International Journal of Modern Manufacturing Technologies
ISSN 2067–3604, Vol. XV, No. 3 / 2023
https://doi.org/ 10.54684/ijmmt.2023.15.3.107

A REVIEW OF THE ADDITIVE MANUFACTURING TECHNIQUES USED IN THE CONSTRUCTION AREA

Catalin Onutu[1], Razvan-Andrei Polcovnicu[1], Nicolae Taranu[1,2], Dragoș Ungureanu[1,2]
Ionut Alexandru Spiridon[1]

[1]Faculty of Civil Engineering and Building Services, "Gheorghe Asachi" Technical University of Iasi, 43 Mangeron Blvd., 700050 Iasi, Romania;
[2]The Academy of Romanian Scientists, 3 Ilfov Street, Sector 5, 050663 Bucuresti, Romania

Corresponding author Razvan-Andrei Polcovnicu, razvan-andrei.polcovnicu@student.tuiasi.ro

Abstract: Additive manufacturing (3D printing) of fiber reinforced mortar/concrete has developed in the last decade as a potential alternative to the classic construction techniques that are used in civil and infrastructure applications. Compared to cast concrete, this technology offers several benefits, including faster prototyping and manufacturing, increased quality, reduced waste and high customization. In this article, there is presented a review of the 3D printing technologies, equipments, mixtures, reinforcements and trending applications that were carried out by various research teams. Also, there are discussed the mix design principles, the role of the superplasticizer and viscosity modifying agents and other factors that may modify the pumpability, flowability, extrudability and buildability of 3D mortar/concrete materials. An important part of this review is dedicated to the desideratum of developing and providing solutions for affordable houses. In this respect, the 3D printed constructions costs are substantially lower compared to the traditional alternatives, being in the same time environmentally sustainable and compatible with the latest European and international plans for climate change.
Key words: additive manufacturing, 3D mortar/concrete, extrudability, printability, buildability.

1. INTRODUCTION

In the past decade, the emergence of 3D printing construction technology has been a remarkable achievement with the potential to revolutionize the construction industry. It offers solutions to residential crises, promotes sustainability and reduces resource waste. The benefits include enhanced resource efficiency, increased construction productivity, compensation for a shortage of skilled labor, and the ability to construct complex structures without formworks. This innovative construction technique involves using additive manufacturing with cementitious materials or real concrete, commonly referred to as 3D concrete printing (3DCP) or 3D printed concrete (3DPC) [1-2]. With the help of robotic assistants, 3D printing technology can convert digital construction data into automated production on the construction site, making it a promising modern technology. In the conventional construction process, shaping of concrete is accomplished through the utilization of formworks that are constructed from materials such as plywood, steel, and aluminum. The formworks are designed to withstand the gravitational load and lateral pressure exerted by the placed material. It is important to note that the cost of formwork typically represents up to 50% of the total construction expenses. If the formwork is not reusable or standardized, this percentage could potentially increase to as much as 80-90% [3-6]. The high cost of formworks in traditional concrete construction has been a major obstacle to its development and optimization, despite the low cost of the concrete material itself. This issue has persisted for centuries, especially in constructing curved or complex structures, and various attempts to find a cost-effective alternative to the temporary false work have not yielded significant results. Nevertheless, the innovative 3D printed concrete technology with layer-by-layer extrusion or selective binding jetting has shown great promise, offering automation benefits in construction and significantly reducing building costs in terms of time, materials, manpower, labor cost, labor accidents and injuries, human errors, and most importantly, by eliminating the cost of false-work [7]. In the realm of the construction industry, the integration of additive manufacturing is closely linked to the pursuit of opportunities to improve effectiveness and profitability within this sector. Recently, the utilization of 3D printing has expanded beyond the construction of residential dwellings to include the fabrication of various structures and urban components. Notable examples encompass a range of impressive creations, such as the 3D-printed bridge in Shanghai developed by Professor Xu Weiguo from Tsinghua University's School of Architecture, the Dubai Municipality building, fully constructed and prefabricated houses produced by Winsun in Shanghai, the headquarters of the Dubai Future Foundation (DFF), the bridge over the

