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Review

Sustainable Non-Conventional Concrete 3D Printing—A Review

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Abstract: In this review article, system materials for concrete 2D printing have been discussed, along with the various other aspects that are connected to sustainable construction. The article consists of an introduction giving the background of manufacturing that started almost two decades ago, including the non-conventional methods of building structures. It has been seen that there are various stainable materials in the field of 3D printing in construction, as the conversion of construction to 3D printing reduces waste generation. Further in this article, the cost comparison between conventional and non-conventional construction methods has been discussed, including the effectiveness of 3D printing; 3D printing is very effective in the sense that it requires the precise use of machinery and construction material. Full-scale 3D printing has also been seen in the building sector, but only to some extent. Some of the components of bridges, and even some of small bridges, have been constructed using 3D printing and ultra-high-performance concrete. Since there are various advantages to 3D building, there are also various disadvantages to 3D printing, such as how much it costs and finding the materials that are suitable for 3D printing, which might increase the cost. Polymers have also been used in 3D printing construction since polymers have a very long lifespan, and polymers may increase the strength of the final product by reinforcing the aggregate. Additionally, this technology gives us the opportunity to use various materials together for construction, such as recycled aggregates and geopolymers, along with concrete and cement, which might pose some challenges but are being used nowadays. A major concern with this technology is its impact on the labor market. Since in traditional construction huge amounts of man hours are required, concerns have been raised about the inclusion of this technology, as this might affect employment. Since most of the work will be done by machines, the need for labor will reduce. These are some of the issues that need attention. Finally, this article discusses the novelty and future scope of 3D printing in the construction sector, and concludes by outlining the scope of potential developments for 3D printing concrete by taking into account sustainability.

Keywords: sustainable materials; AM; 3D printed concrete; 3D printed building materials

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1. Introduction

The 3D printing of sustainable non-conventional cementitious materials is an innovative technique that is revolutionizing the existing construction sector [1]. This technique has the ability to change the construction sector by decreasing its environmental effect and improving its productivity. The fundamental objective of creating 3D printing techniques for the construction sector is to improve construction efficiency [2,3]. In addition, it has the ability to reduce building waste and increase the flexibility of shape of produced objects. Traditional concrete construction methods involve the use of cement, sand, and water, which have a significant carbon footprint due to their production and transportation [4]. In contrast, sustainable non-conventional concrete 3D printing uses a variety of materials, including recycled aggregates, industrial by-products, and bio-based materials, to reduce the carbon footprint of the construction process. In addition to its sustainability

benefits, 3D printing allows for the precise placement of material, reducing waste and increasing resource efficiency. The technology also offers design flexibility, allowing for the generation of complicated shapes and geometries that would be problematic or impossible to obtain with conventional construction techniques [5]. This can lead to the more efficient use of space and improved functionality. One of the key challenges in sustainable non-conventional concrete 3D printing is the development of new materials that meet the mechanical and durability requirements. These materials must also be compatible with the 3D printing process and optimized for efficient and cost-effective production. In comparison to conventional methods of building construction, 3D printing technology can be viewed as an environmentally beneficent alternative that allows for nearly limitless geometric complexity of implementations [6]. The improvement of printing materials and 3D technology has become a priority for organizations in various industries across the globe. Using 3D printing in construction has been reported to reduce fabrication waste, labor costs, and production. In recent years, the 3D printing of cementitious materials has received a substantial amount of attention globally, despite its modest development compared to other construction and architecture industries [7].

About 6% of the worldwide gross domestic product is generated annually by the construction market [8]. The construction and engineering sector is indeed a pillar of the global economy. Always on the lookout for cost-effective methods to enhance productivity, the construction sector searches for novel approaches to increase efficiency. Research indicates that construction sector labor productivity has been falling over time [9]. A lack of deployment of new technologies is one of the factors contributing to this drop. Numerous factors are pushing the construction industry towards automation, including a reduction in labor for safety concerns, a decrease in construction time on-site, a decrease in manufacturing costs, and/or the expansion of design flexibility [10,11]. Moreover, 3D printing helps to address environmental concerns. The construction/building sector has been identified as a major consumer of resources and a major environmental stress factor. In the area of sustainable 3D construction, various materials have been found to date, including geopolymers [12]. In addition, recycled aggregates, such as crushed concrete, brick, and glass, are commonly used as a sustainable alternative to virgin aggregates in 3D-printed concrete [13–15]. These materials not only reduce the environmental impact of construction, but also provide a cost-effective solution for managing construction waste. By-products from industry, such as slag, fly ash, and silica fume, are also commonly used as a sustainable alternative to cement in 3D-printed concrete [16]. These materials are produced as a by-product of industrial processes, and their use in concrete reduces the need for virgin cement, which has a significant carbon footprint [17]. Bio-based materials, such as hemp and bamboo fibers, are also being investigated as a sustainable alternative to traditional reinforcement materials in 3D-printed concrete [18]. These materials are renewable and biodegradable, reducing the environmental impact of construction and increasing the sustainability of the built environment. Recycled aggregates and various other non-conventional materials can be used to reduce carbon footprints. Recycled aggregates and other nontraditional materials can reduce carbon footprints in multiple ways. First, the use of recycled aggregates and unconventional materials typically requires less energy than the manufacture of new materials from virgin sources. This results in energy savings during manufacturing processes. In addition, incorporating regional sources of these materials lessens the demand for long-distance shipping, resulting in lower transportation-related carbon emissions. This serves to reduce the carbon footprint overall. Along with diverting waste from landfills, the use of recycled aggregates and unconventional materials in construction projects prevents the production of waste. This is important because it reduces methane emissions, a potent greenhouse gas, associated with landfill decomposition. In addition, nonconventional materials, such as geopolymers and engineered wood products, have the capacity to sequester carbon dioxide during their production or service life. This means that they store carbon instead of discharging it into the atmosphere, further reducing their carbon footprint. In addition, nontraditional materials frequently possess superior

durability and performance characteristics compared to conventional materials. This extends the lifespan of buildings and infrastructure, reducing the frequency with which they must be replaced or repaired. As a result, carbon emissions associated with the production and transportation of new materials are reduced. Using recycled aggregates and nontraditional materials reduces the demand for new raw materials such as natural aggregates, whose extraction requires energy-intensive processes. By conserving natural resources, extraction- and processing-related carbon emissions can be reduced. Incorporating recycled aggregates and nontraditional materials into construction projects can reduce the carbon footprint of the constructed environment and contribute to more sustainable practices, and we can also use these materials in the sustainable 3D printing process.

Another challenge in sustainable non-conventional concrete 3D printing is the need to establish industry standards and regulations for the utilization of alternative materials in building and construction. This includes the development of testing and certification procedures to ensure the safety and performance of 3D-printed concrete structures. Despite these challenges, sustainable non-conventional concrete 3D printing holds significant potential for transforming the construction industry and creating more sustainable and resilient built environments [19]. By reducing the environmental impact of construction, improving resource efficiency, and increasing design flexibility, technology has the potential to enable the creation of more sustainable and livable cities. The benefits of sustainable non-conventional concrete 3D printing extend beyond environmental sustainability. The technology also offers benefits in terms of construction speed and cost-effectiveness [20,21]. Such 3D printing or additive manufacturing allows for rapid and automated concrete structure construction, reducing the need for labor-intensive and time-consuming construction methods. Moreover, 3D printing can reduce construction costs by minimizing material waste, reducing labor inputs, and enabling the use of alternative materials that are often less expensive than traditional construction materials. This can make construction more accessible and affordable, particularly in low-income and underserved communities, as well as when used in the area of sustainable concretes. Smart materials are also being used, which can also be considered a sustainable contributor in the area of the 3D printing of construction material. However, different restrictions are faced during the 3D printing process, which are viscosity, detail/resolution, weight support, layer adhesion, time/size limitations, complex geometries, mix design, and post-processing.

Nevertheless, plastics, metals, ceramic, and concrete are among the many resources that have been or are being utilized in the field of concrete 3D printing (cement-based material). Ceramics are primarily used to produce scaffolding, while concrete is the most important item in the 3D printing of structures. It is evident that tremendous advancements have been made in 3D printing technology in terms of printer equipment and materials. Nowadays, 3D printers can produce end-user objects with precise dimensions, better surface roughness, and enhanced mechanical qualities. In addition, significant developments have pushed 3D printing into a platform for research in materials, enabling researchers to modify anisotropic behavior, material deposition, and active sensing based on environmental conditions. These accomplishments would pave the road for additional 3D printing technology advancements. Project delays, abandonment, and time overruns, as well as difficulties in safety, inefficiency, budget overruns, design inflexibility, and waste of material, plague the construction sector due to a lack of vital information. Increasing populations have created problems with housing for low-/middle-income families. Only the wealthy and influential can now afford residences where they have complete control over the design and implementation. Not only this, but the 3D printing of concrete has significant effects also on the labor market, as new 3D printing machines will be used, and there may be losses of certain jobs [22]. Here, 3D-printed concrete revolutionizes construction with customizable designs, sustainability, efficiency, and enhanced properties. Curved shapes, material optimization, sensors, automation, and replicability are key advantages. Such 3D concrete printing could revolutionize the construction business, and allows one to customize buildings to individual tastes and site needs. Sustainable construction uses

technology to include eco-friendly materials and lower project carbon footprints. Printing complicated shapes enables organic architectural designs with intricate detailing. Further, 3D concrete printing can integrate practical features such as utilities and embedded sensors directly into constructions. Technology will allow the printing of larger buildings, thus changing large-scale construction projects. Automation and robotics will speed up and improve printing. On-demand construction can speed up infrastructure deployment and disaster assistance. Safety and quality standards must be developed by academics, industrialists and regulators, and 3D concrete printing has the potential to change the construction sector by improving efficiency, sustainability, and design. Research, development, and collaboration will help this technology reach its full potential. Ongoing research drives improvements in printing techniques, materials, and structural capabilities. However, in this article, various aspects of sustainable 3D printing have been added, since huge amounts of the literature have been studied, and most of it lacks an overall combined review of the sustainability approach to 3D printing. In this article, the combined approach has been employed to include the background and possible usages of the SCMs in construction. In Section 2, the background has been discussed, along with the non-conventional methods used in the building sector. Section 4 has been dedicated to the availability of sustainable materials in construction, which includes geopolymers. Moreover, Section 5 includes a cost comparison between the conventional and non-conventional materials, which is also a novelty, as actual data have been reported. Sections 6–8 are dedicated to effectiveness, full scale printing, and the printing of ultra-high-performance materials, respectively. The next section discusses the advantages and disadvantages of concrete 3D printing. Polymers, including reinforced polymers, have also been discussed in Sections 11 and 12, including a multi-material AM in Section 13. In the final two sections, the challenges for and impacts on the labor market have been discussed, which is also one of the novelties of this work, since the labor market will be affected by the inclusion of AM in construction sectors.

2. Background of AM in Construction

In construction, AM is used to create building components, structures, and even entire buildings. This approach has the ability to revolutionize the construction sector by cutting costs, boosting efficiency, and enabling the production of sophisticated designs that would be difficult or impossible to produce with conventional building techniques [23]. AM in construction can be accomplished using various materials such as concrete, plastics, metals, and even organic materials, as we have discussed in the Introduction. The most common substances utilized in construction and the building sector is concrete, as it is relatively easy to work with, readily available, and has excellent compressive strength. One of the benefits of using AM in construction is that it reduces waste, as it allows for precise material placement, reducing the amount of material needed [24]. Additionally, AM can create custom designs and shapes, making it possible to create structures that are both aesthetically pleasing and structurally sound. AM is responsible for the manufacturing of wide range of structures, such as bridges, walls, floors, and even entire buildings [25]. For example, in 2018, a team of researchers from ETH Zurich created a fully functional 3D-printed concrete footbridge in Switzerland. The bridge was printed in six sections, which were then transported to the site and assembled. This project demonstrated the potential uses of AM in construction, and its ability to create complex and structurally sound designs [26]. AM is a promising technology in the construction industry, and it has the potential to revolutionize the way we build. It offers numerous benefits, including reduced waste, increased efficiency, and the ability to create complex designs. As the technology continues to advance, it is likely that we will see the more widespread adoption of AM in construction.

Moreover, in comparison to other industrial methods, digital fabrication techniques using concrete have been the subject of extensive research and industrial activities in recent years. Digital concrete is separated into two subcategories on the basis of the undertaking of formwork during the manufacturing of the concrete: (a) 3D concrete

printing (3DCP) without formwork, which can be accomplished via the layer-by-layer deposition of extrudate, particle-bed selective binding 3D printing, and the technology of shotcrete, also called shotcrete technology; (b) non-conventional formwork and temporary formwork. Figure 1 provides details on the two primary kinds of digital concrete.

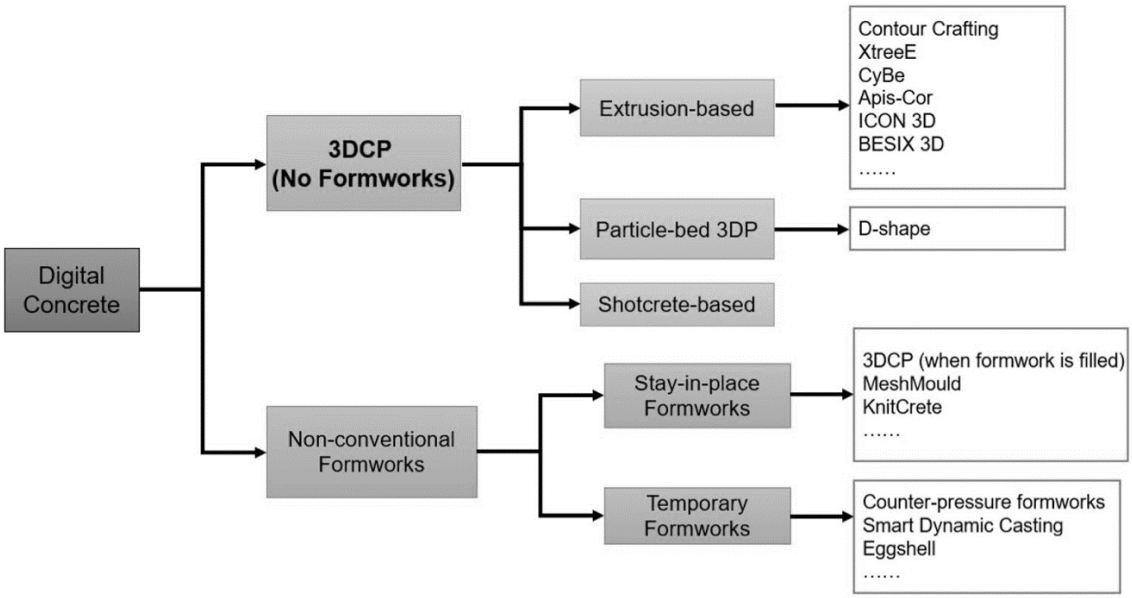


Figure 1. Description of digital concrete fabrication.

