5 or the maximum aggregate size is less than 0.1 of the nozzle diameter, the printed materials will not be clogged during the extrusion process or can be slowly extruded through the nozzle (Khalil et al., 2017).

Practice tests show that a square nozzle increases pressure resistance, surface roughness, and average deviation, making it better for paths such as columns and walls, while a circular nozzle is used for printing shapes and paths with many twists and turns. Consequently, a nozzle with a regular quadrangular nozzle, such as a rectangle or square, has a consistent and better result than a circular nozzle in printing (Fig. 7) (Perrot et al., 2018).

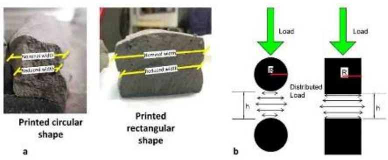

Fig.7. (a) Realized printed shapes in circular and rectangular configurations; (b) Lubrication squeeze flow between two spherical particles (left) and two cubic particles (right), both characterized by an identical half-width (Cwalina et al., 2016)

The theoretical formulas for the concrete extrusion resistance are related to the nozzle parameters. By reducing the speed and length of the nozzle, the resistance can be reduced (Irshidat et al., 2025). To test and check the effect of printing parameters (e.g., printing speed, printing height, and extrusion speed), custom nozzles are used. Results indicate that reducing the printing speed leads to an increase in the limit of layer thickness, and the relationship between nozzle dimensions, printing parameters, and filament dimensions can help to predict the printing quality and adjust the appropriate parameters (Seo et al., 2023).

To qualitatively categorize and compare extrudability, it is possible to measure the distance that the paste can be printed without nozzle clogging, cracking, and separation with three methods, as shown in Table 1.

Table 1. Nozzle distance printing test

1	**Evaluate the distance** (Malaeb et al., 2015; Le et al., 2012a; Khalil et al., 2017)	A paste can be printed without clogging, separation, or leakage of concrete juice.
		The evaluation focused on the continuity and stability of extruded filaments with a total length of 4500 mm emitted from the print nozzle.
2	**Manual simulation testing of 3D-printing to determine extrudability** (Khalil et al., 2017; Rushing et al., 2017)	A simply modified gun was used as a hand tool.
		A clay sample print was selected as a control sample.
		Fresh materials were manually loaded into both machines.
		A quality rating was assigned to each mixture based on the relative ease of extrusion.
3	**Flow behavior of the materials** (Panda & Tan, 2018)	The extrudability is determined by measuring the rheological properties (resistances) and the yield stress of the materials.
		One of the main reasons for inadequate extrudability and blockage issues is high static yield stress.

Comparing the three methods, it can be stated that the first method aims to reveal the actual extrusion process, while the third method describes this process as an intrinsic feature of the mix. However, both methods are simultaneously effective for the quantitative evaluation of extrudability. The second method, which involves a manual simulation test, yields merely qualitative results due to the absence of a device for quantifying the pressure applied to the paste. While this approach is straightforward, its lack of precision and repeatability renders it less reliable and therefore not recommended for rigorous applications in construction and material science.

2.2.4. Open time:

Open time refers to the timeframe from mixing to when the material remains suitable for printing, linked to changes in flowability over time. To reach the appropriate and printable time, retarders and accelerators are influential and decisive elements (Girskas & Kligys, 2025). Retarders ensure smooth material transport and prevent cold joints, while accelerators help materials quickly reach resistance. Retarders work after material mixing, while accelerators work after the printing process (Li et al., 2020).

According to the experiments, using 0.5% retarder can maximize the open time of the mixture, while excessive doses can reduce this time slightly. Also, studies have shown that the help of 0.5% retarder and 1% superplasticizers can extend the open time from 10 minutes to 100 minutes (Le et al., 2012a). The cause of this behavior of the cement material is due to its thixotropic property, which stiffens without stirring or vibration, and the final stress increases over time. Stirring or vibration breaks the flocs, reversibly reduces the final stress, and ultimately increases the open time. In other words, changes caused by vibration in the printing system (especially in pumping hoses) can extend the open time (Roussel, 2006).

There is still no specific standard for measuring the open time in 3D printing, and researchers in this field evaluate it based on the bonding strength of internal layers, of concrete or wood (Barfield & Ghafoori, 2012). Common methods for measuring interlayer bonding strength in 3D printing include direct tensile test, split test, compressive strength test, bending test, shear test, and other cases that are in most tests and scientific articles in the field of 3D printers in Fig. (a) direct tensile test, (b) compressive strength test, (c) split test, and (d) three-point bending test) are presented (Fig. 8).

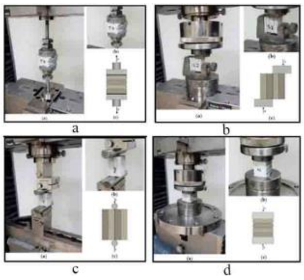
Fig. 8. (a) tensile, (b) shear, (c) interlayer tensile, and (d) compression test (Hager et al., 2022)

The tests that are performed to evaluate the effect of changing the amount of retarder and superplasticizer on the open time are similar to those assessing the tensile strength of the bond between new and old layers.

2.2.5. Buildability:

In the field of buildability, the ability of the printed filament to sustain the load and pressure of the upper layer is very important (Sousa et al., 2024). Factors affecting this include aggregates and fine additives (Li et al., 2020) (Table 2).

Table 2: Buildability important factors

1	**Fine aggregate** (Ma et al., 2017)	To reach actual buildability, a high content of fine aggregate is crucial.
2	**Superplasticizer** (Malaeb et al., 2015)	Increasing the amount of superplasticizer reduces the number of buildable layers but enhances the flowability of the mixture.
3	**Reinforcement fibers and silica foam** (Panda & Tan, 2018)	Reinforcement fibers and silica foam: increase the buildability and final stress of concrete.
4	**Microfibers or slag** (Panda & Tan, 2018)	Adding microfibers or slag helps to make printable geopolymer concrete better.
5	**Calcium sulfoaluminate cement** (Khalil et al., 2017)	Help the initial setting to take place faster and help the fresh material harden more quickly, but the dimensions of the structure must be taken into account.
		Small dimensions: a very short holding time ensures adequate buildability.
		Large structures: Rapid clamping causes problems such as the formation of cold junctions and weak interlayer relationships.

Printing parameters such as nozzle speed, height, and angular velocity also influence buildability (Joh et al., 2020). The shape of the nozzle, such as rectangular nozzles, can withstand more shear force than conical nozzles (Roussel, 2018). In addition, among other factors affecting buildability, we can mention plastic collapse and elastic buckling, which affect the printed filaments (Fig. 9). The yield strength of fresh concrete controls plastic collapse, while its stiffness governs elastic buckling failure (Rahul et al., 2019a).

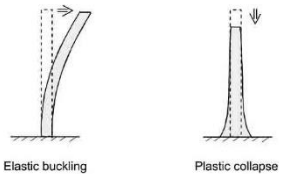

Fig.9. Elastic buckling occurs when the compressive stresses within the layers are insufficient to exceed the buckling load. Conversely, plastic collapse results from structural failure due to excessive compressive loads that exceed the material's capacity to withstand such stresses, leading to a plastic collapse of the structure (Suiker et al., 2020)

2.2.6. Pumpability:

The fluence transport of concrete from the pump to the extrusion nozzle is called pumpability (Le et al., 2012a). Issues such as inappropriate or insufficient mix design, and, as the most important problem, particle segregation along the extrusion path, lead to path blockage.