Oudezijds Achterburgwal in Amsterdam, and the Icon-designed 3D-printed homes in Austin, Texas [8 - 10].
The advent of 3D concrete printing technology has introduced promising advancements in the construction industry, offering benefits such as design flexibility, reduced labor costs, and faster project completion. However, it is essential to critically assess the potential disadvantages associated with this emerging technology. The limitations and challenges of 3D concrete printing in construction includes: material constraints, limited structural capabilities, high initial costs, regulatory hurdles, and environmental concerns [11].
The 3D printing technology has also opened up possibilities for constructing freeform, complex shaped, customized, and aesthetically pleasing designs, and much innovative research work has been done in the last decade to achieve this goal. However, the removal of falseworks in the construction process has presented new challenges and difficulties for the industry, such as material selection and mix design, compatible reinforcement strategies, cost-effectiveness, quality control, environmental impact, and long-term durability [8].
The 3D printing concrete technology allows for the rapid fabrication of architectural designs with any shape or level of complexity. This technology also enables the optimization of structural design, making it easier to provide functionally graded materials and members based on stress distribution [9]. Furthermore, it is possible to print multiple material concrete elements using 3DCP. Therefore, this technology is a combination of various disciplines, including architectural design, structural design, material science, mechanics of robotic systems, and controlling software [10, 11]. Research efforts have greatly influenced the development and improvement of 3DCP, leading to a reduction in waste and dust, minimizing material consumption and energy usage, optimizing mix design, reducing logistical demand, increasing environmental friendliness, lowering labor requirements, and reducing the number of fatalities and injuries onsite. Additionally, the printers can perform dangerous and hazardous works, further improving safety measures. Compared to traditional construction, 3DCP is cost-effective, flexible in design, reduces construction time, minimizes construction errors, improves process quality control, provides design freedom, automates the process, and improves sustainability. Continued investigation and experimental work are necessary to remove restrictions and challenges in the way of this technology. Critical and systematic reviews can reveal research gaps, direct research towards the right direction, and provide more insight and understanding of 3DCP [10-12].
During the period from 1998 to 2015, progress in 3DCP research was slow, with only two or three papers published in any given year before 2012 [13]. However, since 2015, research in this field has experienced a significant surge, making today's advancements possible. In the last five years, Elsevier alone has published 337, 466, 570, 900, and 1053 papers on "3D concrete printing" in 2018, 2019, 2020, 2021, and November 2022, respectively [14]. This surge in interest suggests that 3DCP has the potential to play a crucial role in a new industrial revolution. Nonetheless, there is still a need for more research to analyze reported problems and provide effective solutions, overcome limitations and challenges, and address research gaps. This paper offers a comprehensive review of current design methodologies and operational constraints of 3DCP systems, provides insights into technical issues, limitations, and solutions for efficient 3DCP, discusses printing techniques, materials, and commercial applications of 3D printers, and compares recent 3DCP technological advancements with industrial additive manufacturing methods.
Currently, 3D printing techniques and applications have expanded beyond laboratory use for proof-of-concept prototypes, and are being increasingly utilized in the manufacturing industry. This has resulted in a plethora of new innovative products and an expanded production industry. The 3D printing process involves solidifying successive layers of various substances (liquids, powders, solid bars or sheets) through methods such as extrusion, fusion, sintering, polymerization, etc [15]. Additive manufacturing (AM) has explored multiple printing techniques to produce complex, sensitive, and high-quality structures with finer details and resolution compared to their traditionally manufactured counterparts.
The most widely used technology in AM is Fused Deposition Modeling (FDM), (Figure 1) [16], which primarily utilizes polymeric filamentous materials and was invented by “S. Scott Crump” in 1988 [16]. Other techniques, such as SLS (Selective Laser Sintering), SLM (Selective Laser Melting), liquid binding, contour crafting, inkjet printing, stereolithography, DED (Direct Energy Deposition), LOM (Laminated Object Manufacturing), vat photo-polymerization, and PBF (Powder Bed Fusion) have also been successfully implemented in AM [17].
Each technology has its own advantages and disadvantages, and is targeted for specific applications. Therefore, it is challenging to compare the efficacy and performance of each technology. The merits and demerits of each method can be illustrated by evaluating the quality of surface finish, mechanical properties, precision dimensioning, manufacturing time, and cost of materials.
Additive manufacturing involves several techniques for creating three-dimensional objects by layering material upon material. Among these techniques are binder jetting, ink-jetting, powder bed fusion, selective laser sintering, laminated object manufacturing, fused deposition modeling, material jetting, photo-polymerization,

and directed energy deposition [18-19].
In binder jetting, a thin layer of powder is spread over a solid surface and a liquid binder is selectively sprayed onto the powder in a predetermined pattern. The binder quickly solidifies the powder, and this process is repeated hundreds or thousands of times until the desired structure is complete. Ink-jetting, another common technique is often used to create complex ceramic structures for bioengineering applications, such as 3D-printed scaffolds for tissue engineering. In addition to ceramics, other materials such as metallic alloys, polymers, and sands can be printed using this cost-effective and efficient technology.
PBF involves rolling a micro-sized powder into thin layers on a hard surface, and then fusing the powder with a binder or laser beam layer by layer until the object is complete. Excess powder is removed through vacuuming, but the slow printing speed, high cost, and imperfect fused material limit its use [20]. SLS technology, on the other hand, is able to print highly flexible and strong elements using a variety of materials such as ceramics, metallic powders, and plastic.