In particular, extrusion-based 3DCP is now receiving a great deal of global attention due to the greater level of technological preparedness for building and the strong financial advantages resulting from non-formwork characteristics.

Due to its dual characteristics, concrete involves greater requirements related to material properties than conventional cast concrete [27]. On the one hand, it must have sufficient flowability to be delivered to the print nozzle and extruded from the nozzle or nozzle head. After this, immediately following extrusion, the material must show a high initial durability to sustain successive layers without undergoing severe deformation.

3DCP employs a variety of printers, including gantry printers, robot printers, crane printers, and smart robot systems, among others [28]. Layer-by-layer deposition follows the pumping or extrusion of concrete (usually mortar), which requires the material to have low viscosity. For a 3D-printed structure, as shown in Figure 2, to be successful, the material must have a high yield stress and strong structural qualities following extrusion, which can be regulated by adjusting the mix concentrations on a microscale level. However, wood has not been used in the 3D-printing industry, and its use has not even being tried because of the natural formation of wood.



Figure 2. Examples of 3D-printed structures [29] (reproduced with permission from Elsevier, License number 5574841136192).

3. Non-Conventional Methods of Building Structures

The construction field is always seeking innovative ways to increase the competitiveness and efficiency of projects. Numerous new techniques, including Business Information Modeling applications and project management software, have been developed to facilitate pre-construction and onsite collaboration [30]. Yet, traditional construction techniques have persisted mostly unchanged for years. 3DCP is a fascinating modern technique [31] that has the ability to not only increase project effectiveness and revenue in the field, but also positively benefits the environment. In its current state, this technology is severely constrained by material, size, industrial resistance, and the need for specialized labor. This section examines forward-thinking 3D printing companies that have been able to implement this technology on a wide scale. The objective of the section is to explore the present applications of 3D printing in the construction industry, and to explain the best practices and usages given the limitations of the technology.

The most commonly used and effective non-conventional method in the building sector is 3D concrete printing, because conventional methods do not allow for the rapid construction of the building, as is achieved by 3D concrete printing. This section discusses the principles and techniques of 3D printing. In this context, 3DCP refers to a variety of processes, as shown in Figure 3, that generate objects by successively layering concrete until the desired shape is achieved [32]. The operating concepts of 3DCP devices are identical to those of polymeric and metal 3D printers. However, 3DCP-constructed constructions, such as sidewalls and complete floors, are substantially larger than those made of conventionally printed metals and polymers. The bigger the dimensions of printed features, the more probable it is that minute flaws will occur during the printing procedure, thereby making it more challenging to establish a rigorous quality-supervision procedure. The most appealing feature of this printing technology is the ability to produce complicated geometries without any other framework [33]. One thing that is very important to note is that the cost of the framework could be as much as 10% of the total cost of the project and the total cost of construction [34]. Since they can usually only be utilized a limited number of times, wood formworks are a significant contributor to landfill garbage. In future, the consumption of materials can be reduced by using this printing technology. At the same time, the demand for raw materials would go down, and this would lessen the environmental impact of building operations and concrete production. It also provides architects and engineers more latitude for experimentation with unique shapes in structures for the improvement of air flow and energy efficiency, hence lowering the environmental impact over the lifecycle of the built environment. In addition to material savings, 3DCP guarantees automation-related economic advantages. The deployment of automation in the building industry has the ability to reduce defects in structure, as well as irregularities that result from the manual work environment. The repair or rework expenses associated with these flaws may increase the uncertainty in project planning and construction, which could reach 5 to 15% of the total cost of the project or expenditures [35]. In addition, with limited supervision, 3DCP equipment might theoretically function at night or under adverse weather conditions, when hand building often has to stop. Further, many studies are being carried out on the sustainability aspects of concrete printing with alternative binder materials, such as fly ash, geopolymers and limestone [36–38]. 3DCP materials require more sustainable supply chains to assure their manufacturing, distribution, and reuse. It must be noted that the physical and mechanical properties of the printed concrete components are usually inferior to those of traditional concrete structures, and small changes in the process parameters can affect the built structure [39]. This variability restricts the variety of applications available for 3DCP. In addition, 3DCP experts or companies would likely require a substantial investment in research and development, as well as a long experimentation period, and would have to develop better and more effective means of control over the quality of the final product. After the application of this technology in construction, the designers and experts or engineers would need time for training, and to understand the maximization of potential and the reduction in environmental impact. New technical standards must be

created in accordance with existing legislation. Further, better experimentation methods are required to ensure the long-term persistence of the materials used in this technology. Research addressing the sustainability of 3DCP stresses its advantages, whereas publications describing 3DCP's drawbacks tend to emphasize the technical elements rather than sustainability [40]. The economic and environmental analyses of this technology, which are often undertaken using lifecycle evaluations, disregard issues of sustainability, and are limited to specific case studies, without considering trade factors such as legislation and culture. These contextual considerations can have a substantial effect on how a technique is implemented, the long-term viability of business models, and consequently, the magnitude of sustainability-related advantages. Until now, the literature has not addressed how this technology generates interactions across the triple bottom line dimensions, despite the fact that these interactions are essential for evaluating sustainability performance.

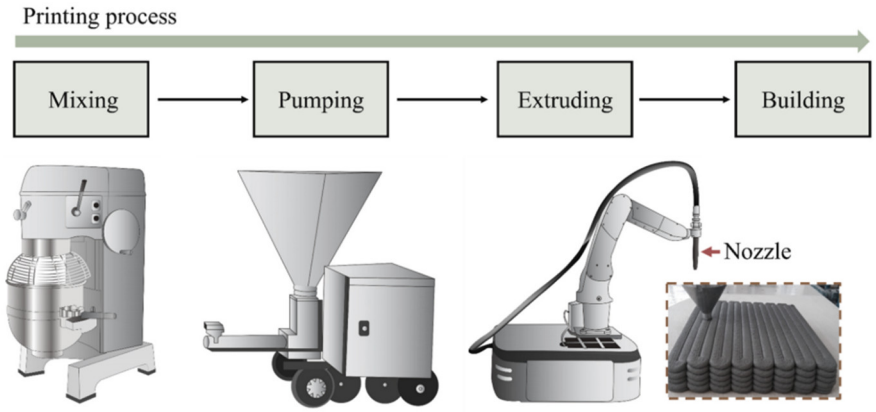


Figure 3. The 3D printing of construction material [41].

4. Sustainable Material Available (Sustainability Aspects of 3D Printing)

Sustainability is currently the biggest issue in the construction sector, and 3D printing in the construction sector provides the best option to achieve sustainability. It is worth noting that when the product can be recycled again and again by use of conventional or non-conventional methods, the sustainability issue can be solved. However, carbon emissions from the construction sector are much greater than anticipated, and research in the sector is seeking ways to ensure that carbon emissions can be reduced [42].

This article's primary subject, 3DCP technology, requires concrete with specific properties. Such combinations are formulated depending on specific key material properties, namely, extrudability, buildability, and pumpability, which essentially refer to the capacities to be pumped up and extruded out of the nozzle, and to support the weight of successively printed layers without them failing, respectively [43]. The abilities to pump and to extrude are determined by the qualities of consistency, cohesion, and phase separation probability when pressure is applied. In addition, the rheology of the lubrication governs the extrudability and pumpability [44]. Concrete's rheology is governed primarily by yield stress, viscosity, and thixotropy. Factors including dynamic shear yield stress, static shear yield stress, early age elastic modulus, and green strength influence the 3D-printability of the combination. These properties change with the time as a result of cement hydration, and are modified by the conditions of curing. Various other important characteristics of the 3DCP include the open time of workability, the printability window, the open time of thixotropy, the bond strength between layers, and the printing time gap. The bond strength of the layer is dependent on the time gap in printing, the shape of the layer, and ambient factors that affect surface qualities (e.g., drying of surface). In addition, a life cycle assessment of the process can help derive the optimal results from the sustainability point of view [45].

Sustainability can also be ensured with the help of LCA analyses of the 3D concrete printed samples and structures, considering all steps—from the mining of raw resources

used in the manufacturing of cement and aggregate, to transporting concrete material and other components, producing power to pour concrete, printing, construction, maintenance, and to the eventual demolition or dismantling. Figure 4 graphically depicts the life cycles of cementitious materials used for the 3DCP process. To evaluate the potential of the technology in question, weigh alternative possibilities, and compare with traditional buildings, it is necessary to be familiar with all pertinent procedures. The first step in evaluating sustainability is defining or delineating the system's boundaries. The various systems that could be studied are categorized as gate-to-gate, cradle-to-gate (ground-to-gate), cradle-to-cradle, and cradle-to-grave, with the system's boundaries determined by the scope and aim of the evaluation [44,46]. According to Figure 4, various system boundaries can be considered within the context of the sustainable evaluation of a 3D printing technology.

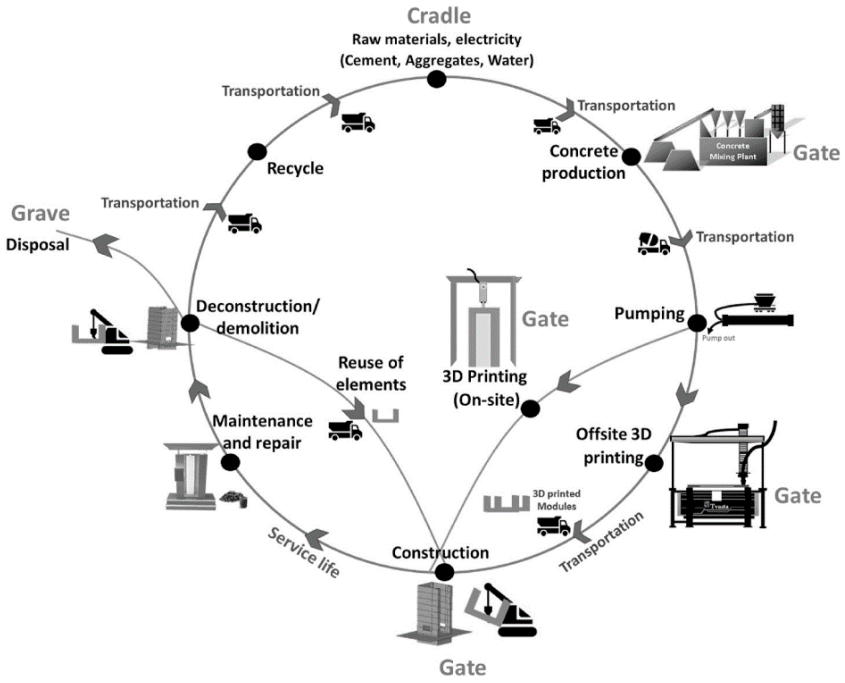


Figure 4. Sustainability assessment of 3D printing technology [47] (reproduced with permission from Elsevier-License number 5574820436912).

Cradle-to-gate systems are the most relevant. However, gate-to-gate systems, such as those that cover the processes utilized in cement and concrete plants up until the industrial production of the 3D-printed component in a factory, or the finalization of construction on-site, may allow for reliable assessment (i.e., without requiring significant speculation sources, as well as different types of raw resources and extraction methods) [48]. Engineering projects are often designed to survive for longer periods, making it nearly impossible to foresee the end-of-life processes of deconstruction, recycling, and disposal, and thus rendering the cradle-to-grave strategy completely useless. Cradle-to-cradle would be the optimal solution, but it is unheard of in the construction sector. In this system, one cycle ends and another one begins, such as when all the concrete from a demolished building is separated into aggregates utilized in cement production. In Table 1, we list the aggregates currently utilized in 3D printing in concrete building industries.

Table 1. Aggregates used in the 3D printing of materials.

Aggregate	Properties	Type
Sand	• Provides bulk and helps to fill voids • High compressive strength and low tensile strength	Granular material
Portland cement	• Binds materials together when mixed with water • High compressive strength	Fine powder
Fly ash	• Reduces the amount of cement required • Improves workability and durability of concrete	Fine, powdery material
Recycled materials	• Can reduce the environmental impact of concrete production	Can include crushed concrete, glass, and other materials
Crushed stone	• Provides bulk and helps to fill voids • High compressive strength and low tensile strength	Angular, irregularly shaped particles
Gravel	• Provides bulk and helps to fill voids • High compressive strength and low tensile strength	Coarse, granular material
Silica fume	• Improves compressive strength and durability of concrete	Very fine, powdery material
Glass powder	• Increases workability and durability of concrete	Fine, powdery material

4.1. Different Types of SCMs

Enhancing the properties of concrete that can be used for 3D printing by adding SCM is a promising area of research. In early life, the strength is typically low, unless metakaolin is given in a very low dose. Despite an increment in carbonation, endurance is improved due to the SCMs, since the microstructure is less porous (e.g., silica and fly ash fume can be utilized to augment the barrier against chloride penetration) [49]. Table 2 includes binder compositions taken from numerous key studies on 3D-printable concrete, providing evidence of the extensive replacement of OPC with SCMs. Improved stability of 3D-printed concrete is achieved using binary and ternary mixed compositions that provide higher resistance to pressure-induced phase separation, in addition to yielding strength and optimal plastic viscosity. The durability that fly ash provides is a benefit, while resistance to phase detachment, increased yield stress, and the plastic viscosity of silica fume are all reasons why it is commonly utilized in 3D-printed concretes. The addition of silica fume enhances the form stability and tensile strength of the fresh printing mixture [50]. It was found that 3D-printed concrete's workability may be enhanced by introducing ultrafine fly ash, which decreases yield stress and viscosity.

Table 2. Use of SCMs as a replacement for OPC.

Investigation	Binder Composition	OPC Replacement Level	SCMs Used	Key Findings
Hadi et al. (2019) [51]	OPC + sand + water	20%	Metakaolin	Increased compressive strength and improved workability compared to OPC mix
Yang et al. (2015) [52]	OPC + sand + water	30%	Ground granulated blast furnace slag (GGBS)	Improved compressive strength and reduced carbon emissions compared to OPC mix
Sandhu and Siddique. (2017) [53]	OPC + sand + water	30%	Rice husk ash (RHA)	Improved compressive strength and reduced shrinkage compared to OPC mix
Li et al. (2022) [54]	OPC + sand + water	50%	Fly ash	Improved compressive strength and reduced shrinkage compared to OPC mix
Wang et al. (2020) [55], Justice et at. (2005) [56]	OPC + sand + water	10%	Silica fume	Improved compressive strength and reduced water absorption compared to OPC mix

A combination of cement, well-dispersed silica fume or microsilica, fly ash, and fine-grain sand results in a significant packing density, which contributes to the material's strength and improves the rheology of the material. Panda et al. [57] have documented

the high volumetric substitution of slag and fly ash, whereas researchers have employed limestone as a constituent in the binder. Although silica fume has shown better results, similar to slag, giving benefits in performance enhancement along with reduced environmental impact, these materials are not widely accessible. The amount of available fly ash is fairly significant; however, more than 66% of it cannot be blended with cement due to quality issues. Scientists have proposed other sustainable solutions based on mixtures of calcined clay and limestone in addition to OPC [58]. The influence of the mixture on the key characteristics of 3D-printed concrete is also examined. Substituting fly ash or GGBS improves sustainability, but adding silica fume raises costs associated with concrete. As silica fume and fly ash improve concrete's use, operational parameters such as pumpability, rheology, and constructability should be considered in the assessment of the sustainability of concrete with SCMs. In this section, the requirements related to the cautious use of SCMs to develop sustainable 3D-printable mixes are discussed. Various characteristics can be discussed, amongst which workability is one of the most critical for 3D-printed concrete, because low w/b ratios necessitate large superplasticizer dosages. In addition to workability, phase separation is a crucial factor relating to the capacity to pump and extrude concrete. Ref. [59] employed desorptivity as a metric for evaluating phase separation, and a reduction in desorptivity was seen as the w/c ratio decreased. Considering mass production and requirements such as curing, concrete requires a substantial quantity of drinkable water of excellent quality. The economy and the ecosystem are affected by freshwater consumption during concrete production. With 3D printing, it is possible to print concrete with a low water-to-binder ratio, hence reducing the water demand. Moreover, structural optimization can minimize total material usage, resulting in a further decrease in water demand. In addition, there are a number of additional characteristics, such as aggregate content type, that have an impact.

