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*Review*

# Framework of 3D Concrete Printing Potential and Challenges

**Adil K. Al-Tamimi [1,*], Habib H. Alqamish [2], Ahlam Khaldoune [1], Haidar Alhaidary [3] and Kamyar Shirvanimoghaddam [4]**

1 College of Engineering, American University of Sharjah, Sharjah P.O. Box 26666, United Arab Emirates
2 Dubai World Trade Centre, Dubai P.O. Box 00000, United Arab Emirates
3 Project Executive, Middle East Engineering Technologies (MEET), Sharjah P.O. Box 66636, United Arab Emirates
4 Carbon Nexus, Institute for Frontier Materials, Deakin University, Geelong, VIC 3216, Australia
* Correspondence: atamimi@aus.edu

**Abstract:** The technology of additive manufacturing, especially 3D concrete printing (3DCP), has been recently adopted in the construction industry as a viable alternative to traditional construction methods. Although the technology offers a wide variety of structural, economic, and environmental benefits, it is still restricted in use due to certain limitations that are still under research. This paper explains the fundamentals of the 3D printing process, its potential, challenges, as well as the different 3D printing systems. The recent literature is explored for recommended materials that possess the required properties for 3D printing, as well as reinforcement methods and techniques. This paper also reviews 3D printing extrusion using concrete and foam and explores the effect of both materials and extruding systems on the final product. The application of different additive construction systems with Building Information Modeling (BIM)-integrated algorithms are also discussed in this paper. It is believed that with providing a comprehensive knowledge of 3D printing for concrete construction, there is a huge potential to change the way cementitious materials are formulated and sustainability aspects are implemented, especially for complicated designs.

**Keywords:** 3D printing; additive manufacturing; additive construction; reinforcement; buildability; printability; green strength; building information modeling

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## 1. Introduction and History

The construction industry plays a significant role in any country's economy and is overall responsible for about 6% of the global GDP [1] with an estimation to grow to 14.7% by 2030 [2]. However, it is still perceived with acerbic criticism for its poor performance and old-fashioned work processes [3]. Despite the necessity for improvements in construction, inheriting new methods and techniques has been historically very slow-paced around the world. The issue with conventional construction methods is that they have unquestionable negative effects on the planet such as excessive carbon emissions and raw material consumption that emphasize the need for more sustainable solutions. In 1997, Joseph Pegna [4,5] first introduced AM-based on an automatic operation of incrementally building up layers of the structure, while in 2003, Behrokh Khoshnevis [6] developed large-scale 3D objects by Contour Crafting using cementitious materials. Richard Buswell then continued the work by enhancing the free-form printing process to build irregular-shaped panels in 2008 [4]. Recently, there has been a growing interest in Additive Manufacturing (AM) in construction and 3D printing using concrete as a potentially sustainable solution. Unlike subtractive manufacturing, in which objects are formed by the removal of material through cutting or grinding, the process of AM involves the formation of objects by depositing layers of materials on top of each other in an additive manner [3]. AM is an optimum solution for the development of the building industry as it is associated with notable advantages including cost, time, and material savings, as well as flexibility in design [4]. The technology also contributes to a reduction in injuries, a more controllable construction process, and better durability, when compared to traditional techniques. Although 3DCP is beneficial on many levels, there is a lack of review on the current situation of 3D printing in the building industry, which limits its implementation. Recent studies such as the one presented by Zhang et al. [4] predicted an increase in 3D concrete printing adoption across the globe due to its remarkable advantages and the increasing demand. The authors of this paper anticipate that the price of 3DCP will be reduced in the future due to the repeated use of the technology in multiple projects. The paper reviews several aspects of 3D printing and compares the challenges and opportunities associated with developing high-performance structures based on 3D printing as compared to traditional techniques.

Considering the technology's limitations, one such limitation is reinforcement. Generally, unreinforced concrete lacks the ductility and strength capacity which limits its application. Different types of reinforcement usually provide enhancements in ductility, tensile strength, load-bearing capacity, and cracking resistance of the concrete, hence making it a crucial element of concrete production.

In the first part of this review article, the process of 3D printing is thoroughly explained followed by different reliable printing systems. For enhanced structural performance, the effects of using various cementitious materials are subsequently covered. This also includes the evaluation of 3D concrete materials' rheological and buildability performance. Finally, this paper also aims to assess the realistic aspect of 3DCP applications by reviewing large-scale 3D printed projects and the potential of Building Information Modelling (BIM) integration in 3DCP.