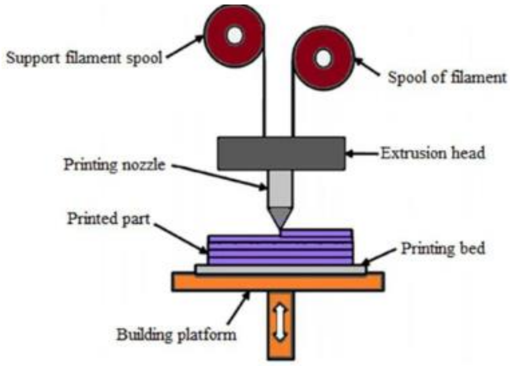

Fig. 1. Fused Deposition Modeling [16]

LOM uses laser or mechanical cutting techniques to precisely cut or laminate material sheets or rollers, which are then fused together to create an object in a process known as "form and bond." This technique is often used in industries such as foundry, paper manufacturing, and electronics.
FDM is one of the most popular AM techniques and involves heating printing material and extruding continuous filaments of thermoplastic polymers and other materials to create objects layer by layer. The heat helps to fuse the layers together and harden them [21].
Material jetting involves dropping material onto predetermined locations to create a prototype. Photosensitive materials are jetted onto a hard surface from a nozzle, and then solidified with the help of an electron beam or UV light to activate chain reactions and harden the layers.
Photo-polymerization uses curing of photoreactive polymers with the help of laser or UV light. Digital light processing and stereolithography are two examples of this technique.
DED is a complex technique that involves fusing more materials onto previously printed components, and is frequently used in strengthening or repairing processes. It is similar to material extrusion and is often used to print materials such as titanium, aluminum, and stainless steel for aerospace engineering. DED is characterized by its rapid printing speed and large work envelopes of up to (6x1.4x1.4)m for commercial printers [22].

2.3. D PRINTING MATERIALS

The wide range of materials that can be produced through additive manufacturing has significantly expanded due to the rapid progress of 3D printing technology. From a simple birthday cake to the most intricate multifunctional materials, AM allows the creation of fully operational objects utilizing diverse substances such as metals, polymers, composites, ceramics, cement, concrete, soil, salt, and even smart or specialty materials.

2.1. Metals and metal alloys

Metal additive manufacturing is displaying great potential for growth as almost half of the companies selling AM systems now involve metal AM [23]. While metal 3D printing has mainly been used for research purposes, component prototypes, and new applications, it has recently been employed for printing short-span and smart bridges. In metal 3D printing, a source of heat or temperature increase, such as an electron beam or laser, is typically used to melt the metallic raw materials. The most common AM technologies used for the 3D fabrication of metallic materials are Directed Energy Deposition and Powder Bed Fusion. However, other relatively new technologies like "friction stir welding," "direct metal writing," "diode-based processes," "binder jetting," and "cold spraying" can also be utilized [24]. Popular 3D-printed metals include stainless steel, aluminum, titanium, and their alloys, while gold has also been successfully printed for the jewelry industry. Nickel-based alloys have been used in aerospace and remote and hazardous environments due to their excellent resistance to corrosive ions and high temperatures up to 1200°C [25]. When compared to conventionally manufactured complex and advanced components, 3D-printed metals using the PBF method have a higher resolution of ±0.02 mm with superior microstructural and mechanical behavior, and the majority of PBF printers are Selective Laser Melting machines [26].

2.2. Polymers and composite materials

The most commonly used 3D printed materials in AM technology are polymers, as they are easily adaptable to various printing systems and are exceptionally compatible with all commercially available AM printers. The adoptable polymers for AM come in various forms such as thermoplastic filaments, reactive monomers, resins, and powders. Polymers and composites have achieved remarkable success in a myriad of applications, including aerospace engineering, fashion and footwear, educational tools and prototypes, architectural components and ornaments, toy fabrication, scaled structural engineering prototypes for buildings, bridges, multi-story structures, and medical applications. Multi-functional AM for polymer nanocomposites and conductive polymers has been applied in countless applications, from soft robotic actuators to tissue engineering, and even organic dual-band antennas [27]. Research on these materials has focused on four main areas: flexible and stretchable electronics, bioelectronics, electrochemical devices, and sensors. Composite and biomass-based materials with incredible versatility, tailorable properties, and low weight have been revolutionizing industries requiring high-performance materials. The most frequently used composites include carbon fiber reinforced polymers (CFRP) (Figure 2) [28], carbon nanocomposites, and glass fiber reinforced polymers [28]. CFRPs are most favored by aerospace engineering due to their high resistance in corrosive environments, exceptional stiffness, and improved mechanical properties such as extraordinary tensile strength for CFRP bars that double that of prestressing strands and ten times higher than that of normal G420 reinforcing steel, combined with some high-quality metallic alloys [29]. Glass fibers are also interesting to many industries due to their high thermal conduction, heat and burning resistance, and low expansion under thermal stresses.