In Table 2, typical binders used for 3D-printed mixtures are listed, along with the test protocols used to generate the mixture. The use of SCMs and large doses of superplasticizer is observed in all the mixes. In some mixes, polypropylene fibers and viscosity-modifying chemicals are also present. Several researchers have conducted research on the durability of 3D-printed concrete [59,60]. In this form of construction, as layer printing is carried out, the duration of printing and environmental conditions may change the surface qualities of the layers and reduce their endurance. Freeze–thaw cycling is considered to make the interfacial connections more brittle and impair bond strength, and the microcracks generated in the layer due to shrinking during the printing time may allow chloride passage and water penetration [61].

4.2. Demolition Waste-Based Geopolymers

In an effort to increase the building industry's eco-friendliness, geopolymers can be considered as alternatives for cementitious materials in 3D printing. For the majority of 3D-printed concrete, Portland cement comprises between 15 and 45% of the total mix fraction [62]. In 3D-printed materials, the content of the binding material is generally more than that of materials that are generated with conventional methods. The manufacturing of Portland cement generates approximately 8% of the world's CO_2 emissions [63]. As a result, the increasing use of Portland cement may result in increased material costs and a decrease in sustainability. Previous studies have investigated the possibility of using an eco-friendly binder geopolymer in extrusion-based or particle-bed printing processes to make long-lasting 3D-printed concrete. Inorganic materials are created from the interaction of aluminosilicate rocks and alkaline activators, also known as geopolymers. Investigations into the 3D printing of geopolymers, as shown in Figure 5 use a trial-and-error approach to assess the effects of reinforcement, matrix composition, test configuration, conditions during curing, and printing settings on the raw and recovered properties [41]. There has been extensive research on the design mix and qualities of 3D-printed concrete materials, especially in their primary stages of development. Unfortunately, few articles have provided even a brief overview of the design mix and the characteristics of geopolymers

used in current technology. The behaviors of geopolymer materials, such as their rheology, differ greatly from those of other cementitious materials, which has a notable impact on the printing ability. A critical evaluation is necessary to assess the current state of usage of geopolymer materials in 3D printing, and to identify the problems that must be overcome for their prospective uses. Geopolymer use has been seen extensively in all parts of the world, such as in India, following the global standards such as IS 15477:2004. IS 15477:2004, which is a widely acknowledged standard for fly ash-based geopolymer concrete. There are regional guidelines that take into account local materials and conditions. The use of geopolymers is limited in comparison to that of cement-based concrete, but their prevalence is growing due to their environmental benefits. Ongoing research and collaborations are seeking to develop exhaustive standards and norms.

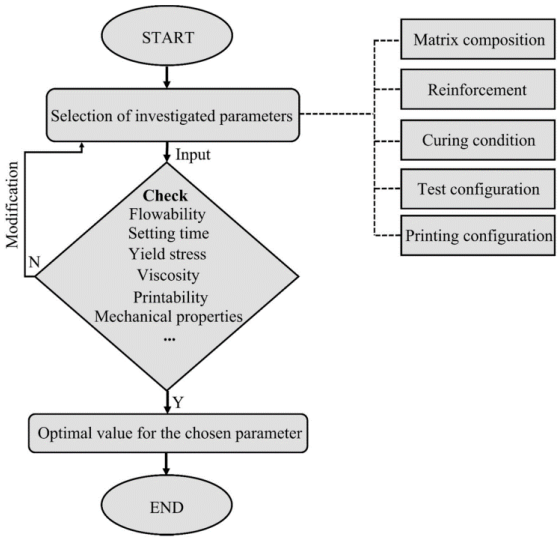


Figure 5. Trial-and-error technique utilized for geopolymer 3D-printing [41].

4.3. Portland (PC) Cement Pastes

PC is amongst the most widely used materials in the area of construction. Specifically, Type I Portland cement has been used by various researchers for various purposes in the construction industry, as well as in research. In one study, Type I PC was combined with kaolin, sand, CIMSIL A55G superplasticizer, and calcium carbonate to create AM concrete mixture pastes [64]. Table 3 provides a summary of the chemical constituents of various pastes.

Table 3. Chemical composition [64]. (Reproduced with permission from Elsevier-License number 5575850586139).

	SIO_2	Fe_2O_3	Al_2O_3	CaO	SO_3	MgO	H_2O	$CaCO_3$	R.I **	P.F *
Portland cement	9.05	0.94	0.79	2.74	2.18	1.03	0	0	0.4	4.18
Calcium carbonate	0.7	0.5	0	0	0	1	0	97	0	0
Kaolin	6.5	0	9.5	0	0	0	4	0	0	13.3

* Fire losses, ** Insoluble Waste.

In this study, the sand was dried at a normal temperature, sieved with a sieve (70-mesh), and then classified. The INVE-321-07 Standards for the manufacturing of hydraulic cementitious material pastes and polymer mortar were observed when preparing numerous compositions. According to the experimental design described in [65], 15 specimens were produced. Several ratios of sand, calcium carbonate and kaolin were used to create pastes with varied characteristics. The geometric consistency of the printed elements demonstrates the suitability of these pastes for usage in printing. To allow the mixtures to be extrudable

through s nozzle, a paste with a water-to-powder- ratio of 0.53 was utilized. To determine the operability of the pastes as well as to assess whether they were appropriate for 3D printing, cylinders with a mean size of 19 mm (diameter) and a height of 25 mm were fabricated for each formulation. Components and specimens were created using AM with DIW in a printer (Make-R). The Repetier Host program was used to define the printing settings, design, and production procedures for the items. The nozzle diameter used was 2.3 mm. The research discussed here focuses on the three AM recipes that were compatible with the printer used. These formulations match samples F5, F10, and F15 [65]. Amongst all of these, only F5, F10, and F15 were suitable for 3D printing. Due to their properties, these formulations have a high degree of geometric consistency and fluidity through the extrusion mechanism. Nowadays, compressive strength must be increased. Mortar pastes used in other applications or with varying production techniques have different rheologies than those used in 3D printing. None of the 3D-printable mortar formulations showed results that fell into the acceptable ranges of the ASTM and INVE specifications. Cement (e.g., Portland) is composed of calcium silicates, whereas geopolymers are composed of alkaline-activated aluminosilicates (fly ash, slag). Cement relies on hydration, which requires time and water, whereas geopolymerization occurs at room temperature and curing occurs more quickly. Geopolymers quickly exhibit strength, chemical resistance, and decreased CO_2 emissions due to the utilization of waste residues. Cement is used extensively in construction, whereas geopolymers have found niche applications as the technology has evolved.

4.4. Composite Cementitious Methods Containing Calcined-Limestone Clay Cement (LC3)

Typical SCMs, such as silica fume, blast-furnace slag and fly ash, might not be accessible in every place for long-term use. The retirement or closure of coal-fired power plants in numerous nations threatens the availability of these materials, as well as fly ash supply. To ensure the ongoing use of SCM, it appears imperative to discover alternatives to these. In comparison to conventional SCMs, LC3 stands out as an excellent and globally plentiful candidate for use as raw material [44]. Often, limestone powder is used as a filler in adhesives. The influence of the powder on rheology is mostly determined by the particle's physical properties, such as particle size and roughness. The addition of limestone can improve the workability of a cementitious material if added in suitable proportions, yielding a particle size comparable to or coarser than PC [66]. On the other hand, if the particle size is finer than that of PC, the workability may be reduced because of the friction in the inner particles and high-water absorption. The impact of the filler is considered to be the most important influencing factor in relation to limestone and the hydration of cement. Because of the increase in nucleation sites yielded by the particulate surface of limestone, replacing a small quantity of PC with limestone could accelerate the onset of hydration at an early sage. On the contrary, if the replacement of PC with only limestone exceeds 10% by binder mass, the mechanical functionality of hardened concrete mixtures may be significantly impacted due to the effect of dilution [67]. Using calcined clay as an alternative to PC could yield numerous advantages for 3DCP. The amount of accessible clay reserves is, arguably, the most crucial factor. Kaolinitic clay is abundant in humid regions, such as India and Southeast Asia, because it is technically the most suitable clay [68]. Another benefit of manufacturing kaolinitic clay is that the burning temperature is 700 to 850 °C, which is much lower than is needed for the PC clinker. According to another researcher, generating 1 kg of calcined clay emits only 0.25–0.37 kg of carbon dioxide, while the amount of carbon dioxide emitted by Portland cement is about 1 kg [69]. Many researchers have produced and investigated ternary mixtures of LC3. Typical LC3-50 cement (15% limestone, 5% gypsum, 30% calcined clay, 50% clinker) has been successfully made in Cuba and India via industrial experiments [70]. Metakaolin, which can be considered the principal reactive phase (consisting of silicate and reactive aluminate) in calcined clay, can generate C-(A)-S-H after reacting with calcium hydroxide. In one study, it was found that low-grade kaolinitic clay, which consists of at least 40%

metakaolin according to a binder scan, possesses compressive strength equal to that of ordinary cement after one week [71]. Low-grade kaolinitic clays are usually affordable, and can be obtained from cement plant quarries. When excluding the pozzolanic reaction produced by metakaolin, calcite from limestone can react with alumina molecules in the pore solution to produce AFm phases (calcium hemi- and monocarboaluminate phases), which stabilize the rapidly formed ettringite. A high number of such occurrences may affect the refinement of the capillary pores in solidified cementitious materials. Recent findings demonstrate that utilizing an LC3 binder may also increase the durability of hardened concrete, i.e., yielding outstanding resistance to sulfate and chloride attacks, and mitigating reactions such as the alkali-silica ones. Another study by Chen et al. [72] explored the possibility of developing cementitious materials based on calcined limestone and clay for the 3D printing of concrete. The addition of calcinated clay has an important effect on the material behavior of fresh mixtures during the printing process.

Adding calcined clay to fresh cementitious materials typically reduces their workability. Because of their layered structure, low degree of fineness, and substantial specific surface area, blended solutions of calcined clays require large quantities of water and superplasticizer. It has been suggested that increasing the amount of calcined clay in the mix will enhance its constructability and structure build-up behavior [73]. It must be noted that impacts on the properties of freshly prepared cements will vary with the type of calcinated clay used.

In a study, Chen et al. [72] found that raising the metakaolin content in calcined clay might potentially reduce the first set time and increase the green strength (in the first 4 h following mixing) of new mortars. Studies suggest that the structuring rate of new pastes could be improved by using calcined clay with a high concentration of reactive aluminate [73]. It appears that the structural build-up tendency of LC3 pastes is affected by the inclusion of uncalcined kaolinitic clay [44].

4.5. Calcium Sulfo-Aluminate (CSA) Cement

CSA cement is an environmentally viable alternative to regular OPC. It has to be noted that the rate of production of CSA is 49% lower than that of OPC. The production of CSA clinker occurs at a temperature (125 °C) lower than that necessary for OPC synthesis, resulting in less fossil fuel consumption [74]. Moreover, CSA clinkers created at a lower temperature are significantly simpler to grind, yielding additional energy savings. Klein's salt (Ye'elimite (50–80%)) is the primary phase of CSA cement. Due to the high rate of hydration of Ye'elimite in the presence of gypsum when generating ettringite, CSA cement hydrates rather quickly. Some researchers have partially substituted OPC with CSA cement to improve the 3D-printability of mixes [74]. For example, Khalil et al. [75] tested the building ability of a combination comprising 7% OPC replaced with CSA cement. The building ability was evaluated on the basis of the number of layers that an asylum gun can print. It was discovered that combinations including CSA cement had significantly greater buildability. In addition, the scientists observed a more rapid increase in yield stress with time for the combination including CSA. A study by Mohan et al. [76] created a formulation for printable concrete utilizing 100% CSA cement. They studied the use of retardants such as borax and gluconate to increase the open time required for smooth pumping. It was discovered that the addition of gluconate increased the open duration, but greatly altered the early development of compressive strength. However, the inclusion of borax enhanced the open time without diminishing the development of compressive strength. An investigation by Chen et al. [77] examined the impact of tartaric acid on the settling mechanism of CSA cement, which is 3D-printable. After one day, the addition of tartaric acid enhanced the settling duration without altering the compressive resilience. In comparison to OPC cement, which shrinks in quantity when it reacts with water, CSA cements swell when hydrated. Realizing that 3D-printable concrete components are quite vulnerable to shrinking due to the absence of formwork and the higher presence of binder material, a further area of application for CSA is in the development of shrinking balancing

binder technologies. In one study, the researcher examined the rheology of CSA cement and OPC using the identical water-to-cement ratio (Ke et al. [78]). The CSA exhibited a significantly greater plastic viscosity and shear thickening tendency. Chen et al. [77] investigated the development of yield stress and thixotropy in 3D-printable CSA configurations modified with metakaolin. The thixotropy was investigated by varying the shear rate and measuring the resulting loop area. Via investigation, it has been seen that the inclusion of metakaolin is responsible for the higher development of yield stress and the increased loop area. Consideration must be given to the pumping response of concrete containing CSA cement for use in sizable 3D printing devices. Further, the rheological characteristics of the lubricating layer formed during the pumping of CSA-based printable concretes using a tribometer have also been studied by many researchers, such as Mohan et al. [76]. Despite having lubricating layer qualities comparable to those of OPC formulations, the CSA combination showed a higher working pressure because of its elevated plastic viscosity. The partial replacing of CSA with limestone (10–30%) decreased the plastic viscosity and hydraulic pressure of the bulk aggregate. Despite its environmental benefits and numerous other advantages, the construction industry has utilized CSA cement to a limited degree. This is mostly attributable to the fact that bauxite, an expensive mineral, is required for its manufacturing. In this context, the usage of cements containing intermediate amounts of Ye'elimite, such as CSAB cement, is gaining favor. As the production of this cement requires less bauxite, the price of CSAB is comparable to that of OPC. With additional study and development, CSAB cement can become a more cost-effective and environmentally benign replacement for OPC cement in large-scale construction projects [79].