Therefore, to prevent problems related to concrete pumping, special attention should be paid to things such as hose blockage, high pump pressure, bleeding, and segregation (de Schutter & Feys, 2016). In order to achieve proper structural strength and performance, as well as to reduce the likelihood of pump blockages, it is better to use materials with low plastic viscosity and dynamic yield stress (Lu et al., 2019). Therefore, aligning the mix design with extrusion requirements is crucial for successful 3DPC.

2.2.7. Anisotropy:

Anisotropy is in the category of mechanical properties of the 3DPC domain and is related to the interlayer and interbond bonds (Feng et al., 2015). In other words, anisotropy is affected by factors such as moisture, layer time, and nozzle height and indicates the structural feature of material non-uniformity in different directions (Muthukrishnan et al., 2021). Anisotropy is exhibited by cementitious materials after hardening (Wolfs et al., 2019), and along with interlayer bond strength, it poses a significant challenge in 3DPC mechanical properties. Reduced interlayer bond strength is not a new issue because standard fluid concrete, like self-compacting concrete, has weak bond strength, which is called "cold joint" or "distinct layers" (Buswell et al., 2018; Assaad, 2016; Wael, 2017).

Typically, the compressive and bending strength in 3DPC is the highest along the axis due to good interlayer bonding, but anisotropy can cause weak bending perpendicular to the printing direction. For this reason, to achieve the appropriate resistance, it is required to understand and control the anisotropy in concrete printing (Fig. 10) (Riyaz et al., 2019).

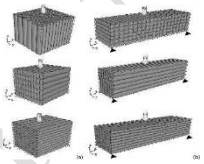

Figure 10: The anisotropic mechanical properties of 3D-printed samples are evaluated by applying loads in orthogonal directions—X, Y, and Z. For (a)cubic samples, maximum strength is observed when loads are applied in the X direction. Conversely, for (b)prism samples, maximum strength is achieved when loads are applied in the Y and Z directions (Liu et al., 2022)

2.2.8. Thixotropy:

In fresh concrete, the yield stress due to the breakdown of the internal structure of Portland cement under shear force decreases from a dynamic to a static state, but it can recover over time and exceed the initial value once external shear force is removed (Kruger et al., 2019). So thixotropy can also be included in the category of reversible processes, a representation of which is shown in Fig.11.

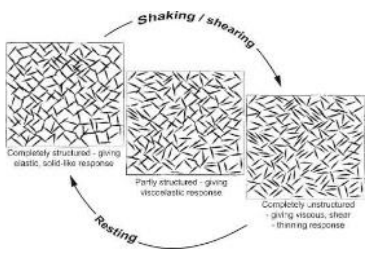

Fig.11. Degradation and reconstruction of a 3D thixotropic structure (Barnes, 1997)

The three factors of reaction time, cement paste composition, and addition of admixtures in fresh concrete, and factors such as printing speed, size, and shape of aggregates, supplementary cementitious materials, and rest time in 3DPC are considered as thixotropic properties (Jayathilakage et al., 2022). Zhang et al. stated in research that the reduction of thixotropy can increase the initial viscosity and yield stress according to the ratio of sand - cement in the mixture. It should also be known that fine aggregates in the mixture can reduce thixotropic properties and affect the dispersion of materials (Fig. 12) (Zhang et al., 2019).

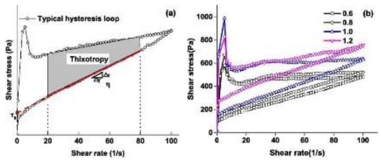

Fig.12: Thixotropy, as measured using a rheometer, indicates that the material should exhibit a high static yield stress and a low dynamic yield stress (Zhang et al., 2019)

2.3. Properties of concrete in 3DPC:

2.3.1. Fresh concrete:

Extrudability and buildability are two important properties of 3DPC (Guangchao et al., 2019), along with workability and printability, which affect the material flow behavior during pumping and printing (Cavalcante et al., 2025). It should also be stated that workability is also related to the ease of movement of the mix from the mixer to the print nozzle (Cesaretti et al., 2014). In addition to the mentioned items, additives are also effective in the mix, which are reviewed in the table below (Table 3). The diameter of the nozzle also impacts the flowability of the mix (Lyu et al., 2021). This aspect will be elaborated in subsequent sections, along with factors and optimal conditions.

Table 3. Material flow behavior

1	**Additives**		one of the main factors affecting the fluidity of cement materials in the fresh state (Malaeb et al., 2015; Rushing et al., 2017)	
	1-1	**Chemical additives**	superplasticizers and retarders	Better control the flowability of freshly printed mixtures
			superplasticizers	improve flow but significantly reduce formability
			air-entraining admixtures	increase the durability of hardened concrete at freezing and thawing temperatures, and improve performance (Barfield & Ghafoori, 2012). The presence of 1.5 to 2% air in concrete is suitable for maintaining efficiency (Zain et al., 1999).
2	**Mineral admixtures**		fly ash, silica foam, slag	Effective in controlling the flowability of fresh concrete
				Effect of particle size, shape, pozzolanic nature, and content of mineral additives/ suitable ratio of aggregate, cement, and minerals (Lee et al., 2003).
			addition of silica foam	Improving the compressive strength, reducing the flowability (workability) (Rushing et al., 2017).
			reinforcing fibers	Improving the strength of cement materials, but it harms the efficiency of the materials (Shakor et al., 2020).
				Adding 0.46 volume percent of short reinforcing fibers (e.g., 0.5-inch steel or nylon fibers) (Rushing et al., 2017)

2.3.2. Hardened concrete:

The situation in which concrete can withstand imposed loads and stresses is called hardened concrete (Li et al., 2020). In the following, the properties affecting the hardness of concrete, including density, compressive strength, bending strength, the tensile strength of the new and old two-layer bond, shrinkage and cracking, and reinforcement, will be examined.

2.3.2.1. Density:

Pump pressure, speed, and print path design are among the things that affect density. Consistent low pressure in the pumping system can achieve higher density and fewer intra-strand voids (Panda et al., 2017a). Among the things that can help to improve print quality and density are the balance of nozzle movement speed, material extrusion speed, and striving for parallel rather than cross-printing paths (Hambach & Volkmer, 2017). Hierarchical method - printing the outer shell of the walls in parallel and the inside as a cross core, and after 24 hours, filling the empty spaces created with simple and cheap mortar (filling material) - creating a dense, integrated, and stronger printed structure with better material efficiency (Meyers et al., 2008).

2.3.2.2. Compressive Strength:

Compressive strength is a key parameter in evaluating the mechanical performance of concrete (Rashidi & Cheraghi, 2025). In the cast and printed samples, the concept of compressive resistance is significantly influenced by materials, speed, and time interval of printing layers, nozzle size and geometry, inter- and intra-strand void distribution, curing conditions, print quality, and pump pressure (Li et al., 2020; Khalil et al., 2017; Shakor et al., 2020; Wolfs et al., 2019; Nerella & Mechtcherine, 2019). In 3D printing, compressive strength initially increases but then decreases with increased print time between layers (Sanjayan et al., 2018). Reinforcing fibers such as glass fibers increase the compressive strength by 1% in cement mortar (Shakor et al., 2020), but the compressive strength of fly ash-based geopolymer mortar decreases slightly with increasing the number of fibers (3 mm glass fibers) from 0.25% to 1% (Panda et al., 2017a). The compressive strength of the rectangular nozzle is like the cast samples in all loading directions, but the circular nozzle shows a large variation in it (Paul et al., 2018). According to the image below, the compressive strength of the printed sample can be measured in 6 modes (Fig. 13).