Fig. 2. Carbon fiber reinforced polymers, [28]

2.3. Ceramic materials

Biomaterial fabrication and tissue engineering are among the top industries interested in ceramic additive manufacturing using 3D printing technology to create scaffolds for teeth, broken bones, patellas, and other applications. Ceramic materials are preferred due to their high mechanical strength, long-term durability, high heat resistance, and ability to be fluidized into various desired shapes before setting and hardening. However, the material poses two specific challenges: a relatively lower printing resolution and a layer-by-layer appearance [30]. Post-processing of the printed ceramic to achieve favorable geometries can be costly, increase the manufacturing cycle time per item, and reduce the value of full automation. Research has shown that by optimizing the rheological properties of ceramics and increasing homogeneity, a honeycomb structure with improved mechanical behavior and geometric accuracy, enhanced microstructure, and crack control can be printed.

2.4. Cementitious materials and concrete

If you search any reliable internet database for a list of the most widely used construction materials globally, you will find that concrete is ranked at the top, followed by steel and wood in the second and third positions, respectively. The use of 3D printing technology for concrete can significantly improve the interior and exterior design of buildings and structures, reduce construction costs, and shorten the construction time from months to days. Since its inception, researchers have been exploring the printability of various materials to partially replace cementitious materials in 3D printing pastes in order to mitigate their environmental impact and cost, since high cement content is expensive and significantly contributes to carbon emissions [22]. Commonly blended materials include industrial by-products, pozzolanic materials, and even blended cement-clay. Admixtures and additives are typically used to enhance the mechanical properties, rheology, printability, and setting and stiffening of the mixes. Bloom is a prominent example of using cementitious materials to 3D print complex architectural structures with multiple curved and colorful walls (Figure 3) [31].

Fig. 3. Example of using cementitious materials to 3D print complex architectural structure, [31]

2.5. Earth-based materials

The future of building and infrastructure construction is being driven by economic considerations, sustainability issues, and the environmental impact of materials. In terms of sustainability and environmental friendliness, earth or soil-based materials are the most viable option. Soil has been used as a construction material for thousands of years and many soil structures still stand today. Over the past thirty years, several building codes and guidelines have been developed for earth-based construction [18]. Large 3D-printed adobe structures have been created by blending pot's clayey-soil with finely graded sand to achieve a natural consistency. The Beacon is an excellent example of a successful 3D-printed soil structure.

2.6. Salt materials

Salt's optical translucency allows for light permeability, resulting in a bright and semi-transparent 3D printed structure that shines under sunlight. It can be selectively bound layer by layer using ink jetting printers. The Saltygloo, a large-scale, lightweight and visually appealing structure, is a prime example of 3D printing with salt and was printed in San Francisco [28].

2.7. Smart and functionally graded materials

Smart materials, also known as 4DP materials, refer to 3D printed structures or objects that can alter their dimensions, shape, size, or function over time in response to external stimuli such as temperature or humidity.
These 4DP items are particularly useful in the biomedical field due to their ability to change their geometry over time. Many branches of engineering see 4DP as a significant advancement in 3D printing. Researchers have also experimented with functionally graded materials and multiple material 3D printing, yielding interesting results such as the printing of concrete with varying porosity and unit-weight by gradually mixing cementitious components with lime or metal powders such as aluminum powder. Other printable materials have included cork [8-9]. Additionally, multi-material experimental plant-like 3D objects called Polyphytes have been printed in full-color rigid photopolymer resin with variable levels of opacity to interact with natural elements.

2.8. Special materials

3D printing can incorporate special materials, such as (i) edible materials like chocolate, meat, candy, pizza, spaghetti, and sauce, to produce food in various shapes and sizes. This process allows customers to select and adjust the ingredients for healthy, tasty, and easily digestible food. (ii) The fashion and jewelry industries can benefit greatly from the evolution of textile 3D printing, which can reduce processing time, accelerate printing of ordered items, and lower costs, especially for jewelry, compared to complex handmade items. (iii) 3D printing of lunar dust can be used for constructing space structures, enabling potential colonization of the Moon and Mars [16].