4.6. Earth-Based Sustainable Material

Earth-based materials are attracting more attention from the traditional building industry because they can be recycled and do not degrade the environment. Table 4 shows some of the earth materials used in research on three building concrete materials. The negative properties of earth products include (a) drying-induced hardness without a hydraulic binder phase, and (b) substantial fluctuation and sensitivity to moisture levels. These deficiencies of earth materials present hurdles to their application in AM.

Table 4. Earth materials used for 3D printing research [80].

No.	Type of Materials	Research/Application	Additives	Merits	Challenges	References
1	Clayey fine soil	Fresh and hardened mechanical property	Alginate	Nutrient retention, water holding capacity, compaction, good shear strength	High plasticity, drainage problems, erosion susceptibility, swelling pressure	[81]
2	Concrete w/expanded clay aggregates	Fresh property, failure mode	HPMC	Lightweight, good acoustic properties, better fire resistance, durability	Higher cost, lower strength, special mix design consideration.	[82]
3	Expanded clay w/cork	Numerical modelling of printed building wall	-	Lightweight, thermal insulation, improved sound absorption	Strength considerations, increased cost, durability considerations.	[83]
4	Clayey material	Non-conventional wall components	Salt, SHMP clay, deflocculant	Cohesion and plasticity, water retention, nutrient retention	Poor drainage, compaction challenges, difficulty in excavation	[84]
5	Cob	Thermal performance of printed specimen	Straw fibers	Sustainability, thermal performance, design flexibility	Labor-intensive, weather sensitivity during construction, limited availability of skilled professionals	[85]
6	Fired stoneware	Printing parameters and geometry design		Versatility, heat resistance, food-safe and non-toxic	Production complexity, brittle nature, limited translucency	[86]

Perrot et al. were pioneers in 3D printing studies focusing on the rapid increase in initial strength in purified clay-based soils (Figure 6) [80]. Alginate, which can also be used

as a binder, is derived from brown seaweed via the method suggested by Perrot et al. [80]. In the first 24 h after mixing, the addition of alginate accelerates the development of the yield stress and elastic modulus of a fresh mixture significantly. The enhanced rate of strength increase could greatly accelerate construction, while an increase in material stiffness reduces the likelihood of buckling-induced structural failure.

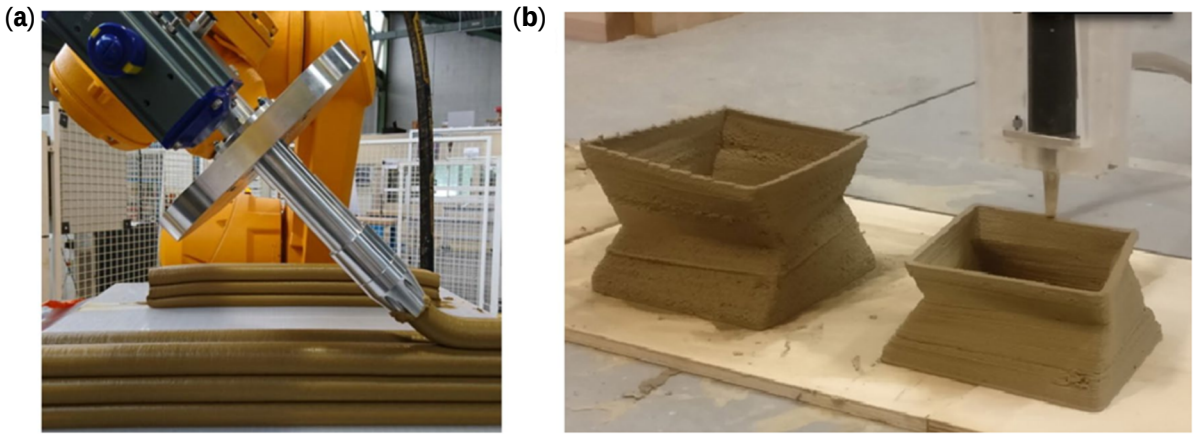


Figure 6. (**a**) Overhanging clay-based constructions process with 3D-printed filaments made from clayey soils (**b**) Parts produced with the clay-based constructions process treated with alginate ($100 \times 100 \times 100\ mm^3$) [87] (reproduced with permission from Elsevier, License number 5574820976061).

Some studies have examined the influence of lightweight expanded clay aggregates on the green strength of cementitious materials combined with fly ash and with good extrudability. The investigators discovered that by adding clay aggregates, both the strength and elastic modulus were enhanced, which they attributed to the increased level of dehydration and the greater internal friction angle, which caused the printed filament to stiffen more quickly. Another work by Kontovourkis and Tryfonos [88] (Figure 6b) (size $100 \times 100 \times 100\ mm^3$) established the viability of printing non-conventional structures based on clay through the development of an algorithm for the optimization of printing variables and the planning of toolpaths.

4.7. Binders Based on Geopolymers

Alkali-activated geopolymers and substances are gathering favor for use as sustainable mixtures for the 3D printing of concrete. The benefit of geopolymer printing lies in the composites' rapid hardening, which can significantly boost buildability without the usage of chemical catalysts. The literature indicates that the use of adhesives containing certain amounts of different alkali activators in printable geopolymers, including FA and slag, can have a significant effect on the early-developing properties. As per Panda et al. [57], relative to FA, the use of ultrafine slag increased the static yield stress and viscosity of substances due to the angular form of slag, thereby enhancing the constructability of three-dimensional structures. In spite of the this, it was suggested that the dose of slag be closely controlled, as the inclusion of slag hampered the curing process while increasing the open time. A study by Alghamdi et al. [89] investigated the rheology of FA-based content activated with sodium-alkali, and observed that shear yield stress and viscosity significantly decrease with the substitution of fly ash with limestone. Because of the greater diameter achieved during the collapse test and the decrease in viscosity, they concluded that introducing limestone could improve the material's processability. The rheological features of geopolymer concrete are primarily governed by the viscosity of activators, and later, by the polycondensation reaction's production of cross-linked polymers. Panda et al. [57] investigated the influence of MR and the ratio of activator solution to binder on the rheology of a geopolymer. With a w/s ratio of 0.3, increasing the MR from 1.8 to 2 caused

a significant increase in static yield stress and viscosity, which was attributed to a rise in activator viscosity with the increasing MR. Nevertheless, when the w/s was raised to 0.35, the yield stress and viscosity decreased substantially, and the increase in MR had a moderately positive influence on the rheological properties. It has been proposed that the proportion of activator solution to binding agent could be an appropriate proportioning measure in relation to practical purposes, so this ratio must be carefully set and maintained during the 3D printing of geopolymers. In the study by Bong et al. [90], the processability and shape preservation of Na-based activators used for 3D printing were compared to those of K-based activators. Under comparable settings, the Na-based activator showed a more notable improvement in fresh geopolymer flowability than the K-based activator. This result can be attributed to the viscosity difference between the alkaline solution and the geopolymer, which eventually determined the viscosity of the geopolymer. Due to the transportation and handling difficulties connected with liquid-based silicate activators, experts have also employed one-component geopolymer mortar in 3D printing projects. It was observed that the fresh qualities of the one-part 3D printing mortar were better when compared to the liquid-based geopolymer, due to the difference in the viscosity of the reaction mixture. Panda et al. [91] studied the effect of SF and slag replacement on the rate of structure formation in FA-based geopolymers. The rapid stiffening of the matrix due to the existence of Ca-containing SCMs was ascribed to the superior performance of 10% slag over 10% SF in accelerating the formation of yield strength within 10–30 min after combining. In addition, the structural disintegration tests show that using both SF and slag enhances the thixotropic index of a geopolymer, thereby enhancing its thixotropy. In a study, Muthukrishnan et al. [92] aimed to enhance the structural formation of a geopolymer through microwave activation. The findings indicate that a novel printing method for forming concrete on demand via 3D printing should be implemented. Regardless of the binder employed, numerous additives can be used to alter the fresh characteristics of a geopolymer concrete. According to one study, nano clay is the most common additive for printable geopolymers and alkali-activated binders [93]. In addition to nano clay, various components, such as CMS and hydro magnesite seeds, have been studied and incorporated into mixtures of geopolymers. Sun et al. [94] reported in his study that the inclusion of CMS raised the viscosity and yield stress at varying rates, which might also reduce the risk of segmentation while preventing filament failure. However, as the dosage of CMS increased, the porosity of the printed filaments increased, resulting in compromised internal structures and a reduction in strength. The inclusion of 1% to 2% hydro magnesite particles had no effect on the rheology of alkali-activated slag binders. Multiple kinds of fibers can also be incorporated into printable geopolymers to enhance their ductility; the ensuing effects on its rheological characteristics have been investigated by a large number of researchers. Using the relative slump value, Al-Qutaifi et al. [95] investigated the effects of steel and polypropylene (PP) fibers on the workability of geopolymers. Due to the significantly lower relative slump value of PP fibers, it was established that the inclusion of 0.5% PP fibers had more adverse effects on the flowability than the addition of 1.0% steel fibers. In a separate study, a negative correlation was found between PP fiber concentration and workability, leading to a higher likelihood of geopolymer pumping obstruction.

4.8. Reactive Magnesium Oxide Cement (RMC)

RMC is produced mainly via magnesite calcination, whereas a relatively small fraction is also generated by transforming the magnesium chloride and sulfate in seawater to $Mg(OH)_2$, and then calcining it to obtain MgO. Utilizing it has multiple advantages from a sustainability perspective. Second, its calcination temperature varies between 650 and 800 °C, which is considerably low compared to OPC [96]. During the curing phase, it is capable of absorbing atmospheric carbon dioxide. It transforms into $Mg(OH)_2$ and then carbonates, resulting in the formation of hydrated magnesium carbonates (HMCs) and the development of strength. The HMCs could be calcined to reclaim the reactive MgO, making total reprocessing possible. Khalil et al. [75] evaluated the viability of employing

RMC in AM with a tiny 3D printer based on a syringe. In their investigation, they tested the printability of a pure RMC paste. The initial combination's buildability was poor, but it has been seen that even the addition of a small amount of highly reactive caustic MgO can improve the buildability. Despite the RMC and caustic MgO additives sharing a similar chemical makeup, the caustic MgO was significantly more reactive due to its poorer crystallinity and greater specific surface area. Its inclusion increased the pace of RMC hydration by providing more active nucleation sites. After three days of atmospheric curing and one week of carbonation in an environmental room, the scientists also examined the microstructure and compressive strength of the printed and casted samples generated with RMC. As regards the elements, a higher compressive strength was achieved with a higher HMRC concentration. The authors ascribe the higher level of carbonation to the increased uptake of CO_2 through the interlayers of the printed parts. Even though Khalil et al.'s [75] research is encouraging, numerous obstacles must be addressed before the RMC can be successfully used in large-scale 3D printing initiatives. First, existing RMC production processes are expensive. Second, the majority of early research on RMC has concentrated on its hydration and carbonation features, and nothing is known about its rheology, early age response kinetics, and pumping behavior. These elements must be understood in order for RMC to be utilized in 3D printing applications. Moreover, further RMC versions have been produced in recent years. For example, magnesium phosphate cement (MPC) can be produced via the interaction of MgO and acid phosphate salts. Weng et al. [55] investigated the viability of using magnesium potassium phosphate cement in small-scale 3D printing. Fly ash was utilized as an addition to modify the setting behavior and increase the open time, while silica fume was used to improve the rheological and mechanical properties. Even though MPC was effectively implemented in this study, it is important to note that similar concerns arise, such as the high manufacturing costs and a lack of research on the fresh and early age behavior of MPC. In conclusion, RMC and its derivatives, such as MPC, provide substantial CO_2 emission-reduction benefits. Before these cements can be used in large-scale 3D printing-related applications, however, additional research concentrating on rheology, early age hydration, and pumping properties is required.

5. Cost Comparison between Conventional and Non-Conventional

The quantity, rate, and estimated cost of preparing a 600 square foot residence in India, and estimating the cost of the home you intend to build, is of the utmost importance. If we begin building a house without proper planning, it will be extremely difficult to complete. Thus, it is necessary to estimate the rate, quantity, and total cost of the building materials, the labor, and other resources that will be used to create the house. Six hundred square feet is a small area. So, we must utilize this tiny space in a progressive and efficient manner. The following project outlines the building materials and other resources required to construct a 700 square foot home. Plot area: 600 square feet. Total bedrooms: one. Contemporary building materials will be used in the residential construction. The material used for constructing houses is the construction material. Concrete, steel, sand, bricks, ceramic tiles, and granite are the primary materials used to construct houses. Kota Stone, wood, river sand, Door, Window, lumber, painting and granite, plumbing, electrification, composite materials, and filling have increased in price in tandem with the rise in population. This expansion has contributed significantly to waste production. To construct a 600 square foot home, specific materials are required.

Each material's price and the total price are listed below.

The construction cost for building a house can be broken down as follows:

To start with, the cost of cement is approximately INR 78,000. This includes 260 bags of cement, with each bag priced at around INR 300. Moving on to steel, the required amount is roughly 1.5 tons, which amounts to approximately INR 67,500, at a cost of INR 45 per kilogram. For sand, the total cost comes to about INR 62,500. The price per cubic foot is INR 50, and we need 1250 cubic feet. Similarly, for aggregate, we require 750 cubic feet, costing around INR 16,500. The price per cubic foot is INR 22. Labor costs for the

construction project are estimated to be around INR 150,000. This is based on the standard hourly rate of INR 250 per square foot, considering a 600 square foot house. The services of a Bhishty (water carrier) are required for a minimum of 6 months, costing approximately INR 33,750 at a daily rate of INR 250. Bricks play a crucial role, with a requirement of 15,000 brick units. At a cost of INR 9 per brick, the total expense comes to INR 135,000. Vitrified tiles are priced at INR 37 per square foot. For a requirement of 420 square feet, the total cost is INR 15,540. The use of granite for construction purposes would cost around INR 30,400. With a price of INR 160 per square foot, we need approximately 190 square feet. Kota stone, priced at INR 22 per square foot, is required for an area of 270 square feet, resulting in an estimated cost of INR 5940. The cost of window grills totals around INR 7800, with each unit priced at INR 1950. We need four units for the construction. Doors are another essential element, with six units required. Each door costs INR 3650, amounting to a total of INR 21,900. Sliding windows, priced at INR 3500 each, are needed in a quantity of four units, resulting in a total cost of INR 14,000. A water tank with a minimum capacity of 1000 L is estimated to cost INR 8000, at a price of INR 8 per liter.

Wall putty and painting for an area of 2850 square feet would cost around INR 54,150, considering a rate of INR 19.19 per square foot. Electrical work is estimated at approximately INR 45,000. The cost of plumbing work amounts to INR 17,000. For ceramic tiles, the total cost is around INR 5500. There is a price of INR 22 per square foot, and we need a minimum area of 250 square feet. Excavation work comes to around INR 13,650, at a rate of INR 7 per square foot. The required volume for excavation is 1950 cubic feet. Each door frame costs INR 1950, and with a minimum order quantity of six, the total cost is INR 11,700. Lastly, other miscellaneous items contribute approximately INR 17,500 to the overall construction cost. Considering all these factors, the total construction cost in Indian currency is estimated to be INR 811,330.