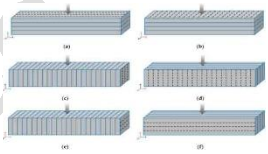

Fig.13. The direction of the compressive strength test for printed samples is categorized as follows: (a) and (b) vertical orientation, (c) and (d) longitudinal orientation, and (e) and (f) lateral orientation, concerning the layer orientation (Li et al., 2020)

2.3.2.3. Bending strength:

The bending strength is determined according to the loading direction, and the highest bending strength is associated with the force along and perpendicular to the printing direction. The highest tensile stress occurs at the bottom of the central region (Le et al., 2012b). Reinforcing fibers, such as 3-, 6-, and 8-mm fibers, increase bending strength with glass fibers from 0.25 to 1% by weight in geopolymer mortar based on fly ash (Panda et al., 2017b), and 18 mm basalt fibers from 0 to 0.7% by weight, also increase the flexural strength (Ma et al., 2019).

2.3.2.4. Tensile strength of the bond between new and old layers:

After the printed layers have been set, they must resist the forces induced into the structure, and there must be sufficient attraction between the printed layers to function as an integrated structure. This attraction means the tensile strength between the layers in the printed material, which is crucial for maintaining the integrity of the printed structure under applied loads. The tension between two layers takes place in a position between two layers that are uniformly connected. Theoretically, bond strength decreases over time and with reduced moisture, impacting the tensile strength between layers (Lee et al., 2007). The adhesion strength of a time interval of 10 (surface moisture) and 30 (mortar paste secretion) minutes is higher compared to the time interval of 20 minutes (Sanjayan et al., 2018). However, in the time interval of 10 minutes, the high resistance is due to the high moisture of the surface, while in the time interval of 30 minutes, the high resistance is associated with the secretion of the mortar paste (Li et al., 2020). Generally, surface moisture is the primary factor.

2.3.2.5. Shrinkage and cracking:

Shrinkage is among the influential factors in the balance of the structure, leading to surface cracking, which, over time, has the possibility of penetrating deep. Two main factors contribute to shrinkage and cracking: 1) Using an abundance of cement paste, which increases hydration activity, heat production, and water evaporation rate. 2) Significant thermal stresses occur due to the considerable thermal difference between the surface and the core of the layers and between the upper and lower layers. In addition to the mentioned factors, other options can also improve the state of shrinkage and cracking. Reinforcing fibers are one of the options that likewise reduce shrinkage and cracking (Li et al., 2020). Adding an internal curing agent, such as a superabsorbent polymer, solves the problem of autogenous (self-generated) shrinkage. Dissolving lime and adding a superabsorbent polymer in the concrete prepared for 3D printing, which has a relatively low water-binder ratio, the possibility of increasing the dynamic yield stress, bulk density, as well as structure and hydration, while reducing the compressive strength on days 3, 7, and 28. The use of 0.2% by weight of superabsorbent polymer not only increases the initial expansion but also effectively reduces the spontaneous shrinkage of limestone pastes for up to 7 days. So, the superabsorbent polymer can act as a rheology modifier in the 3DPC (Chen et al., 2023).

2.4. Strengthen and reinforcement in 3DPC:

In the previous sections, the importance and reasons for concrete reinforcement in the 3D printing process have been sufficiently discussed. This section will examine various methods of reinforcing concrete in 3D printing. Based on the production process, we can categorize the strengthening and reinforcement methods of 3DPC materials:

1) Pre-installed reinforcement: Reinforcement bars are manually placed in their positions in both vertical and horizontal directions, and then the concrete printing process is done in layers through two nozzles on both sides of this structure (Li et al., 2020; TV, 2020). 2) Post-installed reinforcement after 3D-printing of materials: The reinforcement is installed after printing the material. Corrosion of external steel bars is the main disadvantage of this method (Li et al., 2020; ApisCor, 2018). 3) Installation of the in-process reinforcement: steel bars can be added to the mix during printing, metal mesh grids can be automatically placed at the printing site a few seconds before printing, or staple-shaped profiles can be used. Also, the use of fibers is an alternative method that has been widely investigated (Li et al., 2020; Geneidy et al., 2020) (Fig. 14).

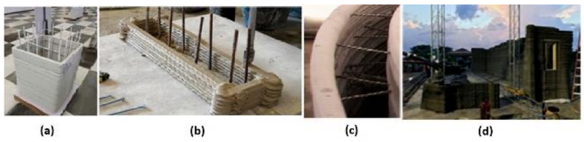

Fig.14. Reinforcement methods for printed concrete include techniques adopted by: (a) (WinSun, 2021) WinSun, (b) (CyBe, 2022) CyBe, and (ApisCor, 2018) Apis Cor. (d) Construction of a concrete building in real dimensions and armed with this method.

In the following, various methods of reinforcement in 3D printing are divided and presented separately, and are fully explained into two categories: reinforcement and separate reinforcement during printing.

2.4.1. Separate reinforcement:

Separate reinforcement is divided into 5 parts, and a comprehensive review of different methods of using reinforcement in the 3D printing process is discussed below.

2.4.1.1. Printing concrete on both sides of steel grids (mesh formwork):

Before starting the layered printing of concrete, the steel rebars are placed in the designated positions in the vertical and horizontal directions. Then, during printing, the nozzles completely cover the vertical bars, which leads to a better standing of the vertical bars, but it creates limitations in the free design of the wall form simultaneously (Scott, 2016).

2.4.1.2. Expanded Mesh Formwork:

The developed mesh formwork with 3D mesh structures including 3D printed polymer structures (Hack, 2014), steel structures formed by cutting, bending, and welding rebar, or robotic arm reinforcements (Fig. 15). To create a coherent and insulating structure, the matrix is filled with spray foam insulation and then covered with a layer of concrete, like the shotcrete method (Wu et al., 2022).

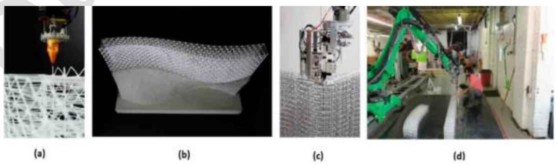

Fig.15. Applications of the mesh formwork concept are as follows: (a) polymer wire mesh extrusion as Hack (2014), (b) polymer wire mesh reinforced concrete wall Hack (2014), (c) steel wire mesh fabrication according to Wangler et al. (2019), and (d) core fabrication of reinforced concrete walls utilizing a robotic arm, as developed by Branch Technology (Shelton, 2017)

2.4.1.3. GFRP sheets (glass fiber reinforced polymer sheets):

This method is quite similar to reinforcing building materials with FRP and is used to provide tensile and shear strength and better performance in compressive strength. This strengthening method changes the failure mode of concrete columns from brittle to ductile and concrete beams from brittle flexural failure to less shear failure. The use of GFRP sheets on the reinforced concrete structure leads to more flexibility before cracking causes the structure to deviate, which also enables higher load tolerance before the onset of cracking (Fig. 16) (Feng et al., 2015).

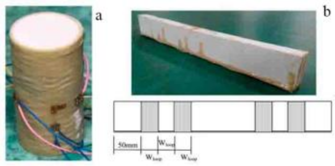

Fig.16. Applications of GFRP (Glass Fiber Reinforced Polymer) sheet reinforcement in precast concrete members include: (a) a precast concrete column wrapped with GFRP sheets, and (b) a precast concrete beam wrapped with GFRP sheets (Feng et al., 2015)

2.4.1.4. 3DPC with coarse aggregates and polypropylene fibers:

In order to analyze the mechanical properties, the concrete used in 3DPC and cast-in-place concrete (MCC) was used, and the combination of normal-weight concrete (NWC) with ordinary portland cement (OPC) was chosen as a binder for comparison. In evaluating printable concrete, variables such as reinforcement with the assistance of polypropylene fibers (FRC), construction method (printing and cast-in-place concrete), and conditions (air and underwater environment) have been considered. Compared to the 3D printed sample, the density of in situ concrete was 34 kg/m3, and the density of the sample made in a normal environment (air) was 45 kg/m3 (Seo et al., 2023).