### *1.1. Historical Development of Printing Methods*

Since 1997, significant fast-track developments were achieved in digital fabrication based on the AM technology proposed by Joseph Pegna. Today, different systems are being employed in the construction field such as the AM by selective aggregates, the relatively mature printing methods of Contour Crafting [7] and the D-shape technique [8], as well as concrete printing [8]. All these methods however utilize Computer-Aided Design (CAD) to define the geometrical parameters and to control the mechanical arms during the printing process. To elaborate, the printing methods are discussed in the following sections.

#### 1.1.1. Additive Manufacturing by Selective Aggregates

Joseph Pegna investigated the use of selective aggregation in additive manufacturing for large-scale construction projects in 1997 [9]. He developed two dimensions for categorizing the procedures utilized in additive manufacturing, which entails creating a product in many layers. The shape of the finished product serves as the first dimension, while the addition of materials at various stages serves as the second dimension [9,10]. The usage of selective aggregation in additive manufacturing is illustrated in Figure 1. The process starts by uniformly placing a layer of sand on the building bed (A) followed by a non-uniform plotting of cement powder on the specified geometric surface, as shown in (B). These two steps are performed once the layer geometry is scanned in the CAD file. Then, water, which is a binding agent, is impregnated by being sprayed on the bed (C) [10].

The method shown in Figure 1 is repeated, according to [10], by elevating the placement of cement and sand in accordance with the height of each layer. Pegna observed that the sprayed water caused surface tension which then created brittle and cracked fabricated samples. To avoid this issue, the fabricated sand/cement layers were exposed to steam and water vapor at the layer's interface instead of water spray. Multiple fabricated samples were tested to evaluate the compressive and tensile strength of Pegna's developed mixture. The results indicated that the samples are twice as strong in compression as they are in tension, mainly due to the high cement-to-water ratio. However, when employing the standard water-to-cement ratio, it was discovered that the difference between the two strengths was around 8%. Although it was noted that the material's shape was consistent, the results also demonstrated that the concrete specimens are not isotropic [10]. Pegna concluded that utilizing concrete in automated buildings is feasible and has a lot of potential [9,10].

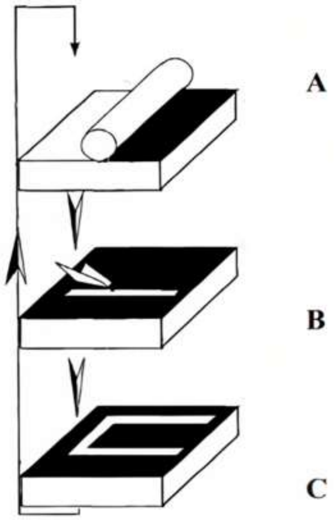


**Figure 1.** Selective aggregate process: (**A**) placing a layer of sand on the building bed, (**B**) plotting of cement powder, (**C**) spraying water on the bed [10].

#### 1.1.2. Contour Crafting

In the last decade, Professor Behrokh Khoshnevis from the University of Southern California developed a 3DCP housing structure using "Contour Crafting" [11]. Unlike the method researched by Pegna in [10], Dr. Khoshnevis viewed the application of additive manufacturing in large-scale building components from another perspective. He believed that the fabrication of assemblies by selective deposition of the construction material is impractical. Thus, he decided to apply the technique by depositing a pre-mixed fluid material that can harden once it gets laid on the building bed [11]. Contour Crafting allows for the 3D printing of concrete structures that include the necessary electrical, drainage, and conditioning channels. The professor argued that the application of rapid prototyping in construction has highly reasonable advantages. Rapid prototyping relies on automated operations which do not require continuous monitoring and is more precise due to minimal human errors. Automation would also minimize the design and execution time required by conventional methods, which will dramatically benefit the global market. Khoshnevis emphasizes that the computer-based nature of Contour Crafting will allow designers to produce geometrically more complex components [11]. The use of automated building processes is expected to reduce construction waste by up to 100% and thus reduce environmental pollution [12]. Khoshnevis's method is considered a possible solution for lowering the cost of housing in low-income countries [13].