6. Effectiveness of 3D Printing

This process has altered the way we conduct business. Technologies have a noticeable impact on our evolving business system. Now we come to the topic of 3D printers; over the previous three decades, it has been observed that the AM business has undergone extraordinary growth. Such 3D printing technologies enable design optimization and offer significant advantages over conventional manufacturing techniques. Most the industries should adapt to this new system in order to survive in this harsh, rapidly changing environment. The construction industry is under immense pressure to adapt to new technological breakthroughs. Hence, 3D printing has attracted a great deal of attention in this sector as a technical revolution that must be accepted for the sake of the survival of the sector [97,98]. This section examines the variables influencing the evolution of 3D printers in the construction sector, including a comparison between the costs of using the traditional approach versus 3D printing technology in building a single-story home, as well as a comparison of the times required to construct a single-story house using the conventional approach against the use of 3D printing technology. AM allows us to make complicated designs, and the best thing is that it takes very little time to produce, requires a small number of laborers, and has cheap estimated costs. The use of 3D printing in the construction business is innovative, and has received a great deal of attention from the global construction industry. In this section, we focus on a few significant applications of 3D printers in the construction business. The technology was developed in the early 1980s, but was of no use at the time, due to its prohibitive costs. In the year 2000, it became very user-friendly, as the design could be created on a computer and the costs were very low, as plastics and waste materials are used to produce the concrete for 3D houses. Suddenly, it became affordable and applicable in a vast array of designs, models, etc. [22].

6.1. Influencing the Growth of 3D Printers in the Building Sector

Decarbonization is a fantastic method for reducing carbon emissions in the construction business. AM or 3D printing have emerged as viable means of reducing energy

consumption, water waste, and carbon emissions [99]. In the context of construction, 3D printing is a futuristic technology that generates three-dimensional objects through the repeated formation of physical layers. From polymers and steel, the industry has recently surged forward, with the potential application of concrete in civil engineering. Anecdotally, these methods have been demonstrated to drastically reduce production time, waste, and labor costs. The obstacles around 3D printing include the absence of standardized building codes, large-scale investments, successful examples of implementation, and architectural designs [100].

6.2. Effects of Using Typical Building Methods on Time, Money, and the Environment

The building industry is essential to the socioeconomic growth of every nation. Currently, the construction business is rapidly expanding due to the rise in living standards, demand for infrastructure projects, and population growth. Its expansion has contributed significantly to waste production. Large amounts of garbage accompany the destruction and reconstruction of buildings [101]. Typically, construction waste consists of bricks, concrete, glass, metals, wood, plastics, and asphalt. Typically, this material is disposed of in a landfill. Not only does this poison the air and land, but there is a requirement of transportation to remove it, and it has a substantial environmental impact.

7. Full-Scale 3D Printing Growth in the Building Sector

The most common trend in the evolution of 3D printing for buildings is the transition from low-scale printing to manufacturing full-scale structures. While full-scale printing is a large-scale manufacturing method that faces significant obstacles, printing full-size buildings without regard for 3D design models or print settings would eventually result in losses or accidents. 3DCP is a developing digital technology that has the potential to automate traditional construction [102]. The building industry has not yet reached consensus on the precise meaning of 3DCP. In particular, 3DCP is an AM technology that can automatically generate structures or construction components straight from refined 3D digital models without human interaction, hence reducing the construction supply chain [103]. The fundamental advantage of this technology is its ability to alter the current condition of a building, which is labor-intensive, environmentally polluting, and high-risk. 3DCP is a megascale production process, unlike typical desktop 3D printing. Without preliminary testing, the printing of buildings will surely result in losses. Namely, printing full-scale structures may cause mishaps. Typically, the main cause involves mistakes in the 3D design model or print parameters. Consequently, it is vital to evaluate the model and its settings before beginning the printing process. Zuo et al. (2019) [103] conducted a study on the transition from scale to full-size 3D printing in the construction industry. The researchers devised an approach, which they have described in depth.

Figure 7 depicts a scale 3D printing technology used in building. Low-Scale Printing Tests and Full-Scale Printing Tests are utilized in this method. The main steps of the technique can be described as follows: Step 1 involves using the Scale 3D Printing Test, whereby the main factors that influence the manufacturing effectiveness and effectiveness of the framework and building models are determined. Numerous tests demonstrate, for instance, that the FDM process is influenced by variables such as the preparation time before printing (t_0), the complexity of the model being printed (C), the volume of the model being printed (V), the printing intensity (I), the printing accuracy (A), the printing pattern (P), the post-processing time (t_f) and the printing orientation (O), among others. Here, t_0 consists predominantly of the time required for the creation of 3D digital models, model conversion, the fixed preparation prior to printing, equipment debugging, etc. 'V' is determined by the variation in height and the cross-sectional area. The higher the 'C' is, the further the print head moves. Typically, 'A' comprises mechanical positioning accuracy and printing resolution. In reality, once the printer has been identified, only the printing resolution affects the printing precision. 'I' represents the rate of filling. With a 100% infill rate, the structure often becomes solid. 'P' is the type of internal infill support. The printed structure and

building model are oriented in a specific way, which can be depicted as 'O'. t_f incorporates the disassembly and surface treatment time. C, V, A, P, I, and 'O' are all associated with the time (total printing time) and the weight of the material used for 3D printing (total supplies weight), whereas t_0 and t_f only impact the total printing time. Their quantitative relationship is described in the section that follows. The quantitative relationship between I, A, P, and O and printing quality is not addressed in this study. A Scale 3D Printing Test is utilized to evaluate and optimize print settings objectively. The aforementioned factors are initially quantified and parameterized. By analyzing the outcomes of a series of Scale 3D Printing Tests, quantitative relationships between the parameters are then determined. The total printing time (TP) relationship and the relationship with the total supplies weight (WS) can be calculated as per the equations (see Figure 7) [103].

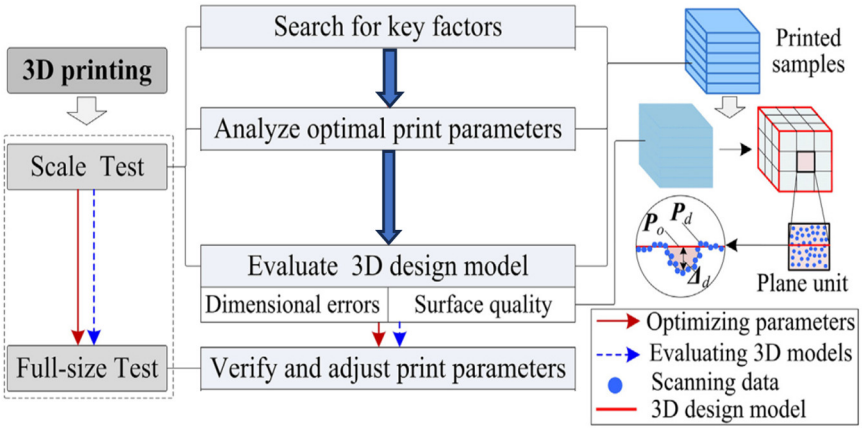


Figure 7. Scale 3D printing technology in construction setup [103] (reproduced with permission from Elsevier License number 5574821298709).

'W' is the required supply weight for factors other than those listed. Lastly, the most ideal print parameters, such as C, V, A, I, O, P, etc., are determined. Step 3: the Scale 3D Printing Test is utilized to assess the validity of a 3D design model. Initially, various tests are conducted by printing low-volume samples. Secondly, several measurement methodologies capture the quality of the printed samples, including the dimensions and surface quality. Using techniques such as laser/optical imaging, PIV and LDV, the surface quality can be evaluated. In addition, a micro-meter, 3D laser scanning, 3D CT, and mass measurement procedures can be utilized to determine the dimensional accuracy. Lastly, the 3D design model's logic is evaluated using statistical methods to examine the gathered data. Analyzing dimensional inaccuracies is essential to this step. In this case, 3D laser scanning serves as an illustration of the principle underlying the calculation of dimension errors (d). As illustrated in Figure 7, the 3D point cloud data of the printed sample produced by 3D laser scanning are referred to as Pd, whereas the 3D design model's coordinates are Po.

To obtain D_d, initially, the 3D design model is subdivided into external surface planar segments. The specific plane unit is described by Equation (1).

$$Z = k_1 x + k_2 x + k_3 \tag{1}$$

where k_1 and k_2 are the parameters to be fitted. To fit Equation (3), the following equations need to be satisfied.

$$\begin{cases} Pf = \sum_{oi=0}^{s} (k_1 x + k_2 y + k_3 - z)^2 \\ \frac{\partial Pf}{\partial Poj} = 0 (oj = 1, 2, 3) \\ 0 \le Pf \le \min(M_s, M_l) \end{cases} \tag{2}$$

M_s and M_l represent the minimum and maximum allowable values of the fitting error, respectively. An equation system is generated as follows:

$$\begin{pmatrix} \sum X_{oi}^2 \sum X_{oi} y_{oi} \sum X_{oi} \\ \sum X_{oi} y_{oi} \sum y_{oi}^2 \sum y_{oi} \\ \sum X_{oi} \sum y_{oi} S \end{pmatrix} \begin{pmatrix} k_1 \\ k_2 \\ k_3 \end{pmatrix} = \begin{pmatrix} \sum X_{oi} \sum Z_{oi} \\ \sum y_{oi} \sum Z_{oi} \\ \sum Z_{oi} \end{pmatrix} \tag{3}$$

By substituting k_1, k_2, and k_3 from the above equations, the equation of any plane unit can be obtained. The Δ_d errors are equal to the point cloud coordinates, which are (x_d, y_d, z_d), and relate to the plane unit distance. They can be obtained as shown in the below equation.

$$\Delta_d = \frac{|k_1 x_d + k_2 y_d + z_d + k_3|}{\sqrt{k_1^2 + k_2^2 + k_3^2}} \tag{4}$$

Step 4: With a full-size test of 3D printing, the print parameters are validated and modified. First, structural and building 3D printing experiments are undertaken. Second, the print parameters Figure 7 are confirmed and rectified. Ultimately, the ideal combination of primary print parameters is used in the production of the full-scale structure and the building. Prior to confirming the printing parameters, it is necessary to establish a number of quantitative relationships. The motion control equation is an example of a velocity vector loop for nozzle speed (ν).

$$\nu = \dot{r} \tag{5}$$

where the position vector is depicted by r. The constitutive equation is shown as

$$\delta = \delta(\nu, D, R, u, ET) + \delta_0 \tag{6}$$

$$\omega = \omega(\nu, R, D, u, ET) + \omega_0 \tag{7}$$

where δ_0 and ω_0 are the external factors that affects the extrusion width and layer resolution.

By following this principle and procedure, the authors applied these techniques to the building of a 3D-printed landscape bridge at full scale. The bridge is located in Shanghai's Putuo District [98].

Based on scale 3D printing, some researchers proposed a method for the evaluation, design and optimization of the parameters of full-sized 3D printing [104–106]. To study the effects of print parameters, six sets were considered in the test of scale 3D printing. The results offer a quantitative basis for the selection of print parameters during 3D printing, saving printing time and materials. As a case study, the rationale of the suggested method was validated using a series of 3D prints of landscape bridges with a 15 m span. Several printing devices and materials were utilized at various stages of the research. For the printing of full-size structures, a five-axis printing system and a large-scale, gantry-type, high-rigidity 3D printer were designed. A series of experiments was undertaken to validate the equipment's print settings. The experimental results demonstrate that the proposed method may be used to print full-size structures and eliminate the losses caused by model and parameter mistakes. Using 3D laser scanning and a digital bridge model for 3D printing, a comparison of point clouds was conducted. The maximum variance of the 3D-printed bridge model was less than 0.9 mm, while an average variation of less than 0.1 mm was observed. According to the optical and laser image evaluation results, the 3D-printed sample's surface was relatively uniform and smooth. We ultimately discovered the best print parameters, such as a layer resolution of 4 mm, for the building of full-scale landscape bridges using 3D printing. In addition, few potential large-scale applications of 3D printing in conventional construction projects were identified (see Table 5). Aside from the layer resolution, the setup procedure and the results for the printing rate and dimensions for full-sized three-dimensional printing are not addressed here. We are primarily concerned with the practical use of 3D printing on a smaller scale, and its eventual transfer to printing on a bigger scale [107,108].

Table 5. Applications of scale 3D printing in a building's lifecycle.

Time	Application	Description
Planning and Design	Concept appearance test	Verification of design appearance
	Structural assembly test	Visual reflection of design ideas
	Creative appearance test	Design structure verification
	Structural performance test	Optimization of structural design
Production and Construction	Bidding appearance test	Bid–hit ratio improvement
	Preparation appearance test	Smooth communication plans
	Implementation appearance test	Construction plan optimization
	Completion appearance test	Supplement corporate incentives
Operation and Maintenance	Operational appearance test	Follow-up operation management

8. 3D Printing of Ultra-High-Performance Concrete

The 3D printing of UHPC is an emerging technology that offers several advantages over conventional casting methods. UHPC surpasses conventional concrete in terms of strength, durability, and efficacy. It is an ideal material for structural applications due to its high strength, minimal permeability, and resistance to corrosion and freeze–thaw cycles. UHPC has superior fluidity, and shows less shrinkage and an extended lifespan. Design, construction, and maintenance must be adequate in order to maximize its potential. UHPC is a cementitious composite with superior mechanical properties, such as high compressive strength, better tensile strength, and better durability, which makes it an ideal material for structural applications. Some of the key benefits of the 3D printing of UHPC are [109,110]:

1. Design freedom—3D printing allows for the creation of complex shapes and geometries that would be difficult or sometimes even impossible to realize with conventional casting methods. This enables designers to create unique and innovative structures that can be customized to specific project requirements;
2. Resource efficiency—the 3D printing of UHPC can reduce material waste and energy consumption compared to conventional casting methods. This is because the printing process can be optimized to use only the necessary amount of material, and it can be automated to minimize labor and energy inputs.

Speed and efficiency: 3D printing UHPC can significantly reduce construction time and costs by eliminating the need for formwork and reducing the number of construction steps. This can also improve the safety and quality of the construction process by reducing the risk of human error. However, there are also several challenges associated with 3D printing UHPC, such as:

1. Material development—UHPC is a relatively new material, and its properties and behavior during the printing process are not yet fully understood. Therefore, there is a need to develop new UHPC formulations that are specifically designed for 3D printing, and to optimize the printing parameters to achieve the desired mechanical properties;
2. Printability—UHPC has a high viscosity and rapid setting time, which can cause problems during the printing process, such as nozzle clogging and layer delamination. Therefore, the printing parameters, such as layer height, printing speed, and nozzle size, need to be carefully controlled and optimized to achieve consistent and reliable printing quality;
3. Structural functioning—The mechanical/physical properties of 3D-printed UHPC are affected by the printing parameters, such as the layer orientation and bonding between layers. Therefore, the structural performance of printed components needs to be carefully evaluated and validated to ensure that they meet the required safety and performance standards;
4. Scaling up—While 3D printing UHPC has demonstrated its potential in small-scale applications, such as with prototypes and decorative elements, the technology is still limited in terms of the size and speed of production. Scaling up the technology for

large-scale construction projects is a major challenge that requires the development of new printing systems, automation, and logistics [22,111].

