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EDITED BY
Walid Mansour,
Kafrelsheikh University, Egypt

REVIEWED BY
Marialuigia Sangirardi,
University of Oxford, United Kingdom
Nahla Hilal,
University of Fallujah, Iraq

*CORRESPONDENCE
Nikolai Ivanovich Vatin,
vatin@mail.ru

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Differences between 3D printed concrete and 3D printing reinforced concrete technologies: a review

Komeil Momeni[1], Nikolai Ivanovich Vatin[2]*, Mohammad Hematibahar[3] and Tesfaldet Hadgembes Gebre[4]

[1]Department of Civil Engineering, National University of Skills (NUS), Tehran, Iran, [2]Scientific and Technological Complex "Digital Engineering in Civil Engineering" Peter the Great St. Petersburg Polytechnic University St. Petersburg, Saint Petersburg, Russia, [3]Moscow State University of Civil Engineering, Moscow, Russia, [4]Department of Construction Technologies and Structural Materials, Peoples' Friendship University of Russia, Moscow, Russia

This review aims to provide a comprehensive analysis of the difference between 3D printed concrete (3DPC) and 3D printing reinforced concrete (3DPRC) technologies, as well as potential future paths for these technologies based on current consolidated approaches. Although 3D printed reinforced concrete technology attempts to strengthen reinforced concrete using 3D printing technologies with polymer ingredients, 3D printed concrete technology concentrates on printing concrete for building concrete structures. In recent years, both technologies have advanced rapidly and become a global research innovation hotspot due to their advantages over traditional construction technology, such as high building efficiency, low labor costs, and less construction waste. Unfortunately, there are several issues with 3DPC and 3DPRC technologies, including competing rheological requirements, integrating hurdles, inadequate interlayer bonding, and anisotropic properties of the material that result in lacking structural performance. The findings of the investigation discuss research gaps and theoretical possibilities for future development in both 3D printing technologies, which can advance concrete technology and safeguard structures under various loads. In the present study, two distinct 3D printing technologies are analyzed, along with their respective uses in material and structural engineering. Additionally, the advantages, methods, and materials utilized for the two types of 3D printing technology are described, and the difficulties and solutions associated with using 3D printed concrete in real-world projects are demonstrated. None of the earlier investigations examined the differences between these two technologies. Although 3DPRC technologies aim to strengthen concrete by incorporating various forms of 3D printed technology, 3DPC technology has been studied for its mechanical qualities and concrete rheology. Meanwhile, engineers in 3D printed concrete technologies try to improve large-scale 3D printers and the mechanical properties of printed concrete, while 3D printing reinforced concrete engineers try to design new patterns of 3D reinforcing patterns due to the improved mechanical properties of concrete. The present study examines the differences between 3DPC and 3DPRC technologies.

KEYWORDS

3D printing concrete, 3D printing reinforced concrete, auxetic, concrete, protect building

1 Introduction

Current limitations like the lack of skilled labor, resource depletion, and safety concerns have had a major impact on the growth of the construction sector as a result of the rapid rate of urbanization and industrialization. The development of technology for 3D printed concrete (3DPC) and 3D printing reinforced concrete (3DPRC) gives engineers and researchers in the building sector new ideas. It has been proven that 3DPC and 3DPRC have significantly influenced civil engineering and concrete structures, respectively (Hematibahar et al., 2024a). Although a few investigations concentrated on 3D printed reinforced concrete, others examined the topic of 3D printed concrete. Both technologies have advantages as well as disadvantages. 3D printed concrete is known as a transformative technology that can change the housing shortage and enable innovative architectural designs. Studies have validated mechanical property testing, including compressive, tensile, and flexural strength, or increased correlation between other conventional test methods and rheometer results. Other studies investigated 3D printing tools through a robot arm or the economic effect of full-scale 3D printed concrete homes (Abdalla et al., 2021; Hu et al., 2024; Park et al., 2024; Phuong Bao et al., 2024). Another example of 3DPRC is the case of cement mortar and reinforced concrete materials with different patterns of 3D printing technology. In this technology, materials are roughly printed through a fused deposition modeling (FDM) technique. Most printing materials are polymers, such as acrylonitrile butadiene styrene (ABS) or polylactic acid (PLA). Thus, the strengthening of concrete with 3D printing is a modern technology that can improve the strength and ductility of concrete or observe the energy of reinforced concrete under various types of loading (Chajec and Šavija, 2024; Xu et al., 2024a; Xu et al., 2024b). In general, 3DPC technology today is looking for generalities in construction, while 3DPRC is at the beginning of scientific research and looking for details in construction materials.

The current study begins with 3D concrete technology. 3D printed concrete focusses on concrete with high mechanical properties in a free form without any concrete mold. Reinforced 3D printing attempts to change the rebar with 3D printing materials. Adding reinforced 3D printing also aims to convert concrete's strain-softening properties to strain-hardening ones. In 1997, Joseph Pegna utilized additive manufacturing to print concrete layer by layer for the first time. Behrokh Khoshnevis then employed 3DPC technology, namely, contour crafting (CC), using cement materials to create large-scale 3D constructions (Khoshnevis, 2004; Rouhana et al., 2014). The nozzle mechanism could be oriented at different angles to construct different buildings (Khoshnevis and Dutton, 1998; Buswell et al., 2007; Kazemian et al., 2017; Vergara et al., 2017). The primary advantage of this technique is that concrete may be 3D printed in freeform geometry without the need for formwork. Therefore, materials of 3D printed concrete must have suitable fluidity and good standing properties before and after extrusion (Lim et al., 2012; Zhang et al., 2018c).

In the process of printing concrete, the bed is covered by dry powder sprayed with water, and the concrete is printed layer by layer (Lowke et al., 2018). The potential of the printer and mortar material mix to extrude uniformly layer by layer is one of the most crucial aspects of this process. In 3DPC printer technology, vibration and low pressure are transferred from the pipeline to the nozzle to print concrete and mortar (Arosio et al., 2007; Cordeiro et al., 2016; Bani Ardalan et al., 2017; da Silva et al., 2017; Saw et al., 2017). Some studies investigated the use of geopolymers such as fly ash to make concrete green and environmentally friendly (Panda et al., 2017; Paul et al., 2018). Unlike ordinary Portland cement, geopolymer 3D printed concrete has not yielded stress and low viscosity (Favier et al., 2014). The slump test is the easiest test to use to understand the workability of concrete. The simplest laboratory test for determining whether concrete is workable is the slump test (ASTM C143/C143M-03, 2003); Tay et al. (2019a) present a new protocol for slump and slump-flow testing for measuring the pumping ability of concrete.

Different types of materials can improve the mechanical properties of 3D printed concrete. Some chemical and mineral materials are affected by the mechanical properties of concrete, rheology, etc. For example, superplasticizers as accelerators can change the long-term strength of 3D printed concrete. There are different types of accelerators, such as earth metals, carbonates, hydrates, and inorganic salts. One of the most important materials is sulfoaluminate cement (SAC), which can make ettringite in concrete (Lossier, 1946; Prudˆ encio, 1998; Souza et al., 2020b; Souza et al., 2020a). Superplasticizers can change the viscosity of mortar, setting retarders, and workability (Malaeb et al., 2019). Hua Shang Tengda Ltd. is a Chinese building company that presented a new type of 3D printed concrete with extruded steel rebar as concrete reinforced. This rebar can extrude rebar inside the 3D printed concrete in both the vertical and horizontal directions.

Some studies suggested replacing the recycled aggregates with natural aggregates in 3DPC. For example, Evangelista and de Brito (2007) proposed using not more than 30%0 recycled fine aggregates. Different studies show that when the mixture design is suitable for recycled sand, the design can be reasonable for 3D printing technology (Jiang et al., 2019; Le et al., 2012).