The need for developing the process of additive manufacturing was raised as a result of the drawbacks of previous processes that utilized photopolymers as primary materials. Photopolymers are resin materials that solidify when exposed to light at a specific wavelength [9]. The previous technique was observed to be slow and unsatisfactory especially considering that speed and the reduction of manducating time are the primary objectives of automation. Moreover, both the surface of the final product and its shape were not of the desired quality and thus requiring elaborate finishing work.

A study performed by [14] affirmed that the products manufactured using the selective laser sintering technique formed small fractures on their surfaces. Furthermore, similar techniques produced breakable elements that failed in a brittle manner, which is considered a deficiency in large-scale applications. In addition, the printing materials used in the previously developed techniques are limited since they are mostly polymers. As a result, another problem occurs, which is the relatively high cost of such materials especially when large assemblies are to be produced using extensive quantities. The products manufactured using those techniques are relatively small, and only up to 1 m. The cost of the apparatus used to operate the process is considered to be another drawback as it reaches up to USD 300,000 on average. The cost is also subjected to more increase as per the desired size and quality of the final product [12]. This leads to a conclusion that due to the discussed disadvantages, there is a necessity to develop and enhance a technology that is capable of solving the drawbacks discussed earlier, such as cost and speed, and capable of being employed in large-scale construction automating applications.

Moreover, contour crafting is a layer-based additive fabrication process where the final product is built by the extrusion of flowing construction material that must solidify after being placed into the designated spot. A nozzle, which is fixed on a mechanical arm, is used to receive the delivered fluid and extrude it in a layer-by-layer fashion [15]. This method also enhances the product's surface finishing through an attached trowel that moves simultaneously with the nozzle and in correspondence to its movements. It is recommended to attach two trowels to the nozzle: one for the side and one for the top surfaces. A major aspect of contour crafting is the ability to specifically control the movement of the extruded material through various mechanisms [16]. In brief, the process is done by pumping material through a barrel and a nozzle. Then, with computer-aided movement, the flowable material is extruded on the specified path and the surface finishing is done by the trowels that are placed at the top and the exterior sides of the nozzle. Contour crafting proved that it can be used in construction-scale applications, yet it is 2.5-dimension technology. This process extrudes products vertically with a constant section; however, it is not capable of producing irregular elements or unsupported ones because it prints one layer upon the other on the same predetermined path. Although this is a drawback of contour crafting, it has a high potential in the field of construction.

#### 1.1.3. D-Shape Technique

The D-shape technique is another rapid prototyping process developed by Enrico Dini in 2008 [8]. This method was developed specifically for manufacturing different construction building components at a construction scale in a fully 3-dimensional procedure. The method allows the printing of irregular shapes and cross-sections, unlike contour crafting which is mostly used to extrude shapes with constant cross-sections. The D-shape technique relies on a frame that outlines the planes at which the horizontal layers of the final object will be printed. The frame also defines the enclosure of the printing area and detects the circumference of the walls. The frame is also able to move vertically on the *z*-axis in four directions, simultaneously. Besides the frame, there is a crane attached to the printer, and it moves in both the x- and y-axes in correspondence to the movement of the frame [17]. Because this is a layer-by-layer fabrication method, a computer-aided design model is required to define the geometrical aspects of the surface of each layer. According to Cesaretti et al. [17], the printing process starts once the CAD model is divided into multiple layers that conform to the thickness of each layer; then, the sliced surfaces get scanned from the bottom to the top of the CAD model. The technique also involves a printing head that builds the layers by depositing grainy materials (sand) at the desired locations that were predetermined by the computer model. The layers are then sprinkled with liquid polymers that solidify the deposited powders to create a solid object. The powders act as temporary support to print overhanging elements as well. This process is repeated for each layer according to the sliced CAD models, and it operates off-site [17].

#### 1.1.4. Concrete Printing

The concrete printing method is very similar in principle and application to contour crafting although some minor variations are reported. For example, after the material gets extruded, the surface of the concrete printed material is not finished as smooth as that printed using contour crafting. This is mainly due to the absence of the trowel attached to the printing nozzle. In addition, the size of the final element is restricted by the size of the printing frame as it is contained within the frame [16,17].