2.4.1.5. The tension of the printed element:

Using available methods in the discussion of optimization of 3DP structures, structures with internal voids in the calculated parts can be created, leading to less material usage during printing. The created cavities can act as auxiliary ducts that are filled with grout after the steel cables are tensioned (Fig. 17) (DaSilva et al., 2020).

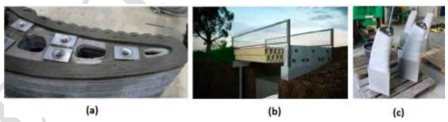

Fig.17. Prestressed reinforced concrete members include: (a) a concrete bench, (b) the conceptual design of a concrete bridge deck as proposed by Salet et al. (2018), and (c) a concrete column (Da Silva et al., 2018)

2.4.2. Reinforcement during printing:

This method describes a process during which concrete printing and reinforcement (rebar placement, rebar welding, etc.) are simultaneously and automatically conducted. Also, one of the advantages of this system is the reduction of time compared to the manual method of reinforcement, and the functional maturity of the 3DPC system in construction. However, many of these innovative methods stagnate in the research stage because they cannot improve the high strength of printed concrete and are far from achieving complete and optimized processes. In the following section, 7 cases of intensification during printing are investigated (Wu et al., 2022).

2.4.2.1. Printing of steel bars:

This automatic system uses a gas metal arc welding process to print steel rebar for structural reinforcement. This process is conceivable to the electric arc between electrodes, melting them to form steel droplets that align to create rebar strands. The process of printing reinforcement and printing filling materials is done with two separate systems. One significant challenge is the effect of printed steel at high temperatures on fresh concrete. High temperature causes the water in the mortar to evaporate and prevents the necessary integration and bond between steel and concrete (Fig. 18) (Mechtcherine et al., 2018).

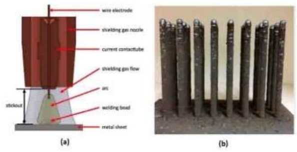

Fig.18. The steel printing concept for the automatic production of steel rebars during concrete printing involves: (a) the use of a gas metal arc welding system, which facilitates the precise deposition and formation of steel rebars, and (b) the integration of printed steel reinforcement elements directly into the concrete structure during the printing process.

2.4.2.2. Automated reinforcement:

This structure is based on a nozzle, a robotic arm, and a filler. In such a way, the reinforcing part consists of small steel components (rebar and mesh) placed by the robotic arm, while the nozzle prints the shell (as a formwork), and the filler is used to fill the formwork with concrete. (Khoshnevis, 2004) (Fig. 19).

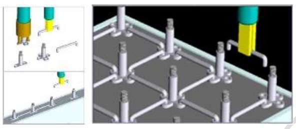

Fig.19. Steel reinforcement elements have been developed specifically for use in printed concrete, enhancing its structural performance and integrity (Allouzi et al, 2020)

2.4.2.3. Fiber reinforcement (discontinuous reinforcement):

This method utilizes fibers of various dimensions in the concrete mix design, which, after concrete printing, leads to improvement of shear, compressive, and tensile strength. Also, with the help of this method, Eindhoven University researchers were able to obtain a bending strength of up to 30 MPa and a compressive strength of up to 82.3 MPa, which is the highest value of resistance (Hambach et al., 2019).

Another approach in this field shows, first, a pre-stressed (2 to 6%) in-memory alloy fiber (Nitinol or nickel-titanium alloy), with a thickness of 0.1 to 0.2 mm in linear, elliptical, and circular form. The concrete structure is printed, and the pre-stressed memory alloy fiber is injected into the concrete at a specific angle (90°) to penetrate through an interlayer interface. Memory alloy fibers throughout the concrete structure are heated to a predetermined temperature and then cooled to room temperature. With this method, it is conceivable to improve interlayer bonding, structural performance, and mechanical properties in 3DPC (Hongwei et al., 2021) (Figure 20).

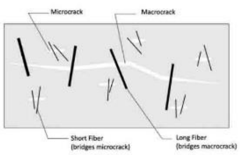

Fig.20. The reinforcement of fibers in printed concrete and the evaluation of fiber performance at various lengths have been investigated.

2.4.2.4. Continuous reinforcement:

The dual printing system (Ma et al., 2018) includes a nozzle for printing concrete and an extruder for placing micro-steel cable (1.2 mm diameter, 30 MPa bending strength) within the concrete during printing (Hambach et al., 2019) (Fig. 21. A). Studies indicate that steel cables are more practical than steel chains and wires due to their flexibility and performance on curved paths (Bos et al., 2017) (Fig. 21.b). 3D printing of UHPFRC[10] is based on two main factors, including the volume of steel fibers (0, 1%, and 2%) and nano clay content (0, 0.1%, and 0.2% by cement mass), which affect efficiency, static yield stress, and dynamic yield stress. The test results show that the addition of steel fibers and nanoclay increases the static and dynamic yield stress and mixture concentration while decreasing workability. Although the use of nanoclay with 2% fiber and a steel fiber mixture with 0.2% nanoclay has little effect on the rheological properties of the prepared mixtures. In addition, in another investigation for the construction of columns with a height of 500 mm with three different printing speeds with a mixture of steel fibers and nanoclay, the effect of rheological changes caused by the new mix design on the extrudability and buildability of the mixtures was investigated. The results indicate the integrated bonding of the mixture during printing and increasing its ability (Arunothayan et al., 2023) (Fig. 21).

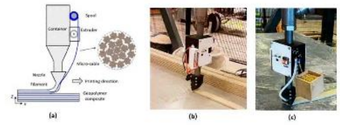

Fig.21. Concrete printing systems have been developed to accommodate various types of continuous reinforcement, including (a) continuous steel cable (Ma et al., 2018), (b) wire rope, and (c) steel chain (Bos et al., 2017)

2.4.2.5. Staple reinforcement:

The Staple Reinforcement method is economical and can be effortlessly implemented. The stapled profiles together form an interconnected wire structure that fuses the printed layers and ensures the overall structural strength of the clay (Geneidy, 2019). The printing machine consists of a printing nozzle and a stapler, whose process is carried out simultaneously and periodically during printing. The integration of this process into the large-scale 3DPC can increase the geometrical constraints in terms of print height, maximum slope, and support spans during printing (Geneidy et al., 2020). The features of this method are 1) Use of steel wires in different shapes for various geometric conditions. 2) Creating a three-dimensional wire mesh post-printing. 3) Enhanced the bond between the printed layers. 4) Increasing the integrity of the structure. 5) No restrictions on the form and path of printing according to steel profile cross-sections (Fig. 22).

Fig.22. Modeling of placement of reinforcing steel elements: (a) modeling for walls, (b) modeling of linear elements, and printed and reinforced samples in the laboratory: (c) for printed mud, (d) for printed concrete (Geneidy, 2019)

2.4.2.6. Mesh reinforcement:

In this method, the rolled steel wire mesh is placed vertically on a spool, and the movement of the nozzle is controlled by a stepper motor. Along the nozzle's and spool's direction, there is a printing nozzle for materials (Marchment & Sanjayan, 2020). With this setup, a vertical mesh can be applied simultaneously with the concrete during printing and held vertically by the concrete beads on both sides. The mesh height ranges between the thickness of one layer (17 mm) and two layers (34 mm). As a consequence, the fracture test (flexural bending test) shows that before breaking the bond between concrete and reinforcement, steel yielding occurs, which indicates the existence of sufficient bond strength between concrete and steel mesh, as well as improving the performance of bending resistance (Figs. 23 & 24).