Adding fibers to concrete can improve its mechanical and durability properties (Momeni et al., 2024; Vatin et al., 2024). Some researchers investigated using rebar to improve the flexural strength of reinforced 3D printed concrete structures. In addition, other studies investigated a special type of "permanent formwork" that is cast with conventional concrete (Lim et al., 2012). Further studies have investigated adding different types of fibers to 3D printed concrete. For example, Panda et al. (2017) added different types of short glass fibers (3 mm, 6 mm, and 8 mm) at 0.25% and 1% in 3DPC, which improves the mechanical properties. Current studies attempt to change the cement material powder with fine aggregates (0.1–100 μm), and the extruding layer thickness was approximately 100 μm (Xia and Sanjayan, 2016). In another example, Hambach and Volkmer (2017) added basalt and carbon fibers to 3D print fibers in 3D printed concrete and found that flexural strength improved. Polyethylene (PE) fibers can increase the mechanical properties and can increase the energy and fiber bridging effect in 3D printed concrete (Yu et al., 2018). The strain-softening effect was observed after the post peak of concrete when steel fiber was added to 3D printed concrete (Bos et al., 2019). Faludi et al. (2015) added cast concrete to 3D printing, which used less energy than usual. Prasittisopin et al. (2019) improved the thermal performance of 3D printed concrete structures. According to Lpez-Mesa et al. (2009), the environmental effect was reduced by 12% when 3D printed concrete was used instead of the *in situ* cast concrete process. Several studies examined reinforced 3D printed concrete using continuous fiber-reinforced polymers (FRP). For example, Zeng et al. (2024) reinforced concrete with 3D printed continuous fiber reinforced thermoplastic polymers (CFRTPs). They found that when CFRTPs were added to 3D printed concrete, the flexural strength increased by more than 100%, and strain behavior changed to strain hardening. Yan et al. (2024) examined 3D printing cylindrical of ultra-high performance concrete (UHPC) with reinforcing FRP wrapping. They found that adding FRP wrapping reduced the large defects. Feng et al. (2015) warped 3D printed concrete with glass FRP (GFRP). They found that cylindrical 3D printed concrete warped with GFRP increased by more than 179%. Sun et al. (2021) examined the bonding strength of 3DPRC with basalt fiber-reinforced polymers (BFRP). According to their results, the slip corresponding to the peak bond stress is between 0.48 mm and 1.46 mm. Moreover, the peak bond strength was more than 0.24–0.65 MPa. Park et al. (2020) studied 3D printing reinforced concrete beams with steel and FRP to improve their flexural strength. They found that 3DPRC has a flexural strength of 10.4 kN, and steel-rebar-reinforced 3DPC has a flexural strength of 26.6 kN.

Luo et al. (2022) analyzed the auxetic tube to cover the cylinder concrete under compressive strength. The compressive strength of auxetic improves the concrete when the auxetic tube covers the concrete. Poisson's ratio and the thickness of the stainless tube can improve the mechanical properties of the concrete cylinder.

The second part of the article is a review of the literature on 3D printed reinforced concrete. The significant improvement of 3DPRC is the increase of mechanical properties such as compressive and flexural strength, in addition to the change of "strain softening" to "strain hardening" to flexural load displacement. Some studies improve mechanical properties such as flexural strength, while the strain behavior has not changed due to the nature of the polymer as a 3D printing material to harden and increase compressive strength (Lao et al., 2024; Li et al., 2024; Zhu et al., 2024). According to the study results, the geometry of 3D reinforcements is the most important factor that is exclusive to this technology, and creativity in reinforced concrete is the greatest advantage of this technology, although the optimization pattern of 3D printed structures has been widely studied. For example, truss, gyroid, and lattice structures perform well under compressive and flexural loads (Nguyen-Van et al., 2022; Skoratko et al., 2022). The lattice structure has many advantages. Auxetic patterns can improve flexural and tensile strength in addition to compressive strength when used as reinforcement in cementitious material. One advantage of the auxetic structure pattern is a negative Poisson ratio (Chen et al., 2023; Xu and Savija, 2024). This behavior can significantly increase the properties of reinforced concrete. Miller et al. (2012) manufactured 3D printed auxetic fibers with a −6.8 negative Poisson ratio and a 30% volume fraction of fiber. Zahra and Dhanasekar (2017) used auxetic foam to reinforce the cement matrix. They understood that auxetic foam can reduce the brittleness of the cement matrix. According to the studies, when reinforced 3D printed auxetic patterns are used in reinforced concrete, confinement effect, stability, shear resistance, and ductility improved (Tzortzinis et al., 2022; Zhong et al., 2022). Many reinforced 3D printed concrete and auxetic material studies are attempts to change strain softening to strain hardening. Xu and Savija (2023) presented a 3D printing method to change the strain softening of concrete to strain hardening. They filled an auxetic polymer shell with cement mortar and found that uniaxial compressive strength improves and changes stress-strain to strain hardening.

This study compares and contrasts two modern concrete construction technologies. 3D concrete printing technology strives to improve the mechanical properties of concrete printing, concrete types, and reduce construction time. In general, 3DPC technology focuses on constructing concrete structures. Meanwhile, 3DPRC technology attempts to add different patterns through 3D printing technology using different materials such as PLA or ABS to increase the flexural strength and ductility of concrete reinforcement. In general, 3D printing plays the role of reinforcement in concrete structures for 3DPRC, while 3DPC plays a large role in building construction. This study analyzes and compares both technologies to prevent mistakes by engineers when choosing and using these disciplines.

2 Existing 3D printed concrete and 3D printing reinforced concrete technologies

3DPC technology focuses on concrete printing through concrete printers and can build structures without concrete formwork, reduce construction time, reduce the number of workers, etc., while 3DPRC technology tries to improve concrete and cementitious materials through reinforced concrete through 3D printing technology, such as fused deposition modeling (FDM) and the use of different polymer materials.

2.1 3D printed concrete technology

2.1.1 Technological aspects

3DPC technology starts with a digital 3D model and "sliced layers" processes and changes file formats to standard tessellation language (STL). Next, the printing process starts, and the structure is completed in the "final element" process (Figure 1) (Pessoa et al., 2021).

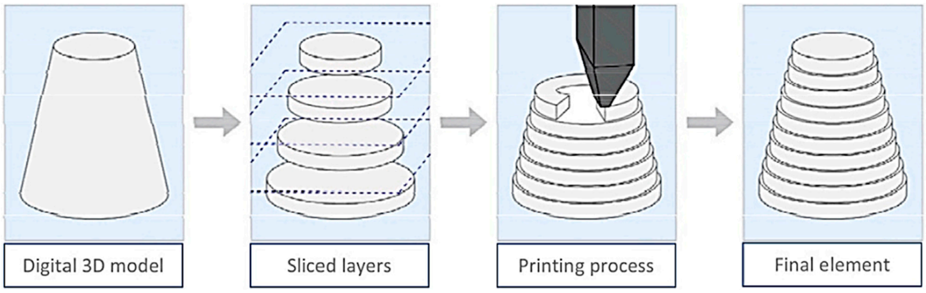

FIGURE 1
Process of 3D printed concrete technology [based on Pessoa et al. (2021)].

Three-dimensional concrete technologies are designed by software and later converted to the printing process. The printing parameters must be defined with regard to printed concrete. The nozzle opening and layer height are defined according to the thickness as well as the geometric complexity. If the nozzle opening is smaller, the fluidity should be higher (Malaeb et al., 2019). There are two types of nozzles, round and flat, for installing concrete. In the case of round nozzles, because of the smaller gaps between the layers, the bond between them is weaker, but sometimes, some types of round nozzles tend to create smoother and thicker layers. The flat nozzle creates thicker layers and improves mechanical resistance, and the shape of the building is improved due to the rectangular opening (Figure 2A, B shows different opening thicknesses) (Liu et al., 2020). Anisotropic properties are another aspect of 3D printed concrete. When the load is applied in the z direction, the compressive strength increases, and in the x and y directions, the tensile strength increases due to the bond strength between the layers, which is related to viscosity, content level, and time interval (Paul et al., 2018) (Figures 2C–E). Sanjayan et al. (2018) found that the moisture level between the layers is probably the main factor affecting the interlayer adhesion and is related to the compressive and tensile strength.

In 3D printed concrete, there are disadvantages such as cracking due to shrinkage, cold bonding due to filament interlock, nozzle blockage, and layers of different widths and heights. Shrinkage cracking is usually caused by high temperature, low humidity, and other environmental conditions. The cold joint problem is due to the rapid hydration process. Nozzle clogging disorder occurs due to the high aggregate content and low flexibility of 3D printed concrete. According to the literature review, the 3D printed concrete is environmentally friendly concrete due to the elimination of formworks and the reduction of labor (Labonnote et al., 2016; De Schutter et al., 2018).

2.1.2 Material properties

Various new studies present new methods. For example, Dvorkin et al. (2024) examined fine aggregates to make 3D printed concrete. They added mineral additives and slag-alkaline binders to concrete. According to the results, the maximum compressive strength was between 7.6 MPa and 18.7 MPa after 1 day. It should be mentioned that the thickness of each layer is a maximum of 4 cm. Figure 3 shows the layers and concrete 3D printing fabrication.