## 2. Breakdown of the 3D Printing Process

In order to build a structure, a concrete mix with appropriate rheological properties should be pumped and then extruded layer by layer. The 3DCP process often begins with a digital model and depends on an automated system for the build. Although many 3D printing methods have been developed by companies and universities around the world, currently the most used 3D printing method is Inject-Head Printing [18]. As shown in Figure 2, this method can be divided into three basic phases, which are mixing, pumping, and printing. The production starts with mixing materials with water, basically mortar that may contain some additives or admixtures. The mixture is then pumped through a hose to the 3D printer where it gets extruded through a nozzle. The 3D printer has a rotational spindle that controls the flow of the material during extrusion and minimizes air bubbles. The extruded material is then deposited at a predetermined location to form a stable object [19]. The material requires special attention since its physical, chemical and mechanical properties change with time and along each stage of the printing process. The concrete mix should be designed to meet the following printing requirements: pumpability, extrudability, buildability, interlayer bonding, open time, and segregation prevention. Here, extrudability may be defined as the ability of the material to pass through the nozzle and be deposited in a well-formed and continuous filament [20]. Buildability is defined as the ability of a printed filament to keep its shape after extrusion and not deform under the weight of deposited concrete layers. Interlayer bonding is the cohesiveness and homogeneity achieved by the adjacent layers as they coalesce together. Open time is the amount of time the fresh properties of the mix are suitable for printing, i.e., the material is still pumpable and extrudable.

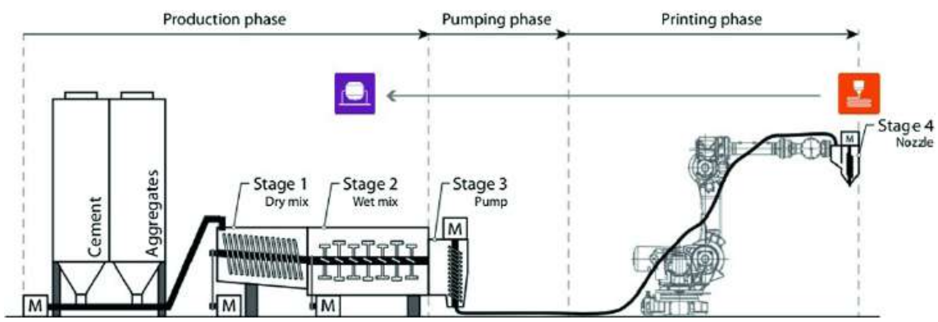


**Figure 2.** Breakdown of the 3D printing process [18].

All the factors mentioned above as well as segregation prevention are dependent on workability or equated to flowability. High flowability is positive for extrusion and negative for buildability. High flowability in a concrete mix can result in segregation. On the other hand, low flowability promotes buildability but negatively affects extrusion and interlayer bonding. Therefore, in terms of flowability, a balance should be found that allows printability. To have flowability that includes all printability requirements, the concrete mix should have thixotropic rheological behavior in which hardening is decoupled and coupled throughout the printing process. The concrete mix should be designed to be viscous, however, this viscosity is reduced when shear stress is applied in the pumping and extrusion processes, only to be regained when the shear stress is removed after extrusion. Thus, the thixotropy requirements should allow the material to be flowable when it is being sheared through pumping and delivery and, then buildable when the shear stress is removed at deposition. In particular, the early-age strength of the material needs to be such that the bottom layers acquire increasing yield stress as the build progresses [21]. Furthermore, since concrete is strong in compression and weak in tension compared to other construction materials [22], it is also advised to incorporate fibers such as glass, basalt, polypropylene, and steel in the mix design to compensate for the absence of steel reinforcement in 3D printed buildings as they improve the ductility and the tensile load-bearing capacity of concrete. However, in comparison to fibers, engineered cementitious composite materials (ECC) offer more promising results as they exhibit strain-hardening behavior which enables them to be more damage and flaw tolerant. Finally, the maximum size of the aggregate in the concrete should not be large enough to disturb the operation of the pressure system or block the hose pipes.

### *2.1. 3D Concrete Printing Systems*

3D-printed buildings or structural elements are either printed on-site or pre-printed elsewhere and assembled at the construction site. Regardless of the printing location, the printing process can be performed using different systems including a gantry-based system, cable-suspended platform, swarm approach, or mobile robotic arm. The selection of a suitable 3D printing system is mostly dependent on the size and geometry of the building or the structural component, and on the construction site.