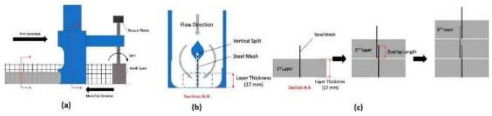

Fig.23. Vertical steel wire mesh reinforcement for printed concrete involves: (a) the placement of vertical steel mesh reinforcement, (b) the cross-sectional design of the nozzle head used for concrete deposition, and (c) the overlap of vertical steel mesh between successive printed layers.

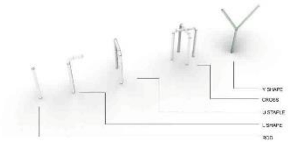

Fig.24. Different shapes of staples to strengthen printed materials

2.4.2.7. AM of reinforced concrete (AMORC) - modified method of rebar printing:

This process is based on 3D printing of concrete without formwork and creating a reinforcing mesh by welding prefabricated steel bars (Classen et al., 2020). The steps and method of 3D printing of a reinforced concrete member are as follows: 3D printing a concrete shell, 3D printing an internal structure, longitudinal voids, longitudinal steel bars, and stirrups (Zhenxian et al., 2022). The 3DPC member does not need to use formwork and can improve the freedom of member design. The 3D printing method can arrange concrete members, reinforcement, and placement similar to traditional methods (Figs. 25 & 26).

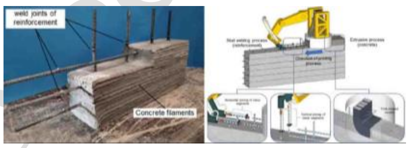

Fig.25. The AMORC 3D-printing process for the production of reinforced concrete encompasses concrete extrusion and the welding of reinforcement studs.

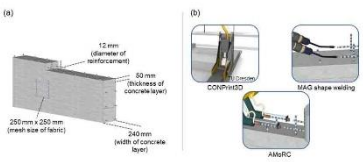

Fig.26. (a) performance criteria and (b) comparison of selected processes

2.5. Mix design:

Achieving an efficient and optimal mix design that simultaneously meets the requirements of printed materials in the fresh and hard state is the turning point of the 3D printing system. The influencing factors of the raw materials selection, in order of importance, are particle fluidity (efficiency control and printability) and the standard amount of aggregates (workability, shrinkage, and cost control) (Li et al., 2020). Although printability is the first parameter to be considered, the effect of the geometric form and the size of the printing nozzle on the particle size of the raw materials cannot be ignored, so it is better to determine the size of the nozzle opening first, and the diameter of the nozzle is 2 cm as optimal. A diameter greater than 2 cm causes structural problems because this layer is not able to support itself, and in a diameter less than 2 cm, problems arise in the separation of concrete components (Malaeb et al., 2015).

Identifying and determining the dimensions (length of the printed layers) during printing is crucial and effective; it controls the bond between the layers and determines the structure's buildability. For the quantity and dimensions of aggregates, researchers (Malaeb et al., 2015) found that the mix design with the clay-to-cement ratio of 1.28 and clay-to-sand ratio of 2 yields the best results after several experiments. A large percentage of accepted and tested mix designs use Portland cement as the binding agent, but some also use limestone powder, clay, fly ash, microsilica (silica dust), or a mixture of these materials as binding agents. Achieving the proper mix design depends on the printing materials and the type of printer. Some examples of used and final mix designs are described below.

In the first example, the combination of clay with Portland cement utilizes the binder, and to enhance the performance of printed materials, 0.02% by weight of the binder is used as a superplasticizer, and 0.0024% by weight of the binder as a rapid-setting agent (Fig. 27 and Table 4) (Chen et al., 2020).

Fig.27. Constructability performance of LCC, MCC, and HCC mixtures (Chen et al., 2020)

Table 4. Plan of mixing of cement materials prepared in this study (Chen et al., 2020)

Constituent	Type		Dosage [kg/m^3]
Cement	CEMI 52.5 R ft/opterra	[kg]	430
Fly ash	Safament HKV/--	[kg]	170
Micro silica Suspension (solid content 50%)	Woermann/BASF	[kg]	180
Sand 0.06-0.2	BCS 413/Ottendorf	[kg]	430
Sand 0-1	Ottendorf	[kg]	380
Sand 0-2	Ottendorf	[kg]	430
Water		[kg]	180
Superplasticizer	MCPF 5100/ MC Bauchemie	[kg]	10

In the second example, the binder component is made of a combination of Portland cement, fly ash, and micro-silica, and three types of sand with different sizes are used for fillers (Nerella & Mechtcherine, 2019).

The third sample consists of ordinary 3DPC composite (parts by weight: 710-730 parts of Portland cement, 70-90 parts of sulfoaluminate cement, 180-210 parts of silica fume, 300-1500 parts of quartz sand, 200-2000 parts of fine aggregate, 4-10 parts of a water reducing agent, 350-450 parts of water) and 3D printed concrete with high-strength (parts by weight: 680-720 parts of Portland cement, 60-80 parts of sulfoaluminate cement, 190-210 parts of silica fume, 330-1500 parts of quartz sand, 350-370 parts of gravel, 7-10 parts of polyethylene fibers, 70-80 parts of steel fibers, 8-22 parts of a water reducing agent). The point of this composite is to use 3DPC with high-strength for reinforcing conventional 3D printed concrete, to solve the problem of simultaneous placement of a reinforcing steel rebar mesh (Guowei et al., 2022).

The fourth invention discloses a concrete material for 3D printing that has the following components by weight: 22 to 67% cement, 0 to 4.5% mineral additives, 0 to 5% nano clay, 21.5 to 66.5% sandstone, 0.03 to 0.2 % water reducing agent, 0 to 0.09% rheological thickening agent, 0 to 1% air-entraining agent, and 11 to 23% water. The concrete material for 3D printing has good fluidity before printing, so that it cannot be clogged or separated by the concrete pump during the pumping process to the concrete 3D printer. Meanwhile, after the printing of concrete materials, the concrete layer of the building can stand quickly without collapsing or flowing, possessing specific strength to support the next printed layer, thus ensuring continuous layer printing. Capable of continuously printing 33 layers without sagging, collapsing, or bleeding (Yunsheng & Yu, 2020).

The fifth invention is related to the field of producing concrete suitable for 3D printing and waste recycling, especially with the help of commercial concrete (concrete used in construction) on-site. To achieve this, the following additive is recommended for 3DPC, which contains the following components by weight: 0.5-2 parts cellulose ether (cellulose ether is carboxymethyl cellulose ether or lignocellulose ether), 0-2 parts anti-foam agent (anti-foam concrete defoamer), 0.1-2 parts of polyacrylamide (polyacrylamide is used for concrete and its molecular weight is between 300-1000 thousand), 0.1-3 parts of accelerator (a non-alkaline accelerator), 0.1-3 parts of primary strength agent (an organic or compound primary strength agent for concrete) and 1-5 parts of attapulgite (nano refined attapulgite clay powder for concrete, consisting of phyllosilicate, aluminum, magnesium). The workability of commercial concrete can be adjusted and controlled by adding special additives on-site so that commercial concrete can meet the printability requirement. This method can address the various needs of 3DPC in pre- and post-extrusion operations, solve the production and transportation issues of printed concrete, and prevent the problems of raw material accumulation and environmental protection (Jianzhuang et al., 2022).