3. PRINTING TECHNOLOGIES OF 3D CONCRETE

3D printing technologies are increasingly being used in the civil construction industry, offering several advantages that traditional construction methods cannot match [18, 20]. These technologies can help to improve efficiency, reduce waste, and provide more sustainable building solutions, making them an important tool for the construction industry of the future [22-24].

Some of the key 3D printing technologies used in civil construction include Contour Crafting, Concrete Printing, Large-Scale 3D Printing, and Modular Construction [7]. Contour Crafting is specifically designed for use in the construction industry and is particularly useful for building walls, floors, and roofs, as it can create complex shapes and curves. Concrete Printing, on the other hand, uses a large-scale 3D printer that can deposit layers of concrete to create walls, columns, and other building components, which is often used for prefabrication [22]. Large-Scale 3D Printing is a more general term that encompasses a range of 3D printing technologies used in the construction industry, while Modular Construction uses 3D printing to create modular components for buildings, reducing construction time and cost [25].

Some advantages of 3D printing technologies in civil construction include efficiency, customization, waste reduction, and safety [10-12]. By automating the production of building components, 3D printing can significantly speed up the construction process, reduce labor costs, and increase productivity. Additionally, 3D printing can be used to create unique, complex shapes that would be difficult or impossible to achieve with traditional building methods, leading to more creative designs and greater flexibility in construction [26]. Moreover, 3D printing technologies use only the amount of material that is needed to create a given component, reducing waste in construction and providing a more sustainable building process. Finally, 3D printing technologies can improve safety in construction by reducing the need for workers to perform hazardous tasks.

However, 3D printing technologies also come with some challenges related to cost, materials, size limitations, and regulatory hurdles [27]. Implementing 3D printing technologies can be expensive, especially for smaller construction projects, and require specialized materials that can be more expensive than traditional building materials. Furthermore, 3D printing technologies are often limited in the size of structures they can create, which can be a disadvantage in the construction industry, where large-scale buildings are common. Finally, regulatory challenges related to the use of these technologies can make it difficult for builders to obtain the necessary permits and approvals to use 3D printing in construction projects [8, 11, 22].

As these technologies continue to develop and become more widely adopted, it will be important to carefully weigh these advantages and disadvantages to determine whether 3D printing is the right choice for a given construction project. Overall, the use of 3D printing technologies in civil construction has the potential to revolutionize the construction industry, leading to more efficient, sustainable, and innovative building solutions.

Building Information Modelling (BIM) is the process of modelling all construction-related information into a 3D database. 3D BIM modelling covers the three primary building dimensions, with the possibility of including time, cost, and sustainability considerations in the form of 4D or 6D BIM [11-12]. The BIM model enables engineers, owners, and contractors to collaborate on planning and design, approving and monitoring activities, events, reports, construction risks, as well as inspecting progress and the structure's state from design to demolition. The emergence of BIM and 3DCP has the potential to aid the development of 3D printing and achieve complete automation of the process. For more information on trending applications of 3DP in this field, please refer to the following references.

The emergence of 3D concrete printing has brought the potential to revolutionize concrete construction by offering various advantages including the elimination of formwork, optimized material usage, improved design freedom, reduced material waste, minimized labor requirements, and cost optimization. Currently, the highly advanced 3DCP technologies are primarily based on extruding concrete filaments, although other techniques such as selective binding have also been explored.

Currently, the most extensively researched and utilized large-scale 3D concrete printing technology is extrusion-based (Figure 4) [32]. This technique involves transporting a well-formulated concrete or cementitious material to a digitally controlled printer, which deposits or pressurizes it through a nozzle-shaped printing head. The concrete is then extruded in sequential layers following a digitally programmed path according to the structure design [33]. After each layer is completed, the nozzle returns to its starting point to print the next layer, provided that the previous layer has gained enough strength to support the next layer and has the appropriate moisture content to bond with it. Some of the most relevant finds related to the working parameters of the extrusion-based 3D concrete printing are listed in Table 1.

Table 1. Print parameters and characteristics of the nozzle utilized in the existing literature

Authors	Design of the nozzle orifice	Nozzle dimensions [mm]	Extrusion speed [L/min]	Printing velocity [mm/s]	Nozzle elevation distance [mm]
Rahul et al. [33]	Rectangular	30 x 20	1.6	44	20
Paul et al. [34]	Rectangular	10 x 20	3	150	_
Panda et al. [35]	Circular	10	0.5	80	_
Le et al. [36]	Circular	9	_	_	6
Asprone et al. [38]	Circular	25	_	20	20
Kezemian et al. [39]	Slice	_	_	60	25.4-38.1

Fig. 4. Extrusion-based 3DCP, [32]

The mixture design for 3DCP typically contains high cement ratios to promote rapid setting and improve mix flowability to meet rheological requirements. However, high cement volumes can increase the process's cost and have negative environmental impacts [34]. As a result, researchers are investigating the use of real concrete in 3D printing structures, and promising results have been achieved.