1. Gantry-based system: It is the most used system for AM in construction. The gantry-based system, shown in Figure 3a, is based on Contour Crafting and has a printing head that moves in the X, Y, and Z directions like a CNC machine [23]. The drawbacks of this system include the printing size of the structure as it is limited by the size of the gantry itself. Besides, the degree of freedom of the gantry-based printing system is limited to 3-4 degrees which constrain the printing of complex and curved parts.
2. Cable-suspended platform: This printing system is made of a frame with suspended cables connected to the concrete extruder, as shown in Figure 3b. The movement of the concrete extruder is controlled by motors in a fully automated way. The advantages of this system are that it offers larger workspaces and is relatively inexpensive. The system can be easily assembled, disassembled, transported, and reconfigured [24]. However, the size of the printed structure is limited by the size of the frame.
3. Swarm approach: It consists of a team of mobile or stationary robots, as shown in Figure 3c. The usage of this system provides greater scalability as a larger printing area is covered by the collective reach of the team of robots. Furthermore, it provides greater flexibility due to having a full 6 or 7 degrees of freedom which allows the printing of complex curved parts. The employment of multiple robots increases time efficiency due to the concurrent printing process. However, the motion of the robots must be carefully planned to avoid collisions. Additionally, to avoid unalignment of printed parts by different robots, the robots should be localized with high precision [25].
4. Mobile Robotic Arm: The mobile 3D printer, illustrated in Figure 3d, is made of a robotic arm on wheels or a continuous track. This system has great flexibility due to having six or seven degrees of freedom which enables it to print complex structural shapes. Although it is more useful to use this movable system when compared to stationary ones; however, at some construction sites, the movement of the mobile robotic arm and the accuracy of its localization is limited by the terrain conditions. There are also other types of mobile 3D printers that do not contain wheels or continuous tracks, and a crane is used to lift them from one printing location to another at the construction site [23].

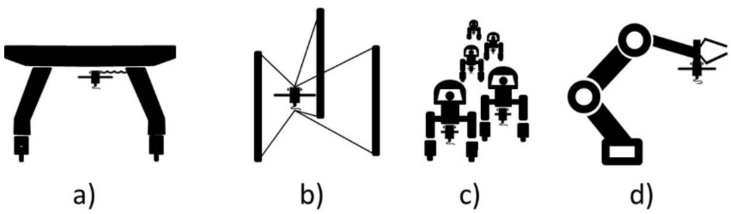


**Figure 3.** Different 3D printing systems: (**a**) gantry-based system, (**b**) cable-suspended platform, (**c**) swarm approach, (**d**) mobile robotic arm [23].

### *2.2. Recommended Materials for 3D Printing in the Construction Industry*

The selection of materials is critical for the successful production of 3D concrete-printed structures. Similar to conventional concrete production, the use of Supplementary Cementitious Materials (SCMs) can be beneficial in 3DCP. Pozzolanic or SCMs incorporated into the concrete mix improves the compressive and tensile strength, reduces the chemicals and water ingress, homogenizes the microstructure, increases the life span, and reduces the carbon footprint. Several studies have researched the effects of using different SCMs on fresh and hardened properties of 3D-printed concrete such as its thixotropic rheological behavior that allows pumpability, extrudability, buildability, and shape stability, along with improving the concrete's chemical and physical properties. Both Panda et al. [26] and Rahul et al. [27] investigated the use of slag-based cementitious materials in 3DCP. Panda et al. [26] explored the use of high-volume slag, with small percentages of Portland Cement (PC) and hydrated lime, in mortar specimens according to the rheological requirements of 3DCP. The results confirmed that high-volume slag/cement is applicable for 3D printing, but with a shear-thinning flow behavior and orthotropic mechanical properties of the printed layers. Whereas Rahul et al. [27] compared the desorptivity effect of GGBS, fly ash, and limestone-calcined clay, and found that binders containing limestone-calcined clay had the highest structural build-up rate. The incorporation of limestone and calcined clay was also studied by Chen et al. [28] to assess the 3D concrete printed extricability and early-age strength development. The authors reported that increasing the content of metakaolin in calcined clay improved both the compressive strength at 7 and 28 days and the green strength. This was due to the reduced initial setting time resulting from increased initial hydration of the cement. The extrusion pressure of the calcined clay samples was reported to be higher than those without calcined clay.