Jiang et al. (2024) analyzed different patterns and paths, such as crosswise, vertical, arched, and diagonal. They found that arched path 3D printed concrete had the best flexural strength (more than 30% improvement compared to other samples) due to the bond between filaments. They used cement, sand, silica fume, and fly ash. Mechanical property results show that arched flexural and compressive strengths are 6.3 MPa and 12.4 MPa, respectively.

3D printed concrete using Portland cement yielded compressive strength of 20 Mpa and 60 Mpa and bending strength between 3 Mpa and 10 Mpa (Higgins and Bailey, 1976; Birchall et al., 1981; Ni and Wang, 2000). Moreover, adding rebar and reinforcement can improve tensile strength and ductility (Khoshnevis et al., 2006; Mechtcherine et al., 2019. Asprone et al. (2018) used a 3D printed concrete beam with steel bars. They found that 3D-printed concrete beams reinforced with steel rebar provide an initial stiffness comparable to that of fully reinforced concrete beams. Some researchers have analyzed the internal voids for post-replacement of reinforcements, and this strategy can be used to improve the tensile and flexural strengths of structures in the assembly of prefabricated components (Lim et al., 2012). Another strategy is using fibers instead of steel rebar reinforcement. Some research shows that 3D printed concrete fiber reinforcement can achieve high mechanical properties similar to 3D printed concrete steel rebar reinforcement (Zollo, 1997; Senff et al., 2014; Senff et al., 2015). Many types of fibers, such as basalt, glass, steel, carbon, etc., are used to improve the mechanical properties such as toughness, ductility, fatigue resistance, impact resistance, and especially the tensile strength of the building structure (Hamedanimojarrad et al., 2012; Yazıcı et al., 2013; Yoo et al., 2013; Mukhametrakhimov, 2022; Kuznetsov et al., 2023; Hemant et al., 2007). There are many aspects, such as fiber orientation, aspect ratio, size, type, and volume fraction, to improving 3D printed concrete strength (Grünewald, 2011). Higher aspect ratio fibers had higher post-crack strength when the aspect ratio ranged from 30 to 150 (Yazıcı et al., 2007; Michels et al., 2013; Malaszkiewicz, 2017).

Some successful mix properties are shown in Table 1, which illustrates that the best sand size is larger than 1.7 mm, and the best rice husk ash size is larger than 0.075 mm and smaller than 2–7 μm. According to Table 1, the maximum water/binder percentage is more than 48%, the maximum superplasticizer is more than 1% of binder weight, and the maximum flowability of 3D printed concrete is 18.35 mm.

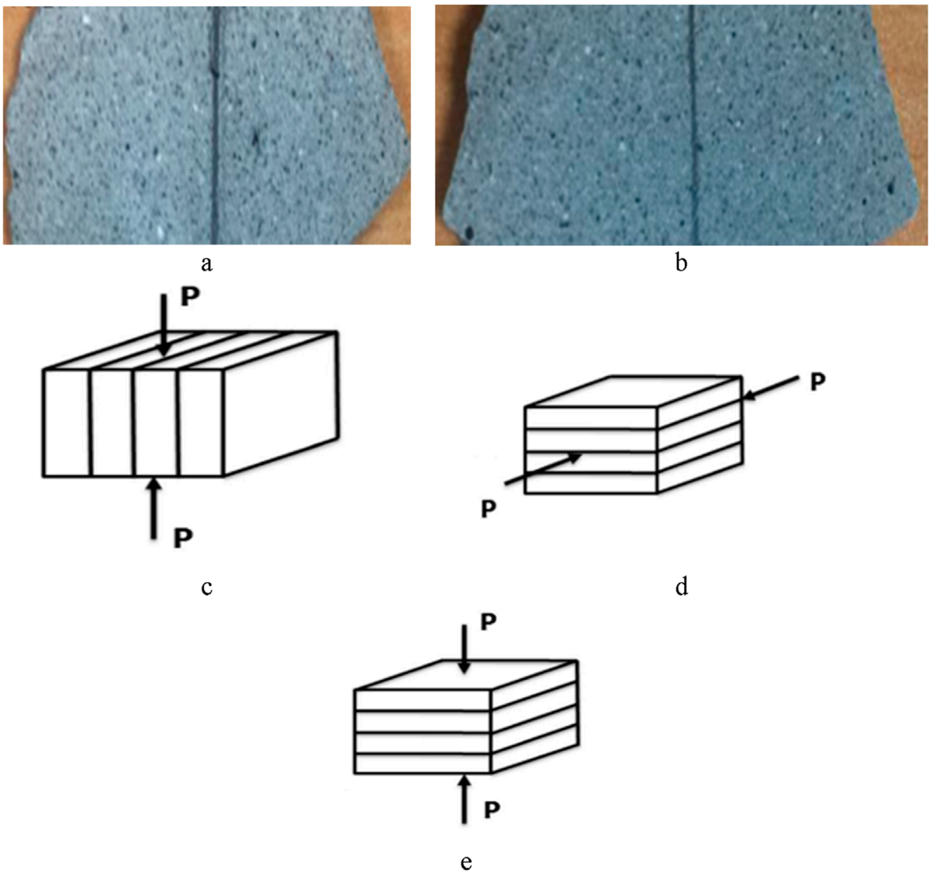

FIGURE 2
3D printing methodology: **(A)** and **(B)** Different thicknesses of opening [based on Liu et al. (2020)], **(C)** Loading in the *X*-direction [based on Paul et al. (2018)], **(D)** Loading in the *Y*-direction [based on Paul et al. (2018)], and **(E)** Loading in the *Z*-direction [based on Paul et al. (2018)].

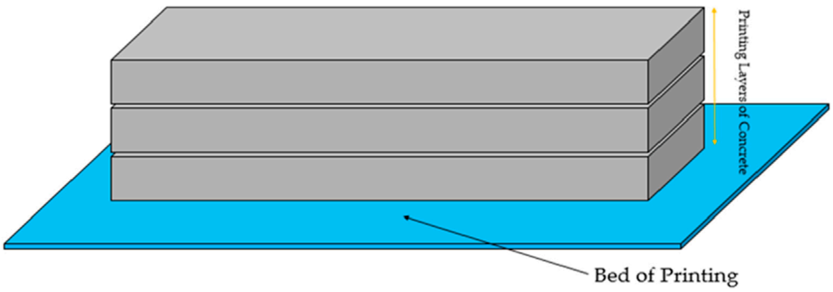

FIGURE 3
3D printing sample test based on Dvorkin et al. (2024).

Fibers on 3D printed concrete can affect the workability, shrinkage, and mechanical properties. For example, adding 1% of steel fiber to 3D printed concrete when cement was 483 g, the aggregates were 1,074 g, the silica fume was 268 g, and the superplasticizer was more than 10.7 g increases the compressive strength more than 109 MPa (Pham et al., 2020). Some studies show that when more than 1% polyethylene (PE) fibers were added, the compressive strength increased by more than 27.3 MPa, when the cement was 1,000 g, the aggregates were g, the water-to-binder percentage was 35%, and the superplasticizer was 1.28 g (Xiao J. et al., 2021). Adding polypropylene (PP) fibers to 3D printed concrete increases the compressive strength to more than 60.5 MPa. In this mixture, the cement was 562 g, the silica fume was more than 81.4 g, the aggregates were 1,144 g, and the superplasticizer

TABLE 1 Best mixture designs for 3D printed concrete.

Reference	Sand (size)	Rice husk ash (size)	Rice husk ash (RHA) (amount of cement)	Binder/sand	Water/binder	Superplasticizer (% binder weight)	Viscosity-modifying agent (% binder weight)	Flowability
Samad et al. (2022)	1.88 mm	75 μm	20%	1:1	0.48 control 0.45 RHA	1-RHA mix	Not available	18.35 mm
Muthukrishnan et al. (2020)	1.7 mm (silica sand)	2–7 μm	20%	1:1.11	0.2 control 0.3 RHA	0.8-control 0.9-RHA mix	0.15	12 mm
Pimentel Tinoco et al. (2023)	Not available	0.075–1 mm	15%	Not available	0.45 RHA	Not available	0.6%	Not available

was more than 4 g (van den Heever et al., 2022). According to studies, when 1.5% of polyvinyl alcohol (PVA) fiber was added to 3D printed concrete, when silica fume was 110 g, the cement was 1,000 g, the aggregates were 1,330 g, and the superplasticizer was 11 g, the flexural and compressive strengths were 10.81 MPa and 45.05 MPa (Zhang and Aslani, 2021).