9. Pros of Using 3D Printers for Building Projects

The advantages of 3D printing over conventional manufacturing include intricate designs, rapid prototyping, cost-effectiveness, material efficiency, customization, time savings, waste reduction, and streamlined production. One must consider material quality, quantity, surface refinement, and cost when choosing manufacturing processes. Based on a survey of the relevant literature, the primary advantages are time, money, geometric freedom, sustainability, and safety [22]. Further, 3D printing significantly reduces construction duration. Construction time is the most frequently highlighted benefit linked to 3D printing. Reductions in construction costs are also recognized as a significant advantage. In the construction of an office in Dubai undertaken with 3D printing, labor costs were 60% lower than those involved in comparable traditional buildings [112]. In addition, 3D printing improves efficiency, which results in savings on expenses. AM is considered an alternative for construction projects with efficiency problems. Using 3D printing technique permits greater geometric flexibility in the design of constructions that would not normally be possible. Geometric freedom is frequently regarded as one of the most important advantages. Sustainability is the primary advantage of 3D printing. That is, 3D printing enables the design and construction of environmentally friendly projects. The utilization of 3D printing decreases construction waste and formwork. This technique thus prevents the unnecessary waste of materials, thereby reducing the negative environmental effects of the production/construction process. Lowering the use of formwork reduces the quantity of wood, and thus, tree consumption. Further, this new technology enhances construction site safety. The use of 3D printing results in safer locations; 3D printing minimizes on-site injuries and fatalities, since printers can do the majority of hazardous and risky tasks.

Furthermore, 3D printing offers numerous benefits to the building business. The four primary areas in which 3D printing can have the most influence are time and cost savings, labor efficiency, environmental/economic implications and design complexity. In the past few years, the requirement for construction initiatives throughout all industry sectors has increased, benefiting the building industry. Workforce expansion has increased the demand for both professional and low-skilled workers. According to the 2017 Workforce Study by the Associated General Contractors of America, 70% of building companies struggle to fill hourly craft positions [113]. In addition, 51% of these businesses have trouble filling positions for concrete laborers [114]. Concrete 3DP can successfully address this shortage. As illustrated in the case study, a single printer technician was able to entirely automate the manufacturing of all masonry walls for a 2700-square foot office building [112]. This demonstrates how 3D printing may decrease the number of workers required to produce walls made of concrete, along with additional components.

Further, 3D printing offers significant benefits in terms of time and cost reductions. By utilizing 3D-printed building elements such as floor panels, walls, and roofing systems, a fully functional office structure was constructed in less than three weeks by a team of 18 laborers. This technique can lead to labor and material cost reductions of up to 80%, as demonstrated by the International Construction Cost Study. One of the advantages of 3D printing is its positive environmental and economic impact. Companies like Winsun and WASP use cost-effective and environmentally friendly materials, such as construction waste, clay, and straw sourced locally. This approach not only promotes ecological design, but also appeals to developing nations. Moreover, by saving between 30% and 60% of expenditures on raw resources, 3D printing is more attractive to developed countries with high labor expenses and environmental restrictions. The design complexity achievable with 3D printing is a notable advantage. Since 3D printers can move along a tri-axial plane, they can be programmed to create intricate and complex patterns that would be challenging and expensive to produce using conventional methods or molds. This means architects can design complex components without incurring additional costs. Another eco-friendly

aspect of 3D printing is the ability to use unprocessed soil and natural residues from the rice production chain as materials. In theory, even abundant materials such as plastic can be utilized for 3D-printed residences. Furthermore, 3D printing allows for the construction of large-scale industrial structures at a comparatively low cost. This makes it an attractive option for various industries. Finally, 3D printing enables the fabrication of unique shapes that would otherwise be impractical or prohibitively expensive to create. This opens up new possibilities for innovative designs and architectural structures [115–117].

Limitations

Although 3D printing has the potential to lower construction costs, the most significant disadvantage lies in the high cost of printers themselves, which offsets the potential savings. Additionally, the utilization of CAD and 3D printing software necessitates skilled laborers, adding another layer of complexity and cost to the construction process. A study reveals that 3D printers consume 100 times more electricity than conventional methods, resulting in a substantial increase in energy consumption. Furthermore, the limited build size of most 3D printers poses a significant obstacle for construction projects requiring large components or structures, thus limiting their feasibility. Despite being capable of producing a variety of materials, including metals, plastics, and concrete, 3D printing still falls short in terms of available materials when compared to traditional construction techniques. Moreover, the resilience and durability of 3D-printed materials may not meet the requirements of certain construction applications, compromising their suitability. In addition to the initial costs of the technology, ongoing expenses such as supplies and maintenance contribute to the overall costliness of 3D printing for large-scale construction endeavors. While 3D printing can be a quick process for small objects, the manufacturing of large or complex structures is time-consuming, causing delays and reducing the overall construction efficiency compared to conventional methods. The complexity of the 3D printing process, including the need for expert operators and specialized software, can be a hindrance for architects lacking the necessary knowledge or resources to effectively utilize this technology. Furthermore, the implementation of 3D printing in construction projects is subject to various regulations and compliance requirements, such as building codes and safety standards, which further add complexity and expense to the construction process [118–120].

10. Technological Methods of Concrete 3D Printing (PB3DP)

10.1. Robotic Methods

Rapid advancements have been made in the use of digital tools for AM in building construction, with prototypes moving from the laboratory to real-world applications in both private and public building projects. Using in-situ AM technologies in this industry has shown a capacity to greatly increase efficiency and material effectiveness relative to conventional manual production methods [121]. These days, gantry systems are the most common type of large-scale fixed system used for in-situ AM because of their enormous payload capacities and great precision when performing end-effector activities [122]. Constrained facilities (wherein the mechanical systems are considerably larger than the framework they build), limited expandability due to complicated parallel processes, large total resource supply distance, the comprehensive efforts needed to set the framework up on work sites, and the typical restriction of applications to newer buildings on vacant lots, are just some of the drawbacks of these stationary systems. While innovations such as multi-nozzle 3D printing have helped these systems function more effectively, the field as a whole would profit enormously from the introduction of in-situ solutions that allow for the wider use of AM techniques in the building sector. Specifically, the incorporation of independent portable robotics into the building construction process creates new possibilities for in situ AM; Mobile AM (MAM) processes for on-site development could offer an unrestrained work area via improved mobility, opening up new possibilities for infrastructure in terms of manufacturing building elements larger than the system's stationary range [121,123,124]. Communication between several robots in a network, or with human workers and on-site

workers, might make this possible, allowing for scalability. They might also allow in situ AM to be used on projects other than brand new buildings, such as in renovation and maintenance.

10.1.1. Concrete Construction Using 3D Printing with a Particle Bed

Particle-bed 3D printing, amongst the other AM methods, enables the production of free-form concrete parts without requiring a formwork or equipment tailored to the individual components. It is easy to make concrete parts that are suitable in terms of force flow or other building mechanical considerations. Hence, this approach may settle the conflict between geometrical optimization and increasing manufacturing costs, making unconventional approaches financially viable. It would broaden the scope of design methods such as visual statics and allow for a wider range of economically feasible forms. Combining 3D printing with new methods in concrete materials engineering has the potential to have a huge effect on the environmental challenges presented by the global expansion of the construction industry. Structural blocks with optimal shapes can minimize the quantity of material required, improve portability, and cut down on energy losses within buildings. Up to 70% less material is needed when undertaking structural optimizations and employing AM methods [125]. Material conservation involves a high economic burden and has a high impact on the environment because of the substantial environmental influence of the construction sector (representing 40% of the global utilization of energy, 38% of worldwide greenhouse emissions, 12% of world potable water usage, and 40% of the production of solid waste in developed nations) [126–128]. In addition, the use of precast concrete that includes functional parts or openings for building services helps speed up the construction process. PB3DP also opens up new possibilities for the aesthetic development of concrete components. The rapidly developing area of PB3DP spans a wide variety of scientific and industrial specializations [129].

10.1.2. The Process of Particle-Bed 3D Printing

Both the deposition of a layer of dry particles and the selective distribution of a liquid onto the packed particles using a 3D printer or nozzle are repeated throughout the printing to bind the particles together. A de-powdering process then clears off the unbound particles. When the printing is complete, the object can be infiltrated or heat-treated to increase its strength and longevity. Figure 8 shows the three main approaches that can be taken when using PB3DP for the manufacturing of concrete: (1) direct printing of the element with a concrete mixture substance; (2) the printing of a formwork that is loaded with traditional concrete mixture and then separated; and (3) the printing of a permanent formwork that generates a composite with the poured concrete. Cement or non-cement substances, including polymer–sand composites, can be used to make the formwork. The particle bed used in selective binder activation comprises a dry combination of very fine aggregate (typically sand of 1 mm) and a binder, and it may be utilized in three different particle-bed 3D printing processes, as shown in Figure 8. Cement is used as a binding agent in concrete. To form a cement paste matrix containing aggregate elements, the cement is locally activated by pouring a water–mixture solution onto the aggregate particles. The particle bed in this case is made up of unbound aggregate particles (diameter usually less than 5 mm). Binder paste is applied to the particle bed via nozzles; this consists of additives, water, and cement. Filling the gaps between the granules with cement paste is essential for producing structurally sound components. Spraying a liquid binder over a particle bed is known as “binder jetting”. The binder used in the 3D printing formwork is often a resin that is cured after reacting with a hardener in the print bed. Particle-bed 3D printing techniques, in contrast to other AM building procedures, impose very few constraints on the final shape. Since dry-compacted granules are so structurally secure, it is easy to make cantilevered beams, suspended rafters, and slanted roofs using them. The very good manufacturing resolution even for large objects is another feature of this method. Particle size determines the minimum attainable resolution, which can be as low

as 0.1 mm. In addition, geometrical complications have little influence on the duration of the manufacturing process. Particle-bed 3D printing has the major drawback of imposing size limitations on components due to the confines of the printing environment. Yet, the first commercially available particle-bed 3D printers are now capable of creating large-scale components. With a maximum width of 6.0 m, D-Shape® uses a large-scale PB3DP for a variety of particle–binder systems. The development of a 4.5 × 2.5 × 1.0 m PB3DP for cementitious materials has recently begun. At present, the 4.0 × 2.0 × 1.0 m particle-bed 3D printer is the biggest available for polymer-bound sand molds. Additionally, the extra steps needed to clear non-bonded materials after printing, and the possibility of recycling these materials, must be evaluated in terms of manufacturing expenses and environmental effect. It follows that this strategy is optimal for use in a precast factory with high levels of automation. The non-bonded substance must be 100% recyclable to avoid any negative effects on the environment.

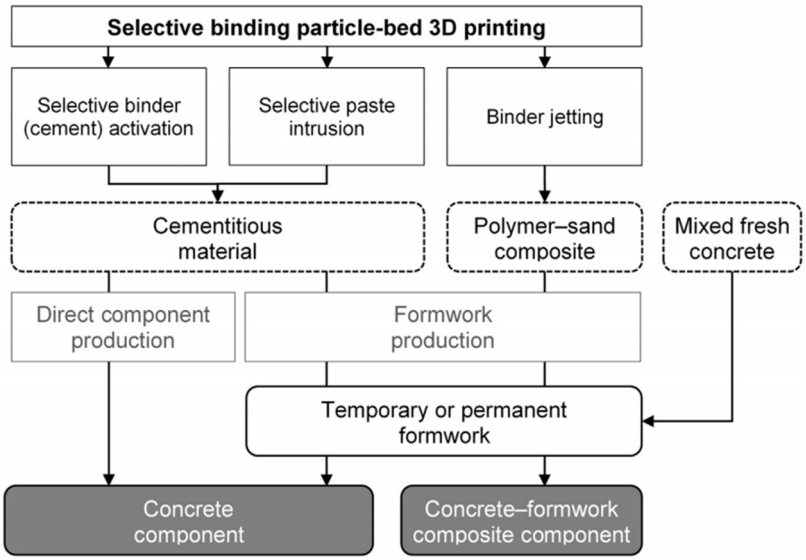


Figure 8. Selective binding particle 3D printing [130]. (Reproduced with permission from Elsevier, License number 5574821438548).

11. Polymers in Concrete

Polymers in concrete have attracted substantial interest during the past quarter-century. PIC was the first concrete polymer composite to attract widespread attention. PIC has remarkable durability and strength, yet it has few practical uses. Since its introduction in the 1970s, PC has found widespread application as a repair material, a thin floor and bridge overlay, and as a precast component. Repairs and overlays are the most common applications of PMC. Numerous restrictions have hampered the usage of polymer concrete. Nonetheless, there are numerous existing and future applications for these materials that make efficient use of their distinctive features. Popular applications of concrete polymer materials include improved and automated repair procedures, advancements in materials, structural applications, substitutes for metals, and architectural components [131]. Some 3D printing materials are environmentally friendly: PLA emits fewer emissions, PETG is recyclable, TPU is less hazardous, and filaments derived from wood are biodegradable. Recycled filaments lend new life to plastic. However, the environmental impacts also depend on energy consumption, refuse management, and the lifetime of an object. Disposal and end-of-life practices are essential to reducing damage.

11.1. Polymer-Impregnated Concrete

While Soviet scientists claimed to have created PIC first, it was extensively studied in the 1960s by scientists at the United States' Brookhaven National Laboratory and the Bureau of Reclamation. To make PIC, often, methyl methacrylate, a low-viscosity monomer, was

impregnated into hydrated PCC or Portland cement concrete, before being polymerized using radiation or heat catalysis. As a result of its incredibly low permeability, PIC typically showed an increased compressive strength by a factor of three to four over the original concrete, as well as improvements in its tensile and flexural strength. It also exhibited exceptional durability, particularly with regard to its resistance to freezing and defrosting, as well as its resistance to acid. Despite the polymer's modulus being no more than 10% of the modulus of concrete, the elasticity of the material was unexpectedly 50–100% higher than that of regular concrete. Due to its extraordinary qualities, it was expected that PIC would find uses in a wide variety of contexts. Some examples include bridge decks, floor tiling, pipelines and conduits for hostile fluids, building cladding, post-tensioned beams and slabs, hazardous waste containment, and stay-in-place formwork. Stay-in-place forms and channel liners are two examples of PIC components that are now manufactured in Japan by only a single firm [132].