The printer size and geometry, printing head details, nozzle properties (e.g., size, shape, and speed), material rheological and thixotropic properties, printing pressure (e.g., deposition, low or high pressure), the number, width, and height of filaments, as well as environmental factors (e.g., moisture and temperature), are all critical factors that can influence the quality and stability of the printed structure [5-7].

Contour crafting, which is a technique used for building large-scale 3DCP structures, is commonly employed. However, other techniques, such as concrete printing, ultra-high performance concrete printing, functionally graded concrete printing, and multi-material concrete printing, have also been attempted by various researchers [15, 35]. Contour crafting, pioneered in 1998, is a large-scale digital construction technology that uses multiple-axes robotic arms to print many large and complex geometry structures successfully, without the need for shuttering [26]. With this technology, a hollow wall is first created by printing two parallel lines of continuous multiple layers of filaments to a desired height. Then, when the concrete has hardened sufficiently, the contour space is filled with a cementitious material or concrete, preferably low-slump concrete, to minimize the lateral pressure on the printed contours. The printed structure with contour crafting can be built more quickly, be as large as desired in top view dimensions, be aesthetically pleasing due to its wall textures and surfaces, and be cost-effective due to the use of a higher volume of real concrete for filling, which already contains less cement than the 3D printing pastes [16]. Concrete printing has been used for many more complex lab-scale structures with finer precision than contour crafting due to the smaller nozzle size. It has been implemented in several 3DP projects with normal strength concrete, and ultra-high performance concrete has also been successfully printed [36].

The typical use of 3DP technology involves printing structural components using a single homogeneous material that is designed to withstand the maximum stress caused by external loads (Figure 5) [37].

However, in reality, the stress on members can be concentrated in specific areas, making the full strength of the material unnecessary in other regions. Therefore, optimizing the cross section of members is required to increase material efficiency, but this can lead to additional costs and difficulties in stabilizing printed layers. Two solutions for this issue in 3DCP are functionally graded 3DPC and multiple material 3D concrete printing. Functionally graded 3DPC involves varying the material's packing density and microstructural gradient along extruded filaments or stacked and adjacent layers in any direction. This creates denser regions with higher strength and weakened regions with no or lesser applied stresses. This stress-based mass distribution can create lightweight structural components with improved insulation properties and cost-effectiveness [38]. In multi-material 3DP, materials like cork, lime, or aluminum powder can be mixed with concrete to gradually extrude a variable density 3DPC with improved behavior, [27].

Fig. 5. 3D concrete printing technology [37]

The 3DCP method of selective binding has been extensively studied as a large-scale printing technique for various components. This method involves the use of dozens of pre-programmed nozzles that selectively spray a liquid binder to connect fine sand particles [20, 39]. The process is similar to SLS printing in AM, where a layer of fine sand is spread out and the nozzles spray a magnesium-based binder to bind the sand particles based on the object's design [17]. The second layer of sand is then placed on top of the first layer, and the process is repeated multiple times. During printing, non-bound sand rises layer by layer with the printing component to support the bound particles, and the extra sand can be removed by vacuuming after printing is complete. Selective binding has several advantages over extrusion-based printing, including the absence of the need for careful monitoring and human interference in crossing gaps [5]. However, printed components with selective binding may have higher porosity, less durability, and lower mechanical strength.

4. CONCLUSIONS

While housebuilding techniques have developed over the last two centuries, the involvement of humans, including laborers, technicians, and engineers, has remained constant. Even with advanced machinery and cranes, human intervention is still necessary. However, large-scale 3D printing technology has now made it possible to construct an entire home autonomously, using extruded concrete or cementitious materials based on a 3D design, in just a few hours. To determine the feasibility of 3D concrete printing, it is important to consider seven key parameters, including materials and mix design, structural performance, process efficiency, environmental impact, logistical requirements, labor, and cost. Success in 3D printing technology cannot be achieved by optimizing individual factors alone but by considering all process parameters holistically.
The current use of 3D concrete printing has primarily been for load-bearing compression members, where concrete's inherent strength in resisting compressive stresses is useful. In some cases, tensile stresses have also been applied, such as in precast members or when temporary lintel or opening supports have been removed after 3DCP hardening. However, there is a significant research gap in testing the structural performance of 3DCP precast members under different stress conditions, such as tensile, compressive, and shear stresses, from various types of loading, including live, impact, cyclic, creep, and their combinations. The lack of an efficient reinforcing method is also a significant hindrance in conducting numerous studies on the structural performance of full-scale beams, columns, precast slabs, etc. At present, preinstalled reinforcement is a suitable solution for straight members and walls, while for bearing walls, the premixed and/or interlayer placement of steel or polymeric short fibers may be sufficient. In the case of curved structures or long precast 3DPC beams, the most promising method is posttensioning by prestressing with the addition of steel fibers to resist shrinkage and temperature strains. Currently, the development of 3DCP technology is mostly dependent on large 3DP construction companies and their researchers to announce new achievements and innovative projects.