According to Table 4, steel, polyethylene (PE), polypropylene (PP), polyvinyl alcohol (PVA), and glass fibers can improve flexural and compressive strengths. For example, Singh et al. (2022) found that when fibers that were 13 mm long and 200 μm diameter with a 1% volume fraction added to 3D printed concrete, the buildability improved. Furthermore, considering Table 2, adding different fiber types changed the mechanical properties of 3D printed concrete.

Fiber orientation and fiber position are important in 3D printed concrete. Isotropic distribution and orientation of fibers can change the strength of 3D printed concrete (Grünewald, 2011). The length, type, stiffness, and flexibility of fibers are other important factors. The best aspect ratio range is from 30 to 150; fiber orientation is usually vertical, horizontal, or random distribution (Tattersall, 1991; Banfill et al., 2006; Ferrara et al., 2007; Martinie et al., 2010; Cao et al., 2017; Hambach and Volkmer, 2017; Malaszkiewicz, 2017; Güneyisi et al., 2019). When fiber orientation was changed to horizontal alignment, the flexural strength increased by more than 120 MPa (Hambach et al., 2016). Further studies analyzed different types and new methods in 3DPC technology. Bai et al. (2021) examined desert sand (small size), river-sediment ceramist sand (medium size), and recycled concrete (large size) as aggregates in 3D printed concrete. According to this investigation, adding this type of aggregate reduced the cementitious matrix shrinkage. The best flow velocity was 2.3–3.5 mm/s, and the expanded diameter was 160–210 mm/s.

2.1.3 Technology applications

Some studies focused on large-scale 3D printed concrete buildings. For example, Lowke et al. (2021) studied the rheological properties, the concrete flow rate, and the nozzle displacement velocity. They found that limestone suspension as the carrier liquid reduced the cost and controlled the rheological properties. They found a new method for 3D printed injection with materials such as artificial coral. The printing method was a robot-guided nozzle, and variables included the cross-sectional area of the nozzle. They found that this technology is the best technique for printing truss-type bridges.

Some concrete 3D printers are made for large-scale printing. Zhang et al. (2018a) designed a 3D printer for large-scale printing of concrete with a robotic arm (Figure 4A). Keating et al. (2017) developed a new method compound arm for 3D printed concrete at the Massachusetts Institute of Technology (MIT) (Figure 4B). Figure 3 shows that the tanker carries the materials, and fine aggregates are suitable for these types of 3D concrete printers. Mechtcherine et al. (2019) designed a new type of 3D concrete printer that is based on the concrete truck. According to Figure 4C, this type of 3D printed concrete is a mobile site that can pump 3D printed concrete with coarse aggregate concrete to make large-scale buildings. Figure 4D is a large style delta that was developed by the WASP Company. A disadvantage of this 3D printed concrete printer is mobility because this printer needs to be assembled for building construction. Figure 4E illustrates a 3D concrete printer developed by Tongji University and the Chinese Green Print Company. The

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TABLE 2 Effect of different fiber types on the 3D printed concrete.

Study	Cement (g)	Silica fume (g)	Aggregate (g)	Water (g)	Super plasticizer (g)	Fiber	Volume fraction (%)	Flexural strength (MPa)	Compressive strength (MPa)
Singh et al. (2022)	1,000	—	1,000	350	1.32	Steel	1	-	40/36
Pham et al. (2020)	483	263	1,074	180	10.7	Steel	1	15	109
Ding et al. (2021)	1,000	—	1,000	350	1.28	Polyethylene	1	14	—
Xiao et al. (2021a)	1,000	—	1,000	350	1.28	Polyethylene	1	-	27.3
van den Heever, et al. (2022)	562	81.4	1,144	205	4	Polypropylene	1	-	60.5
Shakor et al. (2019)	375	—	375	124	2.5	Polypropylene	1	18	68
Sun et al. (2022)	1,000	100	—	—	—	Polyvinyl alcohol	1.2	14	74.16
Zhang and Aslani (2021)	1,000	110	1,330	299	11	Polyvinyl alcohol	1.5	10.81	45.05
Chu et al. (2021)	806	101	1,027	263	—	Glass	0.5	—	115

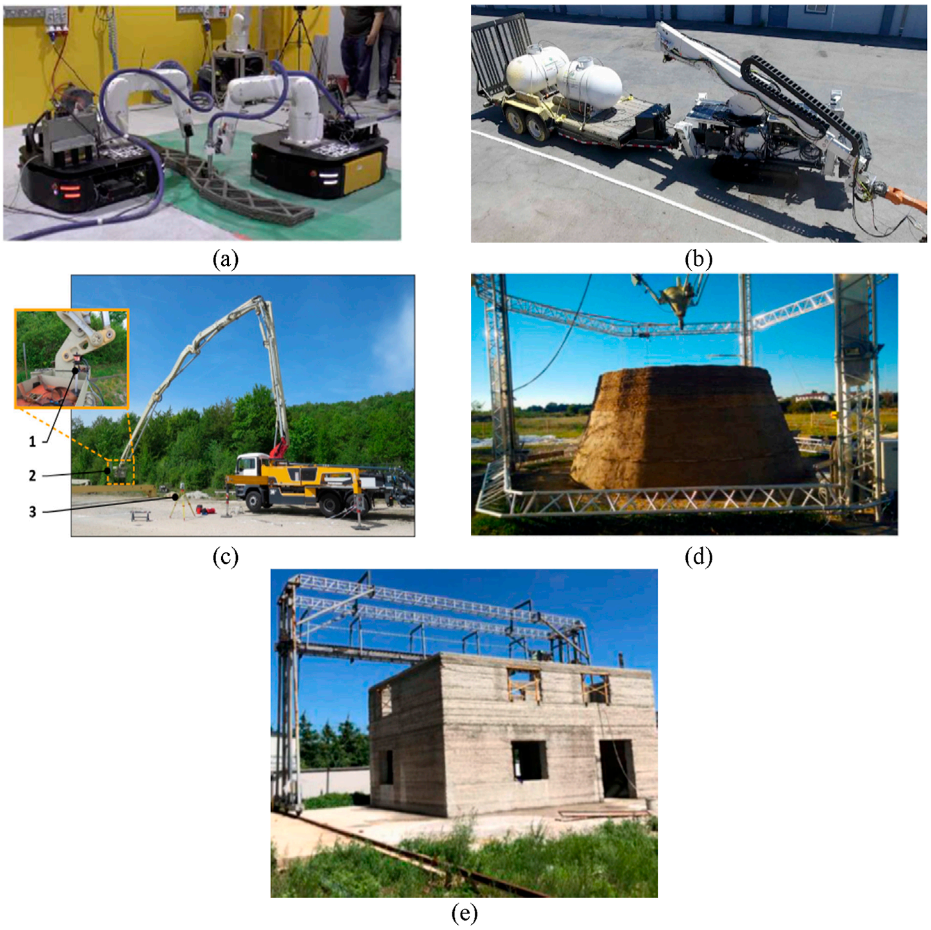


FIGURE 4
3D printed concrete for constructions based on Xiao et al. (2021a). **(A)** Basic arm robotic based on Zhang et al. (2018a), **(B)** tanker base 3D printer (MIT) based on Science (Keating et al. (2017), **(C)** mobile base 3D printer based on Mechtcherine et al. (2019), **(D)** WASP Company 3D printer rails, and **(E)** Chinese Green Print Company.

height of the printer is 10 m, and the printer was moved by rail. In this printer, the maximum material size was 15 mm in the on-site construction project.

The Southeast University and Nanjing Institute for Intelligent Additive Manufacturing developed a new method to design prefabricated and assembled 3D printed concrete particles such as walls, beams, columns, and slabs on-site. Figure 4 shows the 3D-printer technology that can build a 5.15 m high, 286 m^2 building in Nanjing, China. The compressive and flexural strengths are more than 44.6 MPa and 7.4 MPa (He et al., 2020).