Moreover, a study conducted by Muthukrishnan et al. [29] investigated the influence of rice husk ash (RHA) on the performance of 3DCP. RHA is a cementitious material produced from the combustion of rice husks. The experimental results showed that the incorporation of RHA significantly improved the fresh characteristics of the mortar used in large-scale 3D printing. To clarify, when compared to the control sample, the fresh RHA concrete was found to be stronger and met the workability requirements quicker, although it had higher water and superplasticizer dosage, which allows for a longer duration of the continuous printing process. nano-clay is another cementitious material that has great potential in 3DCP enhancement [30,31]. The addition of nano-clay to the mix design improves the buildability properties, green strength, stiffness, shape stability, cohesiveness, and thixotropy. Zhang et al. [30] concluded that an adequate substitution of nano-clay and silica fume enhanced the fluidity of the concrete mix as well as its static state as it allows for better standing. For enhanced 3DCP properties, fiber or ECC incorporation is recommended as it increases the ductility and tensile strength which facilitates reducing or eliminating steel reinforcement in constructing a structure or a structural element. According to the authors, the incorporation of the Thickening Agent (TA) improves the extrudability properties due to exhibiting dough-like rheological properties. The authors also concluded that a High-Range Water Reducer (HWRW) improves concrete's workability and reduces the high water demand that takes place because of the incorporation of pozzolanic materials in the concrete mix design.

### *2.3. 3D Concrete Laboratory Set-Up*

To set up a concrete laboratory to assess the quality of 3D concrete mixtures, certain fresh and hardened tests should take place. However, the focus of this research is only directed at the fresh properties because the procedures of assessing the hardened properties of concrete are widely known and already implemented in almost all construction material laboratories. The targeted fresh properties are the workability, rheological properties (yield stress, plastic viscosity, and thixotropy), green (handling) strength, buildability, penetration resistance, and hydration heat. The laboratory should be equipped with a mix-pump system, robotic arm, control unit with an interface, material storage, and robot base. Furthermore, it should also include other equipment and apparatus to assess the previously mentioned fresh properties, as illustrated in Table 1. The importance of the fresh properties comes from the fact that if the 3D concrete mix design is pumpable, extrudable, and buildable with sufficient shape stability, interlayer bonding, and minimal or no deformation at all, it is highly likely the hardened properties of the concrete are going to be in conformance with the quality requirements of the international standards. Furthermore, since the layers will be deposited above one another in the fresh state, it is important that the fresh properties, especially the green strength (handling strength), are sufficient enough to achieve buildability without lateral deformation, layer settlement, or collapse which reinforces the significance of the fresh properties' tests. Structural build-up, which is the development of the strength of the fresh concrete with time, is one of the main fresh properties that is considered in the tests in Table 2 due to its significance. Structural build-up is basically the underlying principle for buildability, and it is time-related, such that a faster rate of structural build-up would enhance buildability [32]. Moreover, the laboratory should be equipped with a temperature controller to simulate the printing process in an exposed environment to the weather outside the laboratory. Additionally, there are some parameters that should be taken into consideration, such as interlayer bonding. Other testing methods of 3D concrete mixtures lack standardizations as they give indications of the status of the fresh properties of the 3D concrete mix design.

**Table 1.** Rheological Parameters of 3DCP [1,8].

| Parameter | Definition |
|---|---|
| Extrudability | The capability of the material to be homogenously ejected from the nozzle in a continuous manner with no reports of clogging. |
| Open Time | The period at which the material can be extruded continuously without separation. |
| Pumpability | The ease of transporting the material from the reservoir to the nozzle. |
| Extended Workability | The ease with which concrete flows after it is pumped. |