2.5.1. Appropriate mix design for structural 3D printing:

Hu and his colleagues in their research (Hu et al., 2022) proposed the following composition to obtain a mix design for 3D printing of concrete shear wall: silicate cement, sulfoaluminate cement, silica fume, quicklime, mesh quartz sand, a water-reducing agent, a retarder, spreadable latex powder, short polypropylene fibers, and water as raw materials. They produced 3DPC materials with high mechanical strength and good initial fluidity, and facilitated printing by adjusting a variety of cements, additives, and aggregates. It also meets the needs of high-rise buildings regarding the strength and durability of concrete, ensures resistance to anti-collapse and aesthetic properties of printed components, and is suitable for on-site construction operations.

Suitable materials for 3DPC shear walls are prepared from the following raw materials by weight: Portland cement 648 parts, sulfoaluminate cement 80 parts, silica fume 80 parts, quicklime 20 parts, quartz sand 621 parts, mesh 40-20 parts, quartz sand 80-50 mesh, 8.28 parts of a water-reducing agent, 5 parts of retarder, 5 parts of spreadable latex powder, 3.5 parts of short polypropylene fibers, 315 parts of water, and also Portland cement grade 42.5 (Hu et al., 2022).

2.5.2. 3DPC materials based on cross-section modeling and 3D printing method:

To achieve a 3D printing concrete material that can meet the requirements of filling the steel reinforcing mesh with dense reinforcement and rapid concrete setting, and to reach the goal of rapid concrete printing based on the cross-sectional working form and long-term stability of a concrete structure, researchers have reached the following instructions.

The 3D printing concrete material consists of a cement-based retarding mixture and a coagulation-regulating component. Cement-based retarding mixture of aggregate (the mass of aggregate is 10 to 90% of the total mass of the cement-based retarder mixture), a cementitious material (Portland cement, 8 to 70% of the total mass of the cement-based retarder mixture), fibers (one or a mixture of polypropylene fibers, polyvinyl alcohol, glass, steel, and basalt fibers, and the mass of fibers is 0.1-10% of the total mass of the cement-based retarding mixture), the first rheology regulating component (a mixture of one or more water-reducing agents), water and cellulose ether (a molecular compound with an ether structure and made of cellulose), thickening agent, and clay (with 0.1% to 10% of the mass of the cement material) and formed water. The coagulation regulating component includes primary strength retarding (the primary strength retarding component is 0.1-20% of the mass cementitious material). The secondary rheology regulating (one or a mixture of polymer emulsions) is a modified hydrophilic emulsion containing one or more hydroxyl, carboxyl, sulfonic, phosphate groups, and ether bonds in a modified monomer. The relative molecular mass of the modified monomer is between 44 and 1500, and the polymer emulsion remains stable in the cement-based retarder mixture for 5 seconds to 30 minutes. Superabsorbent resin, one or a mixture of several polyacrylates with a core-shell structure, a starch acrylate polymer, a starch-acrylonitrile graft copolymer, and an acrylamide-acrylonitrile-acrylic acid terpolymer, in which the shell is a superabsorbent resin. The superabsorbent resin shell contains ester and amide bonds, and the polymer remains stable for 5 seconds to 30 minutes in the cement-based retarder mixture. Hydrogel, a synthetic polymer that contains acrylamide and its derivatives as the main agents, and N, N'-methylene bis acrylic amide and its derivatives as cross-linking agents, and the second rheology regulating component is 0.5-50% of the mass of the gel material. A cement-based retarder and a setting-adjusting component are combined before use to produce 3D printed materials with high fluidity (easy placement of concrete between rebar mesh), rapid coagulation (quick formation in molds), and strength (concrete stability) (Shouqi et al., 2023).

2.6. Implementation challenges:

2.6.1. Standards and regulations of 3DPC:

Currently no specific product or process standards for 3D printing with concrete. However, the concept of 3DPC is rapidly evolving, and specific, globally standardized codes and regulations are still under development. Several organizations are working on establishing guidelines to ensure the safety and quality of 3D printed concrete structures, including material properties, printing processes, and structural performance. Based on the ISO/ASTM[11] initiative (ISO/ASTM, 2022), a draft standard DIN EN ISO/ASTM 52939[12] "Additive Manufacturing for Construction - Principles of Qualification - Structural and Infrastructure Elements" (DIN, 2022) was published. Also, the ICC[13] is working on guidelines for 3D Automated Construction Technology, including 3D concrete walls, covering both load-bearing and non-load-bearing applications (ICC, 2024).

Although the ASTM documents are not specific to concrete neither define testing procedures, material properties, nor process specifics. Hence, there remains a need to develop tailored standards for 3DPC across planning, design, materials, and execution. The Chinese standard T/CECS 786-2020 "Technical Specification for 3D Printing Concrete Structures" (CAECS, 2020) covers the technical requirements for concrete 3D printing and applies to buildings, structures, components, etc., constructed using concrete 3D printing. 3D printing is also addressed in the new revised Construction Products Regulation (EU) 305/2011, which will presumably come into force at the end of 2024. The new regulation also covers 3D printing, including related products and services (European Commission, 2022).

Finally, could say that the development of robust and globally accepted codes and regulations for 3DCP is crucial for the widespread adoption of this innovative construction method. Continued research, collaboration, and standardization efforts are essential to ensure the safety, quality, and sustainability of 3D-printed structures (Vasilić, 2024).

2.6.2. Implementation's feature of 3DPC:

The most important features of 3DPC are extrudability and buildability, which are interrelated with efficiency and open time (Guangchao et al., 2019). That is, the lower the efficiency and slump of the mortar, the fewer layers can be printed in the fresh state (buildability). In other words, it should be noted in the 3D printed concrete mix design that it can have the feature of being able to extrude through a nozzle (i.e., extrudability), as well as maintain its structure and support the weight of the upper layers after extrusion. While balancing performance and buildability, it should create a strong inter-layer bond (i.e., buildability requirements) (Le et al., 2012a). The sets of rules used to assess the properties of materials in both fresh and hardened states are detailed in the previous sections. In addition to buildability, performance also affects the strength of the printed structure, and the strength limit should also be added to the implementation challenges in 3D printing (Table 5).

Table 5. General objectives of the mixture (Malaeb et al., 2015)

Maximum Workability	at the same time	Maximum compressive strength
Maximum extrudability when printing		Maximum flowability in the system
Maintaining proper adjustment speed for proper connection with the next layer		The maximum setting speed of concrete

According to the table, due to the inconsistency between some data, maintaining balance among all factors is inherently challenging. For example, we can refer to the inverse relationship between compressive strength and water-cement ratio in the mix, while a certain amount of water is required to achieve a proper structure in concrete. Also, Close attention should be focused on the fluidity of the mix in addition to its resistance to self-preservation and the upper layers. The adjustment of the mix as it exits the nozzle should be done swiftly, while this process should be done in such a way as to ensure proper bonding with the next layer. To find the balance point between these issues, practical tests should be done on different mixes to achieve the appropriate balance.

Except for concrete, constructing a printer system capable of automatically performing all tasks from mixing, transferring, and printing materials has its challenges. One of the obvious challenges is the large dimensions of printers. The printers used in this industry are relatively larger than other 3D printers in other areas, which increases the weight of these printers. Having a lot of weight is not a problem since the printer is placed on the floor and the printing operation is done. However, once the printer is used in multi-story structures, placed on the roof, or attached outside the structure as a sliding cover to perform printing operations, its weight becomes a significant factor.