2.2 3D printing reinforced concrete technology

2.2.1 Technological aspects

Currently, many studies attempt to reinforce concrete with 3D printing technology like fused deposition modeling (FDM). This type of study tries to add different 3D printing patterns to reinforce concrete. Unlike 3DPC technology, 3DPRC technology uses FDM technology to print reinforced concrete and improve the mechanical properties of concrete.

The most important tools for 3D printing using the FDM method are nozzles, filaments, hot ends, heating blocks, etc. There are two main types of printing methods, direct drive and Bowden. In the direct drive method, the filament moves the filament toward the heating block, and while in the Bowden method, the gears send the string through the Bowden tube to the heating block (Fernandez-Vicente et al., 2016; Bhagia et al., 2021). The nozzle temperature is higher than the PLA melting temperature. The pure PLA melting temperature is more than 180°C–230°C, the semi-melting point temperature of PLA is 150°C–165°C (T_m), and the glass transition temperature is 55°C–65°C (T_g) (Fambri and Migliaresi, 2010; Abeykoon et al., 2020).

Rosewitz et al. (2019) used different 3D printed patterns fabricated by FDM technology and polylactic acid (PLA) as material to reinforce cement mortar. They found that some 3D printing patterns are suitable to improve the flexural strength, and the application of this type of reinforced technology printing is using the beam to reinforce. Salazar et al. (2020) used a 3D

TABLE 3 Reinforced 3D printed concrete methodology in different studies.

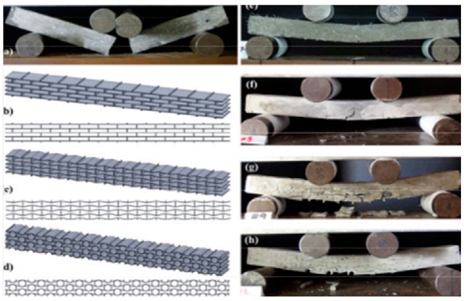
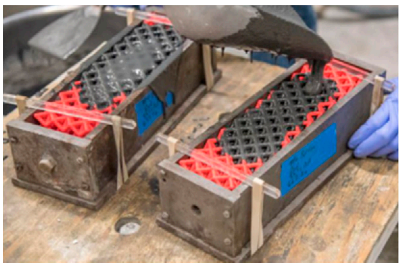
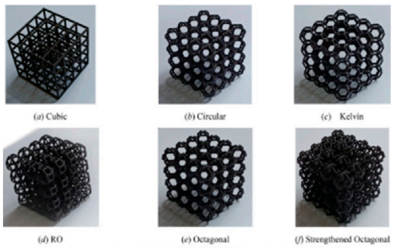
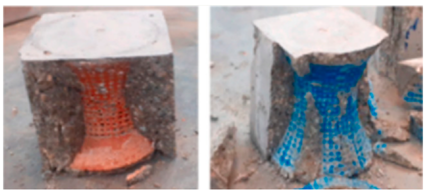
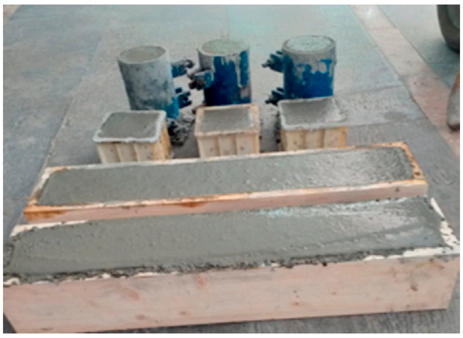
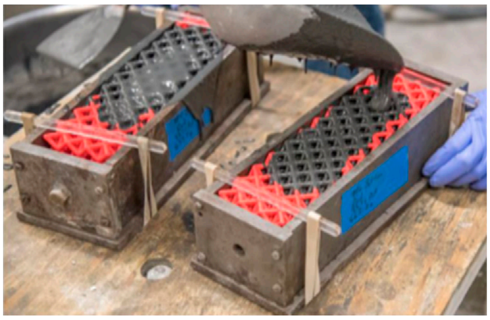
Study	Sample	Materials	Conclusion
Rosewitz et al. (2019)		Different auxetic patterns in polymer materials due to reinforced cement and concrete	Improved ductility and flexural strength
Salazar et al. (2020)		Reinforced ultra-high performance concrete (UHPC) by lattice truss and two different polymer materials	Improved flexural and compressive strength, although it did not cause softening and strain hardening
Hao et al. (2023)		Different polymer pattern types due to reinforced cement and concrete	Improved the compressive strength
Tzortzinis et al. (2022)		Reinforced cement mortar with a hexagon auxetic lattice pattern	Increase the compressive strength by more than 140%
Hematibahar et al. (2023)		Reinforced ultra-high-performance concrete (UHPC) by a hyperboloid shell structure	Decreased the compressive, tensile, and flexural strength, instead of improving the deformation and ductility of samples
Chiadighikaobi et al. (2024a)		Reinforced high-performance concrete (HPC) with different types of trusses	Improved flexural strength and ductility

TABLE 4 Pouring concrete into molds according to different studies.

Study	Sample
Hematibahar et al (2023)	
Chiadighikaobi et al (2024b)	
Salazar et al (2020)	

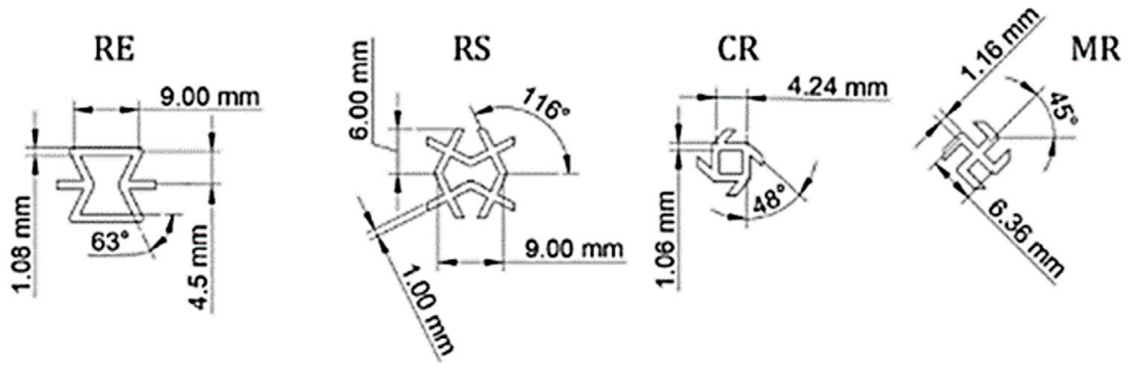


FIGURE 5
Different patterns of auxetic shapes [based on Xu and Savija (2024)].

printing lattice with PLA and acrylonitrile butadiene styrene (ABS) materials to reinforce cement mortar. They understood that the most important factor of adding a 3D printing lattice as reinforcement to cement mortar is improving the strain hardening. The best application of their work was improving the resistance of concrete and cement mortar against earthquake loads. Hao et al. (2023)

TABLE 5 Technology of reinforced 3D printing cement mortar as a self-healing material.

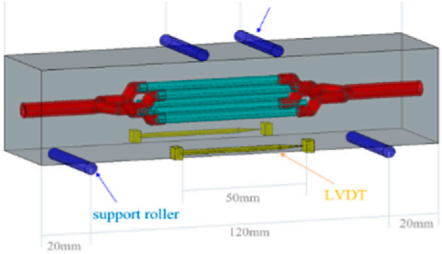
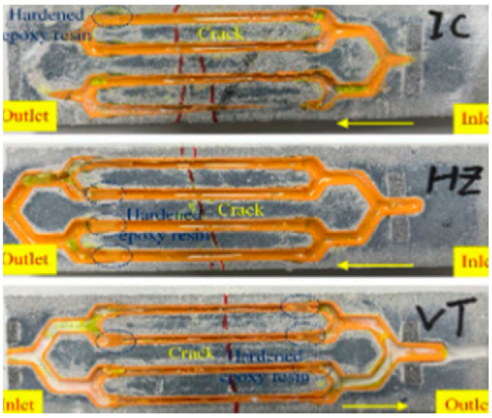
Study	Sample	Applications	Results
Wan et al. (2023b)		Adding self-healing concrete materials via 3D-printing materials	Healing the broken samples and improving the flexural strength
Wan et al. (2023a)		Adding the self-healing ability to concrete through 3D printing	Healing cracks in concrete

TABLE 6 Effect of geometry on the mechanical properties and applications of 3D printed concrete structures.