**Table 2.** Tests of the fresh properties of 3D concrete mixtures [4,24,32].

| Parameter | Test | Equipment | Standard | Remarks |
|---|---|---|---|---|
| Workability/flowability | Flow table test | Flow table, concrete mold, tamping rod, scoop, sampling tray, and measuring tape | ASTM C230/C230M | Due to the high flowability of the 3D concrete mixtures, the Flow table test is used instead of the Slump test [4]. |
| Rheological properties (yield strength, plastic viscosity, thixotropy) | Concrete rheometer test | Rheometer | ASTM C1749 | 3D-printed concrete is considered as a Bingham fluid ($\tau = \tau_0 + \eta.\gamma$) [4]. After plotting (shear stress (Pa) vs. shear rate (1/s)) graph, the rheological properties are obtained from the graph along with the Bingham fluid equation [4]. |
| Green strength | Uniaxial compression test | Compression machine | - | The samples are (70 × 140 mm) cylinders. The fresh 3D concrete mixtures are molded in cylindrical containers. After 5 s of compaction, the molds are removed and the specimens' compression strength is t tested after different resting durations (5, 30, 60, 120, and 150 min) [32]. |
| Buildability | Total height and layer settlement measurement | Measuring tape and digital caliper | - | The achieved total height is measured by a measuring tape and the settlement of each layer is measured by a digital caliper [24]. |

**Table 2.** *Cont.*

| Parameter | Test | Equipment | Standard | Remarks |
| --- | --- | --- | --- | --- |
| Penetration resistance | Penetration resistance test | Concrete mortar penetrometer | ASTM C403 | Strength development at early-age is evaluated using this test by determining the initial and final setting time. Growth of penetration resistance has a linear relationship with the growth of static yield stress; thus, penetration resistance can be used to characterize the structural build-up [32]. |
| Hydration heat | Isothermal calorimetry test | TAM air isothermal calorimeter | ASTM C1702 | The rate of heat of hydration is directly proportional to the rate of structural build-up [32]. |

## 3. Fundamentals of 3D Printing in the Building Industry

Initially, AM was developed to produce conceptual product models to identify design flaws during the design process, but nowadays, furniture, medical devices, and aerospace products are being produced with AM. In the construction industry, AM offers unique characteristics which increased the demand for this technology. For instance, tooling is not required, which consequently reduces production time and cost. Design can also be easily and quickly changed and the potential to produce any design on demand means a shorter supply chain that produces items quickly when needed and without having to keep them unnecessarily in stock [3]. Nevertheless, the challenge in utilizing this technology is associated with ensuring functional extrudability through controlling the fresh properties of concrete such as pumpability, extrudability, and buildability. To clarify, workability must be controlled and maintained to avoid premature solidification before and during extrusion, along with a suitable setting time that enables the printed layer to support the following printed layers [3]. Other challenges include the precise control of material delivery such that it is synchronized with the velocity of the nozzle and the material does not accumulate at sharp corners and bends [3]. It is important to mention that the concrete mixture can contain sufficient proportions of binder (including fly ash and silica fume), water, fine aggregates (including recycled glass and cork), and additives (such as retarders, accelerators, and superplasticizers). However, the size of the aggregate should not be large enough to block the nozzle. Several types of fibers can also be used, such as copper fibers, carbon fibers, and steel fibers, and they play a crucial role in the stability of concrete mixtures. Thus, further research is required to develop new printing materials that can be used in construction along with their testing and characterization standards. Not only that, but the production of large non-supported structures, such as roofs, is also one of the challenges that require more attention and investigation.

### *3.1. Rheological Parameters of 3DCP*

When compared to traditional concrete construction processes, 3DCP technology has a completely different construction system. On the other hand, all these methods including contour crafting and concrete printing are based on one aspect, which is the robotic extrusion of the material to obtain the final product [16]. According to Wang et al. [33], it is crucial to obtain adequate rheology parameters not only for the success of the procedure but also for the safety of the robot and the attached system. This involves the pipes, tubes, or conduits that are used to extrude the material onto the bed through the end nozzle. In other words, the 3DCP material used should be capable of being pumped through the nozzle with no clogging, stoppage, or hardening. Otherwise, the maintenance of the robot itself or the attached delivery system will be significantly costly, which, in turn, negatively affects the economic advantages of 3DCP. This has pushed researchers to study the rheology of 3DCP in both standard methods and newly developed methods. Usually, standard tests including slump, flow table, and V-funnel are used to evaluate the rheological parameters presented in Table 2.