2.7. Eco-friendly reinforced concrete materials:

3DPC is among the technologies that have developed significantly in the last decade and has the ability to revolutionize the concrete and construction industry shortly. This technology can reduce the consumption and production of material waste, reduce the cost and time of construction, and increase the possibility of customizing the design. 3DPC technology can pioneer sustainability and environmental issues and solve the housing crisis with the provision of a $10,000 house (Ahmed, 2023). This technology can take steps in the making of eco-friendly materials and structures, as detailed below.

The first example deals with the environmental impact of using geopolymers or alkali-activated materials (AAMs) in the mix design of concrete used for 3D printing instead of cement. It should also be known that the use of solid activators in the single-component geopolymer structure is a more positive step than liquid activators, with the possibility of corrosive and adhesive properties in two-component geopolymers. Finally, the results of this research indicated that single-component geopolymers have less carbon and environmental footprints than two-component geopolymers and cement. However, in terms of strength, single-component geopolymers are weaker than two-component geopolymers but still outperform cement (Al-Noaimat et al., 2023).

The second example tries to investigate alkali-activated brick waste powder as a binder and a relative substitute for fly ash to develop 3D printable geopolymeric adhesive mixtures. Investigations of new mix designs with brick waste content show improved mix, high yield strength, and initial apparent concentration. However, it must be remarked that the compressive and interlayer strength decrease with the increase of brick waste, although brick waste increases the mixture's stiffness by 10%. In the end, from an environmental point of view and by examining the results of latent energy and carbon emissions, it shows that geopolymer concrete reduces carbon emissions by 60 to 80 percent compared to concrete made from ordinary cement (Pasupathy et al., 2023).

2.8. Implementation projects using 3D printing technology:

Numerous companies and universities are working on 3DP to value this new technology and bring it to relative maturity. In the meantime, some of these entities have taken a step beyond the laboratory environment and applied this knowledge in the global construction industry. In the continuation of this article, some of the projects that have been done on a real scale using 3D printer technology will be discussed (Table 6) (Fig.28).

Table 6. 3DPC projects around the world

Ref.	*Name*	*Use*	*Floor/Area*	*Structure*	*Design Intention*	*Approval*
(Xu Weiguo's Team, 2020)	(a) Wuxi House (China)	Residential	One/40m^2	Mobile Platform of Robotic 3-D Printing Cast-in-situ Concrete	Actual printing /construction of a model house for low-income housing in Africa	Tsinghua University School of Architecture
(Trstech, 2024)	(b) Takhti Field House (Iran)	Service	One/24m^2	Gantry system Concrete 3d Printing	3DPC of rapid and temporary support spaces	RHUD Research Center of Iran

(Dubai Municipality, 2021)	(c) Dubai Municipality (UAE)	Official	Two/640m^2	3D printing onsite directly under external working conditions	An integrated system to construct 25% of Dubai's buildings with 3D printing technology by 2030	Dubai Building Codes
(PERI, 2020)	(d) Beckum House (Germany)	Residential	Two/160m^2	Exterior and interior wall cast-in-situ concrete 3d printing	Demonstrating the potential of the additive construction and development scheme	Local Government Codes
(China Daily, 2018)	(e) Wisdom Bay Bridge (China)	Foot-traffic bridge	Length:14.1/ Width:4 m	The span, created by numerous slabs of 3D printed concrete	Modeled after the 1,400-year-old Zhaozhou Bridge in Hebei province	Shanghai's Baoshan district
(COBOD, 2021)	(f) GUtech (Oman)	Social housing	One/190m^2	3D printed walls with real concrete material	The World's largest 3D printed real concrete building	Oman Building Codes

Fig.28. 3DPC case study projects: (a) Wuxi House (China), (b) Takhti Field House (Iran), (c) Dubai Municipality (UAE), (d) Beckum House (Germany), (e) Wisdom Bay Bridge (China), (f) GUtech (Oman)

As indicated in Table 6 and shown in Fig.28, 3DPC is in the early stages of achieving its ultimate goal of becoming an independent and successful commercial operation. Most of the projects mentioned above were experimental-academic examples, and some have gone further and become used examples. Therefore, it should be noted that this technology is still at the beginning of its growth and development path, and there is a need to study and investigate the areas of materials, structure, implementation, etc. Of course, it should be noted that 3D printing technology has proven to be very effective and successful in many areas, such as reducing time and cost, reducing or eliminating the use of formwork, achieving free forms, and also preventing waste of resources (Al-Raqeb & Ghaffar, 2025).

3. Results and Discussion

The two main issues related to 3DPC, according to the studies carried out in the previous sections, are reinforcement and mixing design. Each of these two issues plays a vital role in advancing the work and should be studied and reviewed according to the intentions of the project. In the following, first, in Table 7, a brief review and analysis of the reinforcement methods of 3DPC will be discussed, and then in Table 8, an analysis and review of the concrete mixing design will be presented. The purpose of this section is to take an analytical and critical look at two influential issues in the field of 3DPC, which will be addressed.

3.1. Features of 3DPC reinforcement methods

With the advancement of 3D printing technology in the construction field, the issue of strengthening printed elements has received widespread attention as one of the key challenges in achieving acceptable structural performance. While 3DPC offers new possibilities for architectural and structural design due to its unique rheological properties and the ability to create complex geometries, the weakness in tensile strength and bonding between printed layers is its main limitation in structural applications. Table 7, presented in this paper, includes a comprehensive review of different 3DPC strengthening methods, which are divided into two main categories: separate reinforcement and reinforcement during printing methods. In this section, these methods are analyzed with a critical and scientific approach, examining their advantages and disadvantages, and assessing the level of addressing structural and industrial needs.

Table 7. Features of 3DPC reinforcement methods (Authors)

	Method	*Key features*	*Strengthens*	*Limitations*	*Structural function*	*Maturity/Usage*
(Scott, 2016)	Printing concrete on both sides of steel grids (mesh formwork) (SR)[14]	Placing vertical/horizontal bars before printing between the two sides of the printed layers	Easy installation; suitable mechanical joint	Freeform limitation; overlap issues; formwork/ movement of mesh	Better bending & shear behavior	Construction/ Structural & bearing walls
(Hack, 2014; Wu et al., 2022)	Expanded mesh formwork (SR)	Steel/polymer 3D mesh formwork; Shotcrete or foam filling	Insulated & integrated core; Lighter wall	Mesh production complexity; Production cost	Suitable thermal operation; Mid to high structural resistance	Research - Limited industrial sample/ Insulated walls; Precast cores; Complex forms
(Feng et al., 2015)	GFRP sheets (SR)	Covering structural members with GFRP sheets	Improvement in tensile/ shear behavior;	More expensive than steel	Increase shear resistance even after cracking	Precast construction – 3DPC research/ Local reinforcement in column, beam, and precast members
(Seo et al., 2023)	3DPC with coarse aggregates and polypropylene fibers (SR)	Using coarse aggregates and PP fibers for strengthening the mechanical features	Reduce cracking; Increase density and resistance	Printability and rheology issues	Increasing compression/bending resistance depends on the mix design	Research – construction/ Bulk members
(DaSilva et al., 2020)	The tension of the printed element (SR)	Prestressed cables; Filling holes with grout	Reducing material usage; Increasing structural resistance	Implementation complexity; Precise control of prestressed cables	Excellent performance on bending/tension behavior	Research/ Large bearing surfaces
(Mechtcherine et al., 2018)	Printing of steel bars (RDP)[15]	Producing rebars with the gas metal arc welding process and combining them with concrete	Automation in placing rebars; Reducing human resources	High temperature and its effects on fresh concrete; Quality of welding	Depends on materials and thermal bonding	Research/ Construction members with the possibility of time controlling
(Khoshnevis, 2004)	Automated reinforcement (RDP)	Robotic rebaring & printing nozzle	Reducing time and increasing precision	Equipment costs; Complex coordination of the robotic arm	Like other forms of rebaring	Research – Construction/ Industrial projects requiring automation and repetitive production
(Hambach et al., 2019; Hongwei et al., 2021)	Fiber reinforcement (discontinuous reinforcement) (RDP)	Adding steel/polymer fibers	Improvement of interlayer tensile strength; Increase the ability to form	Uneven fiber distribution	Can provide high compressive/bending strength	Research/ Small load-bearing members
(Ma et al., 2018; Hambach	Continuous reinforcement (RDP)	Simultaneous insertion of steel	Suitable for curved forms; High	Steel cable extruder complexity	Significant bending and tensile capacity	Research – Small-scale construction/