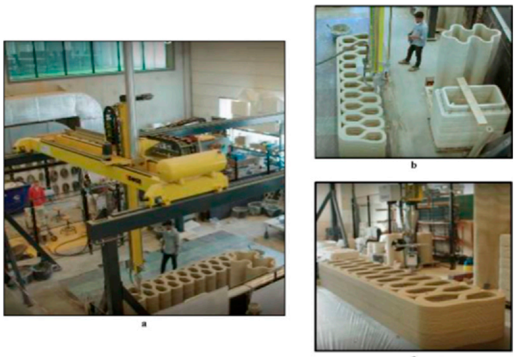
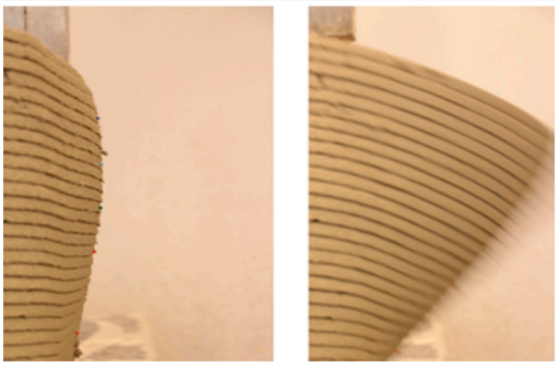
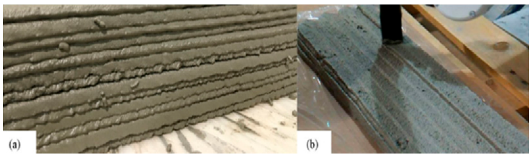
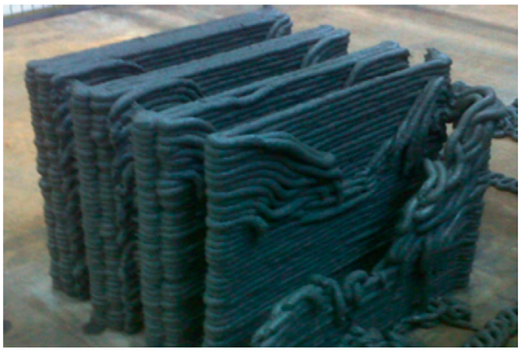
Study	Sample	Application	Result
Salet et al. (2018)		Design pattern and layer thickness to build a new bridge type	Innovative design using cable reinforcement and 3D printed concrete. Suitable design for cycling infrastructure in the Netherlands
Suiker (2018)		Investigation of the buckling and printing layers	According to the results, the 33 layers are the onset of buckling

TABLE 7 Results of studies in the 3D printed concrete properties.

Study	Samples	3D printed concrete properties
Paul et al. (2018)		Anisotropic materials can improve the mechanical properties of concrete
Buswell et al. (2018)		Weakness of the bond between layers might collapse the walls

a b

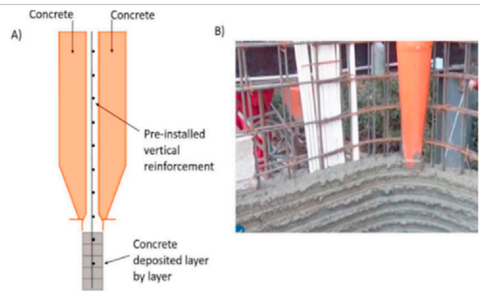
FIGURE 6
Differences between classical and 3D printed concrete building [based on Pessoa et al. (2021)]: **(A)** Classical construction and **(B)** 3D printed concrete [based on Apis Cor. Groundbreaking project: a collaborative project with Dubai municipality (2019)].

TABLE 8 Advantages and disadvantages of 3D printed concrete technology.

Advantage	Disadvantage
Reduces the construction time, otherwise improves the work efficiency (Delgado Camacho et al., 2018) Reduces the carbon footprint and wastage of materials (Rouhana et al., 2014) Increases the recycled materials and environmental-friendly materials (Furet et al., 2019) Decreases the need for human labor (Labonnote et al., 2016) Decreases the building and operation costs (Panda et al., 2017)	Strength of building and structures (Panda et al., 2017) Flowability and durability properties (Panda et al., 2017) Thermal and acoustic behavior (Mechtcherine et al., 2019) Design of a large-scale printer device (Yossef and Chen, 2015) Material properties and material's rheology (Panda et al., 2017) Control of layers and deformation of layers under self-weight (Panda et al., 2017) Layer performance and layer interface properties (Asprone et al., 2018)

investigated using a 3D printed lattice to reinforce cubes and prisms. They understand that reinforced samples increase the compressive strength by more than 71.36%. Using polymer to reinforce cement mortar can improve the durability of concrete and be suitable. Tzortzinis et al. (2022) added 3D printing with hexagon auxetic lattice geometry in cement mortar to understand the compressive strength of reinforced concrete. The compressive strength increased by more than 140%. They understand that using 3D-printing steel fabrication is suitable for resistance structures under cyclic and dynamic loadings. Hematibahar et al. (2023)

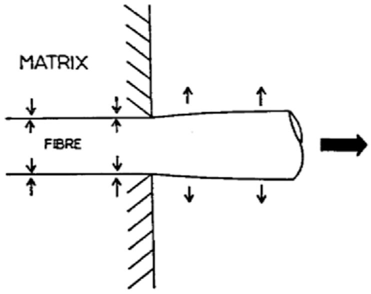
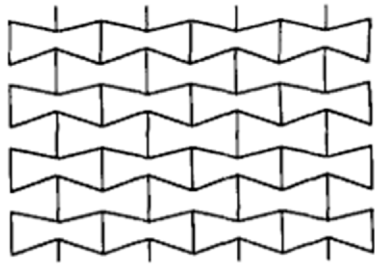
TABLE 9 Applications of 3D printing concrete technology.

Study	Sample	Characteristic	Advantage
Salet et al. (2018)		Cycling bridge using 3D printing concrete technology Span: 6.5 m Width: 3.5 m Construction time: 48 h	Increasing the construction and placing Reduction of structure time
Zhang et al. (2019)		Bus station In different concepts and heights (2.8 m, 3.1 m, and 8.4 m) Construction time: less than 12 h	Reduction of structure time
Lim et al. (2012)		Using 3D printed concrete technology due to architectural issues	Make spaces in 3D printing concrete to install thermal insulation Minimize load or act as a channel for building services
Furet et al. (2019)		Built in Nantes, France, in 2017 95-m square Construction time: less than 54 h	The building was printed with two polyurethane foams and filled with concrete
Marchment and Sanjayan (2020)		Automatically reinforcing 3D printed concrete with rebar	This method can add rebar vertical and horizontal through two nozzles to 3D printed concrete

studied the effect of 3D printing hyperbolic shell structures to reinforce ultra-high performance concrete. They found that 3D printing hyperbolic shell structures can improve the ductility of concrete. Chiadighikaobi et al. (2024a) found that when a 3D printed truss was added to high-performance concrete, the flexural strength improved (Table 3).

At an installation, molds are usually printed, and then concrete is cast into the mold. Molds are prepared according to the design methods of each experiment. Commonly, the structure is first printed using the 3D printing method, then placed into the mold, and finally, concrete is installed into the molds (Table 4).

TABLE 10 First studies of negative Poisson ratio materials (auxetic).

Study	Evans (1991)	Study	Lakes (1993)
			
Cause of study	Negative Poisson ratio fibers	Cause of study	Negative Poisson ratio materials

2.2.2 Material properties

Xu and Savija (2024) analyzed the 3D printed fabrication by PLA as an auxetic shape. They analyzed four types of auxetic shapes: re-entrant (RE), rotating-square (RS), chiral (CR), and missing-rib (MR). According to their results, when RS auxetic structures were added to the cement matrix, the compressive strength increased by more than 18.5%, and ductility decreased by more than 32.2% (Figure 5).

Bol et al. (2024) studied the effect of auxetic added to cement matrix. According to the results, plateau stiffness and strength are approximately 120 MPa and 3 MPa, respectively. They found that when auxetic materials were used, the strain-hardening properties improved by 40% under compression loading. Zhang et al. (2022) introduced a new method to improve the mechanical properties of auxetic materials when added to the cement matrix. They first fabricated chiral lattices with and without circular holes. According to the results, auxetic material with circular holes shows improved load-bearing capacity. Novel chiral lattice composites improved volume fraction by more than 0.1 and 0.5. The investigations show that when different types of materials are used as reinforcement, the mechanical properties of concrete will change. Furthermore, the application of 3DPRC technology is very broad.