Acknowledgement: This paper was realized with the support of COMPETE 2.0 project nr. 27PFE/2021, financed by the Romanian Government, Minister of Research, Innovation and Digitalization.

REFERENCES

1. Wangler, T., Lloret, E., Reiter, L., et al., (2016). *Digital Concrete: Opportunities and Challenges,* RILEM Technical Letter, pp. 67-75.
2. Hack, N., Lauer, W. V., (2014). *Mesh-Mould: robotically fabricated spatial meshes as reinforced concrete formwork,* Architect. Des 84, 3, 44-53.

3. Prater, T., Kim, T., Roman, M., Mueller, R., (2018). *NASA's centennial challenge for 3D-printed habitat: phase II outcomes and phase III competition overview, in: Astronaut. Forum Expos.*, American Institute of Aeronautics and Astronautics Inc. AIAA.
4. Patane, S., Joyce, E. R., Snyder, M. P., Shestople, P., (2017). *Archinaut: in-space manufacturing and assembly for next-generation space habitats, in: AIAA SPACE and Astronautics Forum and Exposition*, American Institute of Aeronautics and Astronautics.
5. Dorfler, K., Hack, N., Sandy, T., et al., (2019). *Mobile robotic fabrication beyond factory conditions: case study mesh mould wall of the dfab house*, Construction Robotics, 3(1–4), 53-67.
6. Bos, F., Wolfs, R., Ahmed, Z., Salet, T., (2016). *Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing*, Virtual Phys. Prototyp., 11, 209-225.
7. Tay, Y. W., Panda, B., Paul, S. C., et al., (2017). *3D printing trends in building and construction industry: a review*, Virtual Phys. Prototyp., 12(3), 261-276.
8. Bos, F.P., Ahmed, Z.Y., Jutinov, E.R., Salet, T.A., (2017). *Experimental exploration of metal cable as reinforcement in 3D printed concrete*, Materials, 10(11), 1314.
9. Perrot, A., Rangeard, D., Nerella, V.N., Mechtcherine, V., (2018). *Extrusion of cement-based materials-an overview*, RILEM Technical. Lett., 3, 91-97.
10. Jeong, H., Han, S.J., Choi, S.H., et al., (2019). *Rheological property criteria for buildable 3D printing concrete*, Materials, 12(4), 657.
11. Jayathilakage, R., Sanjayan, J., Rajeev, P., (2019). *Direct shear test for the assessment of rheological parameters of concrete for 3D printing applications*, Mater. Struct., 52(1), 12.
12. Krause, M., Otto, J., Bulgakov, A., Sayfeddine, D., (2018). *Strategic optimization of 3D concrete printing using the method of CONPrint3D*, ISARC - Int. Symp. Autom. Robot. In Constr. Int. AEC/FM Hackathon: the Future of Build. Things, Int. Association for Automation and Robotics in Construction IAARC.
13. Tay, Y.W.D., Ting, G.H.A., Panda, B., He, L., Tan, M.J., (2018). *Bond strength of 3D printed concrete*, Proc.Int. Conf., Pro-AM.
14. Ma, G., Wang, L., (2018). *A critical review of preparation design and workability measurement of concrete material for largescale 3D printing*, Front. Struct. Civ. Eng., 12, 382-400.
15. Tay, Y.W.D., Ting, G.H.A., Qian, Y., et al., (2019). *Time gap effect on bond strength of 3D-printed concrete*, Virtual Phys. Prototyp., 14(1), 104-113.
16. https://www.mdpi.com/2073-4360/15/1/28, last accessed on 05.03.2023.
17. Verma, R., Kaushal, G., (2019). *State of the art of powder bed fusion additive manufacturing*, 3D Printing and Additive Manufacturing Technologies, Springer Singapore, Singapore, pp. 269-279.
18. Derby, B., (2010). *Inkjet printing of functional and structural materials: fluid property requirements, feature stability, and resolution*, Annu. Rev. Mater. Res., 40(1), 395-414.
19. Glasschroeder, J., Prager, E., Zaeh, M.F., (2015). *Powder-bed-based 3D-printing of function integrated parts*, Rapid Prototyp. J., 21(2), 207-215.
20. IEA, (2022). *Roadmap for Energy-Efficient Buildings and Construction in the Association of Southeast Asian Nations*.
21. da Silva, W.R.L., Fryda, H., Bousseau, J.N., Andreani, P.A., Andersen, T.J., (2020). *Evaluation of early-age concrete structural build-up for 3D concrete printing by oscillatory rheometry*, Advances in Additive Manufacturing, Modeling Systems and 3D Prototyping, Spr. Advances in Intelligent Systems and Computing, pp. 35-47.
22. Roussel, N., (2007). *Rheology of fresh concrete: from measurements to predictions of casting processes*, Mater. Struct., 40(10), 1001-1012.
23. Ahmed, H.H., Ali B., Alyousef R., (2021). *Assessment of high performance self-consolidating concrete through an experimental and analytical multi parameter approach*, Materials, 14, pp. 985.
24. Drewniok, M.P., Cygan, G., Gołaszewski, J., (2017). *Influence of the rheological properties of SCC on the formwork pressure*, Procedia Eng., 192, 124-129.
25 Ahmed, G.H., (2021). *Influence of mixture proportions on fresh and mechanical properties of self-consolidating concrete*, Polytechnic J., 11(2), 17-25.
26. Aziz, O.Q., Ahmed, G.H., (2012). *Mechanical properties of ultra-high performance concrete (UHPC), 12th int. conf*, Recent Advances in Concrete Tech. And Sust. Issues, SP-289, ACI Special Publication, Farmington Hills, MI, pp. 1-16, 289.
27. Wolfs, R.J.M., Bos, F.P., van Strien, E.C.F., Salet, T.A.M (2018). *A Real-Time Height Measurement and Feedback System for 3D Concrete Printing*, Springer Int. Pub. Cham, pp. 2474-2483.
28.https://www.researchgate.net/figure/Typical-structure-of-Carbon-Fiber-Reinforced-Polymer CFRP_fig2_283308870, last accessed on 05.03.2023.