et al., 2019; Bos et al., 2017; Arunothayan et al., 2023)		cables during printing	reinforcement continuity			Curved elements & arched beams
(Geneidy, 2019; Geneidy et al., 2020)	Staple reinforcement (RDP)	An interconnected wire structure that fuses the printed layers	Cost-effective; Bonding and integration of the interlayer	Corrosion of wires, Difficulty of implementation on a large scale	Improvement of interlayer bonding and shear strength	Research/ Clay material walls
(Marchment & Sanjayan, 2020)	Mesh reinforcement (RDP)	Simultaneously placing rolled steel wire mesh from a spool while printing	Simple implementation; Steel continuity	Limited to printed layer height; Mesh overlap management	Suitable layer bonding and bending behavior	Research/ Thin or multilayer walls
(Classen et al., 2020; Zhenxian et al., 2022)	AM of reinforced concrete (AMORC) - modified method of rebar printing (RDP)	Printing a concrete shell and an internal structure without formwork	High design freedom, Similar sequence to the traditional method, but without formwork	Precise Welding and joints, Complexity of robots	Like traditional construction	Research/ Structural elements

Among all the methods mentioned in the table above (Table 7), from SR methods that form a balance between structure and performance to RDP methods that are a transformation towards automation and integration in the printed structure, and the use of innovative processes such as AMORC to metal bonding reinforcement, all have positive and negative characteristics that affect the 3DPC process.

According to Table 7, it can be concluded that none of the currently available methods is capable of solving all the structural and operational challenges of 3DPC alone. SR methods, although they have acceptable structural performance, have limitations in architectural innovation and automation due to the need for temporary formworks and a lack of full integration with the printing process. In contrast, RDP methods, by integrating reinforcement into the printing process, are moving towards integration and automation, but are still limited by technical challenges such as temperature control, material distribution, and multiple coordination of printing and reinforcement systems. Therefore, it is suggested that future studies focus on developing concurrent processes that allow for the precise integration of reinforcement and concrete. Also, the development of numerical models and simulations to predict structural behavior, fiber distribution, and thermal effects can help improve design and reduce experimental costs. Ultimately, combining SR and RDP methods in a hybrid process can lead to the creation of structures with high performance, wide applicability, and environmental sustainability.

3.2. Features of 3DPC mix design

Mix design for 3DPC must simultaneously optimize four key parameters: pumpability, buildability, open time, and mechanical properties (strength, interlayer adhesion, and durability). This anomalous relationship between fresh and hardened properties, which is less common in traditional concrete, makes mix design in 3DPC more complex and multivariate. Table 8, presented in this paper, provides a comprehensive overview of the different 3DPC mix designs and allows for comparison of recent research achievements. In this section, this data is analyzed and evaluated with a scientific and critical approach.

Table 8. Features of 3DPC mix design (Authors)

Ref.	*Mix design*	*Fresh concrete*	*Harden concrete*	*Strengthens*

(Chen et al., 2020)	Cement (CEM I 52.5R); Fly ash; Microsilica; Sands; Water; Superplasticizer	Low water/binder ratio; Superplasticizer for better pumpability & printability; Continuous printing	Improved strength & density by pozzolans; Reduced porosity & permeability	Suitable rheology; continuous printing; high-quality surfaces
(Nerella & Mechtcherine, 2019)	Portland cement; fly ash; and micro-silica; Three types of sand with different sizes	Proper aggregation; Suitable printability & initial strength	Better particle packing for increased durability & reduced porosity	Optimal particle packing
(Guowei et al., 2022)	Ultra-high-performance concrete (UHPC): Portland cement; Sulfoaluminate; Cement; Silica fume; Quartz sand; Gravel; Polyethylene Fibers; Steel Fibers; Water reducing agent	Complex mix design & nozzle coordination	Increased bending behavior and a change of failure mode to ductile	Localized placement of high-performance materials
(Yunsheng & Yu, 2020)	Cement; Mineral additives; Nano clay; Rheological thickening agent; Air-entraining agent; Water	Continuous printing ≥33 layers without deformation	High geometry stability; Mechanical strength	Shape retention time; Producibility
(Jianzhuang et al., 2022)	Cellulose ether; Anti-foam agent; Polyacrylamide; Non-alkaline accelerator; Primary strength agent; Attapulgite	Possibility of ready-mix concrete	Sustainable and economical approach; Recyclability	Waste and cost reduction
(Hu et al., 2022)	Portland cement sulfoaluminate; Cement; Silica Fume; Quicklime; Quartz sand; Mesh; Water-reducing agent; Retarder; Spreadable latex powder; Short polypropylene fibers; Water	Extrudability & initial strength; Suitable for large-scale printing	Suitable strength & durability	Proper for structural or shear wall use

In general, all the studies mentioned in the table emphasize the importance of balancing the properties of fresh concrete and hardened concrete. This balance, which is recognized as one of the main challenges in 3DPC mix design, requires careful attention to parameters such as water/binder ratio, rheology, shape retention time, and drying rate. According to the presented analysis, it can be concluded that the design of 3DPC mixtures is a multidimensional and balance-based process that requires the integration of materials knowledge, structural engineering, and printing technology. Although significant progress has been made in improving the rheological and mechanical properties of concrete, challenges such as the coordination between fresh and dried properties, recyclability, and economic costs remain. Therefore, it is suggested that future studies focus on developing numerical models to predict the behavior of concrete during the printing process, along with assessing the environmental and economic impacts of the mix design. This integrated approach can lead to the establishment of a design framework based on the principles of sustainability and structural performance in 3D printing technology.

4. Conclusion:

This research provides a comprehensive review of topics related to 3D printers, their components, the materials used, and the necessary properties these materials must possess. From the physical and chemical properties required for printed materials to the types of tests used in this method, explanations were provided in the simplest possible manner to ensure that all construction professionals can find answers in this article. It has been made to explain and overview of various components and provide efficient materials for utilizing this technology in the country's construction industry. Despite more than two decades of innovation and 3D printing technology, numerous issues remain that require the continued efforts of scientists worldwide. Some of these issues pertain to material compatibility, optional mix design, and environmental impact. The most important challenge of this work is earthquake resistance, which necessitates extensive and high-level scientific research.

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12. Appendices:

1. Stereolithography
2. Fused Deposition Modeling
3. Additive manufacturing
4. 3D-printed concrete
5. Occupational Safety and Health Administration
6. Ministry of Cooperatives, Labor, and Social Welfare
7. Computer-aided design
8. Massachusetts Institute of Technology
9. Self-compacting concrete
10. 3D-printable ultra-high-performance fiber-reinforced concrete
11. ASTM International: ASTM International is developing standards like ASTM WK89706 specifically for fresh and early-age properties of printable concrete.
12. ISO/ASTM 52939:2023: This standard outlines requirements for the production and delivery of high-quality 3D-printed structural and infrastructure elements.
13. International Code Council (ICC)
14. Separated reinforcement
15. Reinforcement during printing