2.2.3 Technology applications

Different FDM properties are related to the mechanical properties of 3D printing fabrication. The experiments illustrate that the mechanical properties of cement matrix will change when the geometry and material properties of 3D printing fabrication will change. For example, Wan et al. (2023b) used additive manufacturing to print vascular networks with PVA materials. According to their experiments, the vascular tube made using wax-coated PVA material can dissolve when the proxy resin is injected into the vascular tube as a self-healing material. Finally, the four-point bending test shows the good performance of the proxy resin as a self-healing cement matrix. Similarly, Wan et al. (2023a) analyzed a new method to print vascular tubes via fused filament fabrication (FFF) technology. The resin is injected into the 3D-printed vascular network, the vascular network is dissolved, and the resin self-heals (Table 5).

3 Mechanical behavior of 3DPC and 3DPRC

3.1 Mechanical properties of 3D printed concrete

It is difficult to combine computational modeling and additive manufacturing technology to create new materials and produce 3D printed objects with high dimensional accuracy and high mechanical properties in various industries such as biomedicine, aerospace, automotive, and energy. According to previous research, fresh flowability at the time of extrusion affects the mechanical properties of 3DPC technology (Pal et al., 2014; Seidel and Zaeh, 2018; Wolfs et al., 2018). Various studies show that when silica fume is added to concrete, calcium silicate hydrate (C-S-H) is formed during hydration. C-S-H improves the durability and mechanical properties of concrete, thus creating a bond between layers of 3D printed concrete (Zhang et al., 2018b; Hosseini et al., 2019; Al-Muhit and Sanchez, 2020). According to the geometry of 3D printed concrete, the interface bond between layers and different types of reinforcement, the mechanical properties, and the failure modes of 3D printed concrete are different from conventional concrete. Therefore, there is not yet a design theory for concrete 3D printing. Table 6 shows many parameters, such as design patterns, height of layer patterns, etc., for different studies (Salet et al., 2018; Suiker, 2018; Wolfs and Suiker, 2019).

One important factor in improving the mechanical properties of 3D printed concrete is the distribution of fine aggregates between cement and water. Due to adding the fine aggregates, the nozzle must be so narrow for these sizes to overcome the size of extrusion aggregates (Rushing et al., 2017). Unlike other types of 3D printed concrete, different studies show that concrete with recycled aggregate and industrial waste to replace natural sand had lower concrete mechanical properties (Ma et al., 2018; Xiao et al., 2020). Another important factor is the mixture properties of concrete. According to the research, the compressive strength of 3D printed concrete is less than that of cast concrete with the same composition. Therefore, when the compression of 3D printed concrete printers is reduced, the strength-loss coefficient is used to find the reduction of compressive strength. As a sample, when F-class fly ash and silica fume are added to concrete, they help to

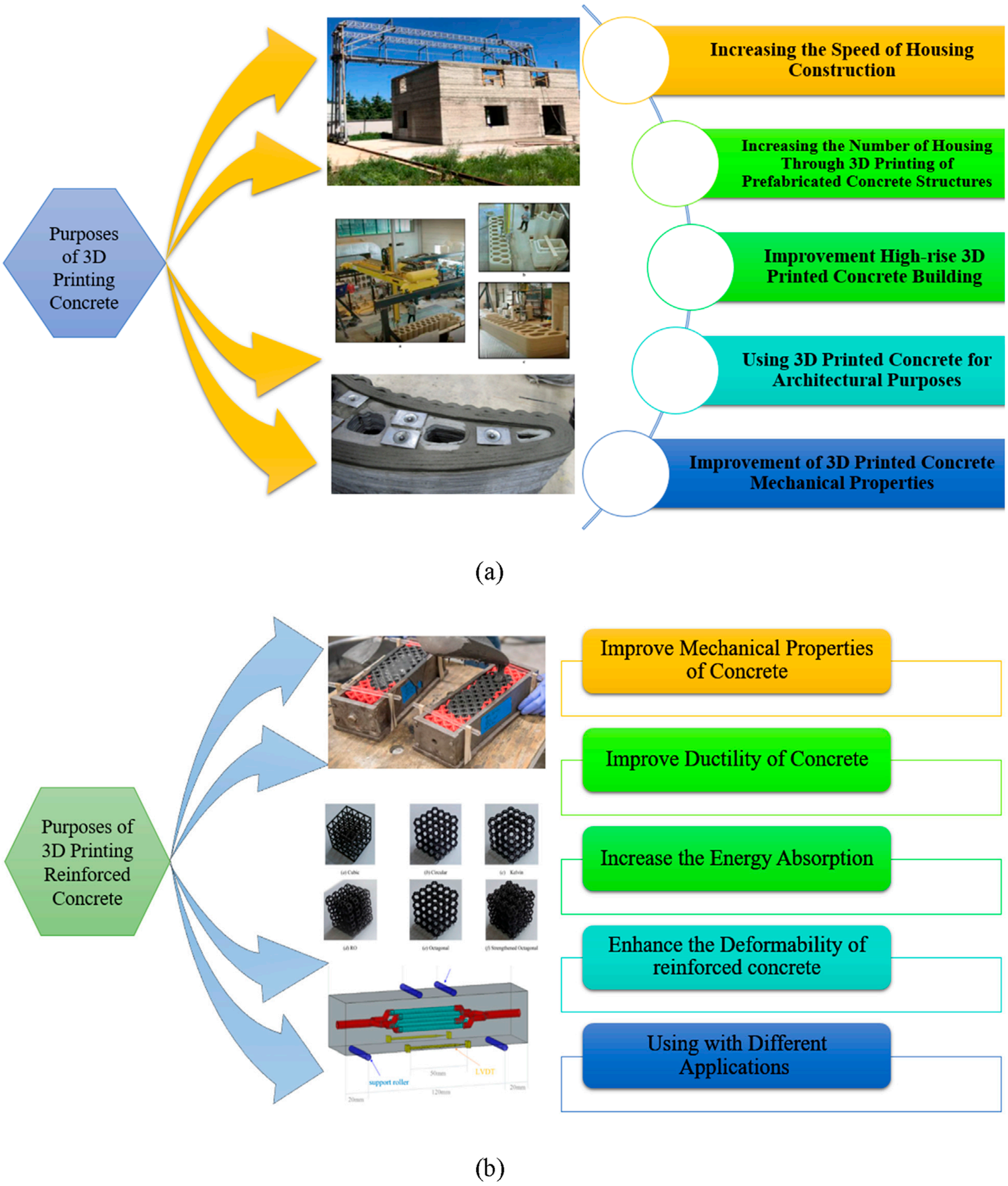


FIGURE 7
Comparison between **(A)** 3D printed concrete technology and **(B)** 3D printing reinforced concrete technology.

decrease the coefficient of strength-loss (Nerella et al., 2019). For example, the water-to-binder ratio and surface moisture condition are two important factors that change the mechanical properties. Results illustrated that although water surface free water is an essential issue in concrete printing, adding more water to concrete due to bonding the cement matrix will weaken the compressive strength of concrete (Papachristoforou et al., 2018; Sanjayan et al., 2018; Keita et al., 2019). Another factor related to tensile and compressive strengths is anisotropic properties. When concrete is printed in the anisotropic direction, the resistance between the layers increases. Another issue is the time interval between printed strings and speed. If the time interval was short, the walls might collapse, and if the time interval was long, the bond between the layers would weaken (Table 7) (Buswell et al., 2018; Paul et al., 2018).

Finally, various research shows that although the addition of fibers, additive powder, and different types of aggregates may improve the strength of concrete, the geometry of the structure, the method of mixing concrete, the ratio of water to binder, etc., can improve the strength of concrete.

There are different applications for 3DPC technologies. Table 7 illustrates the opportunities and challenges of 3DPC technology in construction. The largest challenges in 3DPC technology are improving the strength of the building, flowability, thermal and acoustic behavior, and the rheology of concrete. Other challenges are related to controls of layers, layer properties, and designing large-scale printers.

Using 3DPC technology has numerous benefits. For instance, there are opportunities to increase the usage of recycled materials while reducing building time, carbon footprint, labor requirements, and construction and operation expenses. One of the main benefits of using 3DPC technology over traditional construction methods is that it allows for faster construction than the traditional construction of blocks and mortar.