11.2. Polymer Concrete

In 1958, the United States began using PC to make cladding for buildings. PC is composed of an aggregate bound by a binder, mainly polymer, and does not contain PC or water. Acrylics, epoxies, and polyester–styrene are the most commonly utilized resins/monomers, but furan, urethane, and vinyl ester have also been employed. Sulfur is also regarded as a polymer, and it has been utilized in applications when high resistance to acid is required. In addition to its use in precast cladding, PC was the first, and remains the most popular, material used for lavatories, cultured marble countertops, and other sanitary equipment. Great efforts has been directed towards develops and employ PC as a concrete repair material. Its superior adhesion to concrete, rapid curing, steel reinforcement, exceptional strength and longevity make it a highly desirable material for use in repairs. It can be applied at a thickness less than 10 mm as mortar. Due to the costs, a lack of knowledge, and competition with other materials used for repairs, such as rapid-setting PC formulae, it is not as commonly employed in repairs as was originally anticipated. PC is typically mixed in mixers of concrete, and poured and prepared as concrete. When using PC, various construction methods will benefit from the material's excellent features. Several breakdowns have occurred as a result of incompatibility between a concrete substrate and PC due to the difference in the coefficient of thermal expansion and the high modulus of PC. Changes in temperature can result in strong shear and tensile strains at the interfaces along the borders, which can cause the repair to become delaminated. PC overlays and screed have also grown popular due to their ability to form thin layers, their extremely low permeability, their quick curing, and their ability to be used in aesthetic and architectural treatments. The overlays are used in various applications, including floors in arenas, labs, bridge surfaces, factories and hospitals. The usage of overlays for flooring has matched expectations, but their application on bridges has lagged behind. Underground boxes, drains, manholes, acid tanks, cladding for buildings, highway median barriers, hazardous waste containment, shells for repairing machinery foundations, tunnel linings, tunnel forms, stay-in-place curb floor tiles, sleepers, machine tools and architectural moldings have all been manufactured using precast PC. Due to the material's quick curing, flexibility in producing complex shapes, and superior vibration dampening, precasting is an excellent mode of application of the material. PC was initially used as a concrete substitute, but was eventually utilized in substitution of other materials, such as cast iron, which is used for machine bases, tools and metals. PC is particularly advantageous for these applications due to its high strength and stiffness-to-weight ratio, strong damping characteristics, low heat conductivity, and formability [133].

11.3. Polymer-Modified Concrete

Latex-based PMC has been utilized since the 1950s. PC treated with a polymer such as acrylic, SBR, PVA (wood glue), or EVA is used to create PMC. From a construction standpoint, the similarity between PMC and conventional PCC is a desirable characteristic.

Typically, the proportion of polymer in the PC binder is between 10 and 20%. Very few polymers are suitable for addition to concrete; at the same time, the majority of polymers yield a PMC with inferior qualities. SBR has been extensively utilized in bridge overlays and floors, despite the fact that a minimum thickness of 30 mm is allowed. The benefits include the superior strength of binding to concrete, decreased permeability, and increased flexural strength. Typically, 24–48 h of wet curing is required to allow the concrete to build strength prior to the formation of the latex layer. Using acrylic latex, mortars that may be sprayed onto architectural finishes have been manufactured. Moreover, it is useful for adhering ceramic tiles to flooring. Acrylic PMC is capable of maintaining its color, making it a desirable material for architectural treatments. The addition of fibers to PMC can result in increased tensile strength and decreased cracking. Spray-on treatments for vertical surfaces have been shown to be quite cost-effective. PMC is less expensive than PC, since it uses less polymer [134].

11.4. Bonding Agents

Another application of polymers is in sealing and protecting concrete cracks. Crack formation is a well-known and prevalent defect in concrete. Crack repair has posed difficult challenges, one being epoxy injection, which was developed to offer structural restoration; however, it is exceedingly expensive and time-consuming. The emergence of HMWM for use in sealing cracks in the 1980s was a significant advance. The HMWM can be brushed, mopped, or sprayed on a surface, and it will fill fissures with widths greater than 0.2 mm. The HMWM moistens the crack extraordinarily well, and if the fracture is clean, more than 90% of its depth is typically filled; in this case, the manual application required is less than that of epoxy injection [135].

11.5. Polymer Limitations in Concrete

In the past 30–40 years, the use of polymers has shown remarkable advancements in the concrete industry. Initially, it must be acknowledged that cost is amongst the most significant limits when using composites of concrete–polymer. Although the cement's specific gravity is approximately 21 times that of polymer, polymer composites have significantly greater costs per unit volume is than PC concrete. Owing to the increased costs, the volume of polymer concrete per unit area must be reduced, making its use impracticable for applications with large volumes, such as foundations, pavements, hydraulic structures, and walkways, unless durability renders concrete unsuitable in extremely rare circumstances. Due to the material's inability to endure high temperatures, particularly flames, it cannot be used as a building material for structures that house humans. A third limitation during construction or fabrication relates to the odor, toxicity, and flammability of monomers including resins. Despite the fact that these restrictions only exist for a brief period of time before curing, the usage of these materials can pose problems for the safety and comfort of the worker, which must be considered throughout construction [136].

12. Reinforced Polymers Structures in Concrete

FRP composites provide designers with a chance to develop novel and ingenious solutions to ever-increasing infrastructure degradation issues. Considering that it has been over fifty years since the first application of FRP components in the building sector, this section provides a state-of-the-art study of the previous and current developments of FRP in reinforcement and rehabilitation uses for civil engineering. This overview emphasizes some of the traditional and current experimental, numerical, and analytical research related to the incorporation of FRPs into constructions such as buildings. This section also examines the use of FRP systems in concrete-reinforced components and the endurance of FRPs, including bonding agents, in extreme situations, such as conditions with an elevated temperature, saline environments, and freezing and thawing cycles. This section also provides a summary of the limitations, obstacles, and research requirements associated with the sustainable, successful, and long-lasting implementation of FRPs in civil structures.

FRPs belong to the class of composites materials that are produced by combining more than two constituent materials to create a compound with better functional qualities. Generally, these materials consist of continuous fibers of high strength embedded in a polymer resin. The inserted fibers are the primary reinforcements, while the binder is the polymer matrix that protects the fibers and enables the transmission of stresses between them. Aramid fibers (Kevlar 49, aromatic polyamides,), E-, S-, and Z-glass fibers, and carbon fibers (high-strength, high-modulus, ultra-high-modulus) are the three primary types of fibers utilized in the construction sector. In contrast, polymer matrices (resins) are divided into two categories: thermosetting and thermoplastic. Under the category of thermosetting matrices, vinylesters, epoxies and polyesters can be found. Thermosettable matrices are cross-linked polymers produced using addition or condensation polymerization. Once created, they do not melt, soften, or dissolve in solvents when reheated or placed in liquid. Thermoset resins, which are utilized more frequently due to their enhanced mechanical performance, provide superior fiber impregnation and adhesion capabilities. In contrast to thermoset materials, thermoplastics such as polyvinyl chloride, polyethylene, polyurethane, and polypropylene are more expensive to manufacture, and extremely sensitive to weather circumstances.

Resins are typically composed of polymers, various metals, or ceramics. Polymer matrices are the most prevalent substance because they are simple to manufacture and relatively affordable to produce. CFpRP, AFRP, GFRP, BFRP, and a few newly made PEN and PET composites have been generated by the combination of a matrix and fibers. The mechanical characteristics of FRP composites can vary significantly based on the kind of fiber and the matrix of polymers (Table 6). In Figure 9, a comparison of the stress–strain curves of common FRP materials is shown. FRPs were initially used in the automotive, aerospace, and marine industries as lightweight materials with high modulus and strength. Due to the cost and production complexity, FRPs are impractical for use in civil applications; instead, unreinforced composites, which are less expensive to produce, are used as cladding and finishing materials in non-structural applications. Yet, with the advent of current technologies, FRPs have become an attractive option for retrofitting and reinforcing structures due to the variety of benefits they provide over conventional construction materials, such as steel and concrete [137].

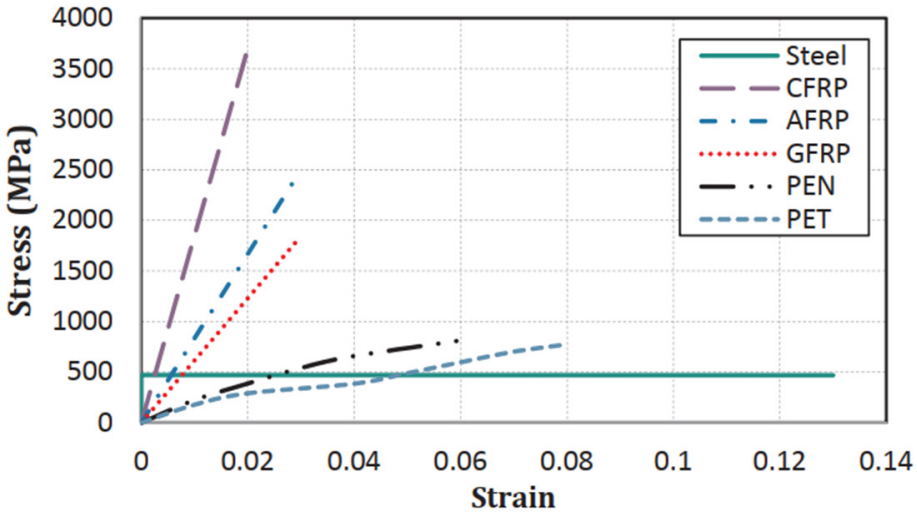


Figure 9. Tensile stress–strain curves for structural steel and various FRP materials [138] (Reproduced with permission from Elsevier, License number 5574830095954).

Table 6. Properties of typical commercially produced FRP products [139–143]. (Reproduced with permission from Elsevier, License number 5575850914994).

	Type	**Fiber Volume**	**Tensile Strength (MPa)**	**Fiber Architecture**	**Tensile Modulus (Gpa)**	**Thickness (mm)**
FRP	Standard Modulus Carbon-reinforced	65–70	2690–2800	Unidirectional	155–165	1.2–1.9
	GFRP	65–70	900	Unidirectional	41	0.4–1.9
	High-Modulus Carbon-reinforced	65–70	1290	Unidirectional	00	0.2
	Hybrid FRP Plate	NA	376	Unidirectional	4.4	0.65
	BFRP	68.7	1417	Unidirectional	9.2	0.27
	Carbon-reinforced Vinylester	60	2070	Unidirectional	131	2
		Fiber architecture	**Tensile modulus (Gpa)**	**Fibre volume**	**Tensile strength (Mpa)**	**Dimension**
FRP bar	Glass-reinforced Vinylester	Unidirectional	41–42	50–60	620–690	3 mm diameter
	Carbon-reinforced Vinylester	Unidirectional	124	50–60	2070	3 mm diameter
	Glass-reinforced Vinylester	Unidirectional	41	50–60	551	25 mm diameter
	AFRP	directional	70.3	NA	1448	8 mm diameter
	BFRP	Unidirectional	0.2	NA	676	8 mm
	Carbon-reinforced Vinylester	Unidirectional	145	50–60	2255	3 mm diameter
		Fiber architecture	**Thickness (mm)**	**Tensile strength (Mpa)**	**Tensile modulus (Gpa)**	**Strain at rupture**
FRP sheets and fabrics	Standard Modulus Carbon Fiber Tow Sheet High Modulus	Unidirectional	0.165–0.330	3760	230	0.2–1.5
	Glass fiber (Unidirectional)	Unidirectional	0.356	520–3240	2	3.5
	Carbon Fiber Tow Sheet	Unidirectional	0.165	3520	370	0.0–1.5
	T900 (Unidirectional)	Unidirectional	0.276	40	0	7
	EN900 (Unidirectional)	Unidirectional	0.273	90	15	5
	Basalt fiber *	Bidirectional	0.17	100	1	0.4

* Unidirectional.

Owing to recent developments in the environmental durability, corrosion resistance, and inherent customizability of FRP materials, the application of FRP has expanded beyond the recovery of existing structures, and into the reinforcement of modifications to new facilities. FRP has various applications, including in beams of metal and wood, the seismic retrofitting of bridges and buildings, girders, and the recovery of structures including historical monuments. In addition, it has been seen in the past few years that in this sector, polymers are being consumed at a higher rate.

13. Multi-Material AM in Construction and Architecture

As an extension of AM, MMAM is a developing manufacturing technique that is becoming popular in construction and architecture [144]. By combining diverse material qualities or materials in a single additive process, objects made of multiple materials can be created. Finally, this strategy presents a new method of manufacturing and construction in which it is no longer necessary to assemble multiple materials. In addition, the utilization of MMAM can address a variety of applications, leading to components with a varied composition of materials and a high degree of adaptability in terms of design, structure, and environmental impact. The construction sector faces significant challenges as a result of increasing material and energy consumption, and nearly stagnant productivity development. A 2017 analysis by the consulting company McKinsey indicated that yearly production progress in the construction industry averaged only 1% over the previous two decades [145]. This contrasts to 3.6% for manufacturing in general, and 2.8% for the global economy. Even though structures are becoming more complex day by day, and there is a need to satisfy the target of environmentally friendly construction and the accompanying (more stringent) building performance requirements, construction techniques have only marginally advanced. Most of the construction is still carried out in an inefficient and labor-intensive manner. Moreover, prevailing construction methods are associated with several problems, including a higher vulnerability to flaws in construction due to poor planning, communication and implementation, higher construction margins, and the neglect of activities essential to align parts appropriately. MMAM is a technique that enables the construction of objects featuring varying materials or material attributes throughout their volume [144].

According to Gibson et al., there are three approaches to altering material composition via AM [146]:

- A procedure in which two or more distinct materials are juxtaposed (Discrete Multiple Material Processes);
- A process-dependent technique (Porous Multiple Material Processes);
- A method in which the feedstock consists of more than one separate element (Blended Multiple Material Processes).

Furthermore, the potential to make such things is inherent to the majority of processes based on AM, and can be realized by combining multiple materials or by altering the processing parameters of the corresponding material. AM has the ability to drastically modify the manner in which products or frameworks, such as structures, are produced. A crucial aspect of most manufactured items or buildings is that they are composed of multiple materials, each of which typically serves a distinct function. Traditional manufacturing (including AM for a single material) depends heavily on the assembly of individual pieces to combine these materials. In contrast, this technique permits the combination of diverse materials or material qualities within a unique process. Thus, the requirements for future assembly and the accompanying restrictions are eliminated. In the end, this method enables greater customization in terms of geometry, as individual components do not need to be created for assembly, as well as in terms of changes to the materials inside a single product [147].