29. Matos, P.D., Zat, T., Corazza, K., et al., (2022). *Effect of TiO2 nanoparticles on the fresh performance of 3D-printed cementitious materials,* Materials, 15, pp. 3896.
30. Liu, D., Savija, B., Smith, G., et al., (2017). *Towards understanding the influence of porosity on mechanical and fracture behaviour of quasi-brittle materials: experiments and modelling,* Int. J. Fract., 205, 57-72.
31. Jo, J.H., Jo, B.W., Cho, W., Kim, J.H., (2020). *Development of a 3D printer for concrete structures: laboratory testing of cementitious materials,* Int. J. Concr. Struct. Mater., 14, pp. 13.
32. Anleu, B., (2018). *Quantitative micro XRF mapping of chlorides: possibilities, limitations, and applications, from cement to digital concrete,* ETH Zur.
33. http://emergingobjects.com/project/bloom-2/, last accessed on 05.03.2023.
34. https://3dconcreteprinting.info/, last accessed on 05.03.2023.
35. Rahul, A. V., Santhanam M., Meena H., Ghani Z., (2019). *3D printable concrete: mixture design and test methods*, Cem. Concr. Compos., 97.
36. Paul, S. C., Tay, Y. W. D., Panda, B., Tan, M. J., (2018). *Fresh and hardened properties of 3D printable cementitious materials for building and construction*, Arch. Civ. Mech. Eng., 18.
37. Panda, B., Unluer, C., Tan, M. J., (2018). *Investigation of the rheology and strength of geopolymer mixtures for extrusion-based 3D printing*, Cem. Concr. Compos., 94.
38. Le, T. T., Austin, S. A., Lim, S., Buswell, R. A., Gibb, A. G. F., Thorpe, T., (2012). *Mix design and fresh properties for high-performance printing concrete*, Mater. Struct. Constr., 45.
39.https://www.bft-international.com/en/artikel/bft_Chemical_Admixtures_For_3D_Printing_of_Concrete-3772184.html, last accessed on 05.03.2023.
40. Asprone, D., Auricchio, F., Menna, C., Mercuri, V., (2018). *3D printing of reinforced concrete elements: technology and design approach,* Construct. Build. Mater., 165.
41. Kazemian, A., Yuan, X., Cochran, E., Khoshnevis, B., (2017). *Cementitious materials for construction-scale 3D printing: laboratory testing of fresh printing mixture*, Construct. Build. Mater., 145.

Received: April 27, 2023/ Accepted: December 15, 2023 / Paper available online: December 20, 2023©
International Journal of Modern Manucaturing Technologies