Figure 6 illustrates the differences between classical construction and 3D printed concrete construction. In terms of economics, it is a zero-waste, low labor cost, and faster and more accurate way to create complicated members. According to Table 8, 3D printed concrete can be used in various structures such as bridges, bus stations, architectural issues, on-site construction buildings, and reinforced 3D printed concrete. Considering Table 9, the common application of 3DPC technology is reducing the construction time and supporting building structures in different forms and designs.

3.2 Mechanical properties of 3DPRC

One important factor to improve the strength of 3DPRC is the use of auxetic material. Auxetic materials are known to be energy absorbent and have negative Poisson ratios (Evans, 1991). Evans et al. (1991) were the first to call this type of material "auxetic." Lakes (1987) achieved a −0.7 Poisson ratio for the first time. Auxetic materials have high mechanical properties such as shear resistance, indentation resistance, potential energy, absorption capacity, and fracture resistance (Table 10) (Lakes, 1993; Evans and Alderson, 2000; Hou et al., 2015; Hu et al., 2019; Li and Rudykh, 2019; Wang, 2019).

Due to the desirable mechanical properties of auxetic materials, many researchers are attracted to the use of these types of materials to improve the mechanical properties of concrete. Zhong et al. (2022) reinforced concrete with auxetic material for energy absorption performance and low density. They used alloy auxetic material to reinforce concrete. They understood that concrete reinforced with auxetic material improves the peak of compressive strength. GÖDEK et al. (2023) studied the effect of 3D concrete printed with different patterns of reinforced cement matrix. They analyzed honeycomb and triangular patterns printed by PLA, ABS, and polyethylene terephthalate glycol (PETG) as materials. They found that when the honeycomb pattern is used with different materials, the load deflection becomes deflection hardening. In another investigation on 3DPRC, Barri et al. (2023) reinforced a conductive cement matrix with auxetic polymer lattices. In this process, the cement is made conductive with graphite powder, with electrical contact between the layers under mechanical stress. The system of auxetic polymer networks achieved more than 15% compressibility cycle loading improvement.

Many studies on reinforced 3D printed concrete have found that when concrete is reinforced with 3D printed polymer, the flexural strength may increase. Another positive effect of adding 3D printed polymer to concrete is changing the strain behavior in terms of strain softening and strain hardening.

For example, when Katzer and Szatkiewicz (2020) reinforced cement mortar with honeycomb and found that the height-to-thickness ratio was high, the flexural strength increased to more than 6 kN, and the strain behavior changed to strain hardening. In another example, Salazar et al. (2020) reinforced UHPC with a 3D printing lattice produced with polymers. The results show that when lattice structure was added to UHPC, the flexural strength improved, and the strain behavior of the beam transferred to strain hardening. Other studies show different results. For example, when Hematibahar et al. (2023) reinforced high-performance concrete (HPC) with a 3D printing shell structure, although the flexural deformation of the beam improved compared to the control samples, the flexural strength decreased, and flexural strain changed to strain softening. In another example, UHPC was reinforced with 3D printing trusses. The authors understood that the flexural improved while the behavior of the beam changed to strain softening (Chiadighikaobi et al., 2024a). Reinforced 3D printed concrete can increase flexural strength. This type of reinforcement can sometimes change strain to strain softening or strain hardening. Differences between concrete reinforced with 3D printing and concrete with steel rebar are mostly related to the strain behavior of concrete beams. The concrete reinforced with steel rebar can change the strain behavior to strain hardening. For example, Belay et al. (2024) compared the concrete reinforced with steel rebar and GFRP and BFRP. They found when concrete was reinforced with different types of rebar, the strain behavior changed to strain hardening. Another study indicated that when concrete was reinforced with steel rebar, the flexural strain behavior changed to strain hardening (Imjai et al., 2024). The differences between reinforced concrete beams and reinforced 3D printed concrete are usually in terms of the strain-hardening behavior of reinforced concrete through steel and rebar types.

4 Discussion

The most important difference between 3DPC and 3DPRC is the difference between the applications of these two technologies. 3DPC technology is related to casting concrete in different ways to achieve the highest mechanical properties, whereas 3DPRC tries to improve the mechanical properties of concrete structural elements. 3DPRC tries to improve the deflection of concrete to the hardening phase.

As an example of 3DPC, Vaitkevicius et al. (2018) created a new binder to improve the compressive strength of 3D printed concrete to 50 MPa over 28-day curing periods. They used cement, silica fume, glass powder, gypsum, and sand (0/2 mm). In their mixture design, the water/cement ratio was 0.46, and the hydration temperature was 36.75°C after 1,493 min. Vaitkevicius et al. (2018) improved the mechanical properties of 3D printed concrete. In another example, Tay et al. (2019a) studied slump and slump-flow tests in 3D printed concrete to find the maximum printing layers before collapsing. They used water, sand, silica fume, and fly ash as mortar materials. They achieved a maximum of 28, 26, 19, and 22 printing layers without collapsing with different types of mortar mixture design. Five mixture designs of 3D printing geopolymer concrete were analyzed by Panda et al. (2017). They found a special freeform structure that was 60 cm tall. They analyzed thixotropic open time, shape retention, and build ability of mixture designs. In another example, Tay et al. (2019b) investigated different 3D printing parameters to find the best construction material. According to their results, the solidity ratio is related to the nozzle travel speed and material volume flow rate, which are two important parameters. As seen, the 3DPC technology tries to improve the mechanical properties of the mixed designs and create a better structural form. Various researchers have analyzed how 3DPC technology can improve concrete structures. Unlike 3DPC technology, 3DPRC technology attempts to improve the mechanical properties of concrete structures and build a new reinforced type with 3D printing, such as the FDM method.

Figure 7 illustrates the differences between 3DPC and 3DPRC technology. 3DPC technology attempts to increase the response to the challenge of population increase by building 3D prefabricated concrete structures and improving the properties of structural materials, and the current technology has a more general view of 3D printing reinforced concrete (Figure 7A). By increasing the mechanical properties of concrete, 3DPRC technology paves its way into the world of civil engineering as new research (Figure 7B).

This research shows that researchers use machine learning and artificial intelligence (AI) to predict the mechanical properties of 3DPC and 3DPRC. Another proposal is to combine 3DPC and 3DPRC and use machine learning and artificial intelligence to predict the mechanical properties and mix design. The design is 3D printed concrete with a 3D printing reinforced concrete reinforced pattern (Hematibahar et al., 2022; Hematibahar et al., 2024b; Chiadighikaobi et al., 2024b).

5 Conclusion

This study analyzed two types of 3D printing technology in concrete technology. Both types of 3DPC technologies help to protect buildings and structures. 3D concrete printers can extrude and print concrete without the need for molds. This technology attempts to print large-scale buildings with high-strength materials and mortars. The reviewed studies employ diverse concrete types and components, which include various types of aggregates in varying sizes. Furthermore, 3D printing has the advantage of not affecting the environment because it replaces the need for casting. Many researchers have studied the mixture of concrete, rheology, flow ability, printability, etc. Finally, 3DPC technology allows for the construction of large-scale concrete structures.

Unlike 3DPC technology, 3DPRC attempts to improve the strain hardening of concrete and cement matrix reinforced by 3D printing structures. When 3DPRC is added to cement materials, the mechanical properties improve. In this way, different types of patterns have different effects on the cement matrix and concrete. For example, auxetic materials improve the strain hardening of concrete. The main results are listed below:

- Both types of 3D printing technologies can improve concrete technology and protect buildings under different loadings.
- Concrete with 3DPRC technology has better mechanical qualities under various loading conditions, including dynamic and seismic loadings.
- 3D printed concrete can make any concrete structure with a variety of designs and different concrete mixing methods. This method can protect various aspects of buildings from an environmental point of view.
- In this study, it is suggested that researchers investigate the 3DPRC columns, the response of 3D printing reinforced concrete structures with seismic dampers, and increasing the scale of experiments due to the rapid progress in this scientific field. In addition, the combination of 3DPC and 3DPRC technology is a possible proposal.

Author contributions

KM: conceptualization, data curation, formal analysis, software, and writing–original draft. NV: funding acquisition, conceptualization, investigation, methodology, project administration, resources, validation, visualization, and writing–review and editing. MH: conceptualization, writing–original draft, data curation, formal analysis, investigation, methodology, and writing–review and editing. TG: conceptualization, data curation, formal analysis, investigation, software, validation, and writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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