AM in Construction and Architecture

In association, alongside this trend, the architecture and building sectors may experience a parallel expansion in AM [148]. In the wake of the initial applications of AM at the construction scale, such as 3DCP, Contour Crafting, and D-shape, the trend has shifted from research in laboratories to structure construction employing AM techniques. A number of initiatives have taken up this task since then, and new endeavors continue to stretch the material and methodological limits of using AM in the construction industry for the sake of improvement, and AM-based design approaches and applications. Additionally, a number of suppliers have emerged who employ 3D printing devices for building construction. According to one online source, aniwaa.com, which offers an exhaustive catalogue

of products such as 3D scanners, 3D printers, and software, there are at present thirteen distinct suppliers, with ten commercial firms providing prototypes and a few other firms providing services for the printing of structures. Additionally, more reputable construction firms are creating new 3D printing-related services and goods. Peri, an established manufacturer of structure and scaffolding equipment that offers technical assistance, has lately added 3D printers to its inventory of services. The Swiss company Sika AG has demonstrated the same pattern (Sika, n.d.). Since initial projects applied the ideas of AM in architecture and construction, the variety of available materials and production procedures has expanded significantly. Additionally, an investigation was carried out on the refining and application of metals, ceramics, and plastics, alongside concrete. Since then, a number of scientific articles have investigated this breakthrough in greater depth. Nonetheless, these publications place a heavy emphasis on AM methods specifically based on concrete, primarily in addition to extrusion techniques. To expand possible functions besides load-carrying frameworks, it is important to maintain a focus alongside development on widely suitable materials and, consequently, material characteristics. In addition, the production rate of conventional manufacturing is much higher than the production data of concrete structures suggests, which has also been cited by various articles and researchers. The articles [26,149,150], along with a description of MMAM initiatives in the architectural and construction sectors, provide a comprehensive and detailed overview of the benefits of 3D printing with various examples (see Figure 10).

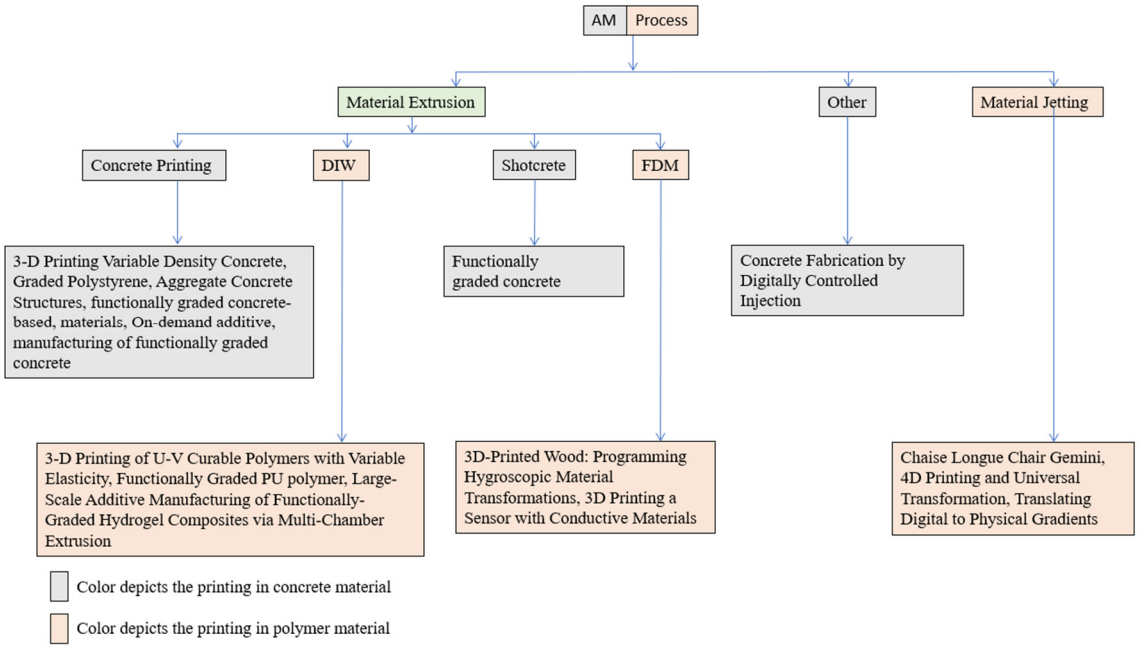


Figure 10. Categorization by manufacturing principles and materials (authors interpretation).

14. Challenges in the AM of Cementitious Composites

The AM of cementitious composites is a promising technology; however, several challenges need to be addressed in order to achieve the widespread implementation of the technology in the construction industry. Some of the main challenges are as follows:

1. Material properties—Cementitious composites have complex rheological properties, including high viscosity, thixotropy, and rapid hardening, which can cause problems during printing, such as nozzle clogging, layer delamination, and shrinkage. Therefore, the development of new cementitious materials with improved printability and physical performance is crucial for the success of AM in construction;
2. Printability—The printability of cementitious composites is influenced by various factors, such as printing parameters (e.g., layer height, nozzle size, printing speed),

material properties (e.g., yield stress, viscosity), and the geometry of the structure. Achieving consistent and reliable printing quality across different geometries and scales is a major challenge in the AM of cementitious composites;

3. Structural performance—The physical properties of cementitious composites, such as compressive strength, flexural strength, and durability, are critical to the structural performance of printed components. However, the process of curing cementitious materials in AM is often different from that of traditional casting, which can lead to variations in strength and porosity. Therefore, the optimization of the printing process and post-printing treatment is essential for achieving the desired mechanical properties;
4. Scaling up—While the AM of cementitious composites has demonstrated its potential in small-scale applications, such as prototyping and decorative elements, the technology is still limited in terms of the size and speed of production. Scaling up the technology for large-scale construction projects is a major challenge that requires the development of new printing systems, automation, and logistics;
5. Standards and regulations—The lack of standardized testing methods and certification processes for the AM of cementitious composites is a major barrier to the widespread adoption of the technology. Therefore, there is a need to establish industry standards and guidelines for material characterization, printing process validation, and structural performance testing to ensure the safety and quality of printed components in construction. There are four categories of obstacles: materials, printers, design and construction, and laws. Figure 10 depicts the primary categories and their accompanying difficulties. Based on a survey of the relevant literature, the most significant obstacles are 3D printing materials. Printability, buildability, and open time are the three most significant material issues. The material must possess the desired printability, so that it can be extruded from the nozzle, and buildability, so that it can hold its shape [151].

Since there are various challenges that are being faced nowadays, as can be seen in Figure 11, printability is frequently cited as the greatest obstacle. It relates to the manner in which the material will be pumped and printed. Buildability is a further important obstacle. The substance must be able to rapidly hold its own weight, and sufficient adhesion must develop between the layers. The third difficulty is open time. Researchers have defined this as the period during which the buildability and printability are uniform within the range of tolerances accepted for the process. There is a limited window of opportunity for material printing. Delays could result in concrete hardening. Hence, specific material mixtures are required to give sufficient time for printing. Scalability, directional reliance, and cybersecurity are obstacles associated with the 3D printer. The scale of construction projects presents 3D printing with extra obstacles. Directional dependence is frequently identified as a major obstacle. Cybersecurity is an additional difficulty. As the construction procedure is automated, all information is contained within the 3D model, and so cybersecurity and the risk of hacking are issues to be aware of.

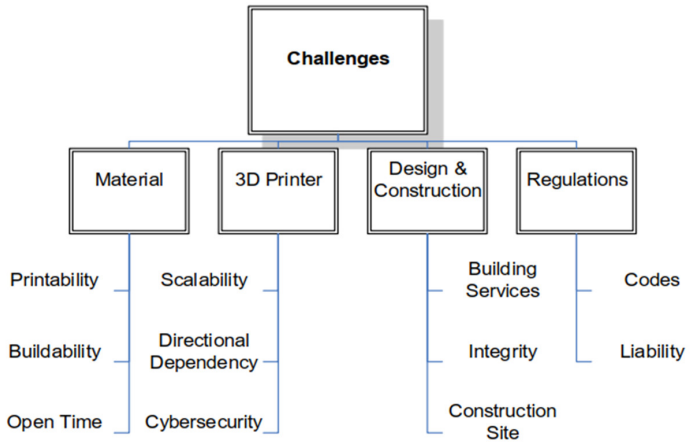


Figure 11. Challenges in 3D printing [152].

15. Impact on the Labor Market

In aiming towards sustainability concepts, particular care must be taken to consider the area of the labor market that is affected. There may be losses in jobs in some industries that cannot contribute to non-conventional 3D concrete printing. Low reliance on labor and more contented occupants contribute to social sustainability. Nowadays, the Dutch construction industry primarily relies on immigrant laborers. Regarding concrete construction, including iron strands, the majority of employees are Bulgarian or Portuguese, and Dutch workers are rarely seen. Importing labor is less expensive than employing Dutch citizens, and in the Netherlands, construction laborers are facing a shortage. Management does not view this position as sustainable in the long term. The originary nations of workers are anticipating economic growth, and the costs of labor will increase. In addition, it is projected that the labor shortage will intensify in the near future. These tendencies are the primary motivators for the pursuit of automation. In the next 40 years, there will be fewer individuals with the knowledge required by the profession; thus, industries will have to move production. One can observe negative trends in the learning of trades, such as in carpentry. From this vantage point, technology is not in a position to force workers out of industries; rather, labor shortages motivate the incorporation of technology and automation into the industry. By lowering the demand for seasonal employees, 3DCP would be another factor contributing to the removal of workers from the market, and the removal of consideration of social issues resulting from the insecurity of employment amongst seasonal workers (including the difficulties in the integration of foreign workers, and the potential for immigrant labor exploitation). The usage of 3DCP in construction will impact the number of jobs, as 3DCP will be taking over all the possible jobs. Now, the question of the usage of 3DCP also depends on the mode of usage, be it offsite or onsite, as offsite usage will impacts fewer people in countries such as the Netherlands. In the Netherlands, they already use prefabrication techniques, and 3D printers would just be added to the huge number of machines present in the factory, thus eliminating few jobs. However, in countries where prefabrication is undertaken on a huge scale, the technological impact will be bigger. The number of jobs lost will be higher. On the other hand, if the use of this technology is carried out onsite, then it would act as a preprogrammed robot, which would only require a few people to program. Manual laborers would lose their jobs in this process. Only a few persons, including supervisors and the least manual job roles, would be needed for this operation. Still, there remain some operations, such as plumbing and electrical equipment work, which would still be carried out by human labor. At the same time, there will be a favorable impact on the safety of workers, as in manual operations, some people have lost fingers, for example in woodworking. By using 3D printing in construction, injuries will be reduced as machines can be used. When 3DCP is utilized offsite, the dangers to manufacturing workers are comparable to those who undertake conventional prefabrication techniques. Given the elimination of work-at-height jobs and the absolute command of the production surroundings, the hazards associated with offsite construction are deemed to be significantly reduced compared to those associated with onsite construction. This contrasts with the anarchy that is frequently observed on huge construction sites, where "at busy moments . . . there are approximately 150 people roaming around outside. There are still many individuals present. I wonder if 3DCP printing can be of assistance there". When applied on-site, 3DCP could potentially minimize the frequency of accidents by minimizing congestion and worker contact [22,151].

Our examination of how the sector assesses the advantages and drawbacks of 3DCP reveals that, despite 3DCP's ability to considerably improve the environmental impacts of construction initiatives, early users confront a variety of trade-offs in the triple bottom line parameters. Table 7 provides a summary of the findings, and identifies the 3DCP characteristics that cause friction between the environment, profit, and people. According to its proponents, the horizontal columns demonstrate the primary advantages of 3DCP. The columns represent the triple bottom line's dimensions.

Table 7. 3DCP characteristics [153,154].

3DCP Characteristic	Effect on People	Effect on Planet	Effect on Profit
Design freedom to make complex geometries	+ Design may be more readily customized to user preferences. + Encourages the creation of highly qualified employment.	+ A multidisciplinary design strategy can increase energy efficiency and other performance metrics. + Holistic concepts can be less flexible and violate circularity concepts.	+ Combined designs cannot be readily compared to conventional designs, making it difficult to determine whether 3DCP is cost effective.
Automation	+ Automation-related employment is more stable and better compensated than seasonal migrant jobs. + If there are insufficient construction employees in the future, automation will be the only alternative. + 3DCP needs fewer workers than traditional construction.	+ Greater quality control reduces waste and failures.	+ Significant reductions in terms of failure costs. Lower fluctuation reduces project managers' uncertainty. + Expenditures must be substantial on equipment, R&D, and quality control.
Reduces material usage	+ No need for workers to construct formwork.	+ Reduces the environmental impact of concrete production and transportation; eliminates the need to construct formwork, which has limited reusability. + Even when its utilization is reduced, concrete remains large and problematic. + Material supply for 3DCP is limited and may require lengthier transport distances.	+ Substantial potential savings in material and formwork costs. + 3DCP alternatives are more costly than traditional concrete. + Alternative materials to concrete may be even more expensive.

16. Conclusions

This article delves into sustainable non-conventional concrete 3D printing, presenting a comprehensive state-of-the-art review that covers various comparisons and provides background information on non-conventional methods. While AM has been utilized in the construction industry for the past two decades, the focus remains on achieving full-scale 3D printing. Despite the successful printing of certain building and bridge components, the development of a complete residential building structure faces several obstacles.

Further, the article explores the potential use of sustainable materials to mitigate CO_2 and other greenhouse gas emissions. It highlights the utilization of artificial aggregates and geopolymers as sustainable alternatives. Additionally, composite cementitious materials, calcium sulfur aluminate, earth-based sustainable materials, binders based on geopolymers, and reactive magnesium oxide cement are identified as viable options for concrete 3D printing. Finding sustainable materials is crucial to reduce dependency on Portland cement, which is responsible for approximately 8% of emissions, thereby increasing material costs and compromising sustainability. While composite cementitious materials such as calcinated limestone clay cement offer improved workability, they exhibit reduced mechanical functionality due to the dilution effects. Earth-based binders serve as alternative sustainable options for concrete 3D printing. The article also includes a cost comparison for constructing a 600-square foot house using 3D printing, indicating a cost of INR 1352 per square foot. Another noteworthy aspect is the ability of concrete 3D printing to produce ultra-high-performance concrete. However, the current technological limitations prevent the printing of substantial concrete volumes, representing a challenge for large-scale projects. In terms of sustainability, the introduction of polymers into concrete can play a significant role in reducing carbon emissions, as polymers are major contributors to such emissions. Incorporating or reinforcing polymers in concrete offers potential means

of controlling and minimizing carbon emissions. The article concludes by discussing the impact on the labor market, noting that a rise in the 3D printing in concrete may decrease the demand for manual labor, potentially affecting employment rates. Nonetheless, the increased adoption of 3D printing is regarded as a sustainable and faster approach to concrete 3D printing.

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Abbreviations

3DP	three-dimensional printing
AFRP	aramid FRP
BFRP	basalt FRP
C3DP	construction 3D printing
CFpRP	carbon FRP
CMS	sodium carboxymethyl starch
CSAB	calcium sulfoaluminate belite
DIW	direct ink writing
EVA	ethylene vinyl acetate
FRP	fiber-reinforced polymer
GFRP	glass FRP
HMWM	High-molecular weight methacrylate
LDV	laser doppler velocimetry
MGO	magnesium oxide
PC	polymer concrete
PCC	Portland cement concrete
PEN	polythylene naphthalate
PET	polyethylene terephthalate
PIC	polymer-impregnated concrete
PIV	particle image velocimetry
PMC	polymer-modified concrete
SBR	acrylic or styrene-butadiene latex
SQFT	square foot
UHPC	ultra-high-performance concrete

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