Kolan et al. [14] also investigated the performance of direct shear tests and rotational rheometry to evaluate the rheological parameters of 3DCP samples using cementitious materials. The authors reported that there were some limitations in using rheometers due to the insufficient maximum applicable torque; however, they suggested that a direct shear test would be amongst the most adequate testing methods for evaluating the fresh properties of the samples [16,34–36]. In addition, extrudability is another essential parameter in the evaluation of 3D printing using mortar mixtures. Extrudability refers to the capability of the material to be ejected from the nozzle in a continuous manner [9]. A material is said to be extrudable if the printed strings are homogenous and the flow is continuous with no reports of clogging during the printing process. Li et al. [37] and Le et al. [38] emphasize that the longer the strips are printed without segregation and without being fractured the better the extrudability of the material. As illustrated in Figure 4, to evaluate the extrudability of the material used in 3DCP, it is recommended to extrude a 2000 mm long continuous strip that returns eight times every 250 mm, creating eight subsegments [37]. The proposed method is a YES or NO test, as the conclusion is based on observation of continuity and no separation of the strips during the process.

**Figure 4.** Top view of 2 m long printed mortar strip [37].

Open time is one of the rheological parameters used to evaluate the fresh properties of 3D concrete printing. Open time is the period at which the material can be extruded continuously without separation [37]. The open time is related to the setting time of the material, and it is determined by the Vicat apparatus or slump tests. It is worth noting that these methods are not useful when considering the printing of the material. This is because they only target the initial and final setting time, which helps in evaluating the overall workability but not a specific parameter that varies over time. Specifying the flow of the material over time is crucial for the extrusion process. Alternatively, Le et al. [38] employed the vane shear test to evaluate the open time of mixes used in 3DCP. The shear stress indicates the workability and pumpability of the material and represents their variations with time [39]. Hence, the open time can be defined as the time required to reach certain shear stress that corresponds to a workability level that exceeds the limit of acceptable printability. Another simplified method to measure the open time was proposed by Lim et al [37], and it is done by extruding mortar strips with equal dimensions at equal time intervals. The open time will then be the period until the first separation or blockage happens during the printing process.

### *3.2. Reinforcement in 3D-Printed Concrete*

In the last century, structures were designed based on the congenial relationship between concrete and steel to form reinforced concrete, which was mainly used in constructing ingenious shell structures, bold roof structures, and bridge constructures [40].

Nowadays, reinforced concrete is used in masses and is associated with various environmental concerns and geometric restrictions, leading to increasing demand for technological developments in 3D concrete printing [40,41]. To elaborate, the greatest obstacle to utilizing 3DCP is an effective reinforcement method that would ensure structural integrity and optimize the load-bearing capacity of 3D concrete-printed structures [40–43]. Thus, researchers have been studying and exploring the feasibility of constructing reinforced 3D concrete-printed buildings using different materials and methods. Reinforcing 3D concrete-printed structures using continuous cable or fibers within the printed layers was explored by [44–47] and showed promising results. In a study performed by Wang et al. [45], a micro-cable-reinforced geopolymer composite that was based on fly ash was used to assess the strength of a 3DCP structure, especially its toughness and post-crack moment capacity. To verify the applicability of utilizing the micro-cable-reinforced geopolymer composite, three printing path scenarios were designed and evaluated using four point bending tests. The results showed that the flexural strength and deflection resistance of the reinforced printed layers were, respectively, eight and seventy times higher than that of non-reinforced printed filaments. This result was only obtained when the reinforced layers were printed in an inclined-crossed configuration [45]. The in-process steel-cable reinforcement method studied by Pham et al. [46] also demonstrated that the flexural strength of concrete can be increased up to 290% when it is reinforced using steel cables. Similar results were obtained when Mineral-impregnated Carbon-Fiber (MCF) was implemented in reinforcing layers printed by layered extrusion [47]. The addition of chopped fibers to the print mixture was also investigated by [24,48,49] and led to an enhancement in the structural characteristics of the printed layers. It was noticed that the rate of enhancement, especially in flexural strength, depends on the type of fiber [48,49].

According to Marchment et al. [42], the previous reinforcing methods only consider the direction that is parallel to the printed layers, while the interlayer reinforcement coming from the perpendicular direction is excluded. However, few experimental studies have explored interlayer reinforcement methods using small vertical meshes rolled off a spool and robotic wielding [46,50,51]. The recently investigated interlayer reinforcement methods have not yet been applied to large-scale applications as it requires more complex printing processes [42]. Currently, manual processes such as post-tensioning, printing over pre-installed reinforcements, or reinforcing cavities that are filled with grout or concrete are used to overcome the interlayer reinforcement in 3D concrete-printed structures [42,52–54]. Despite their efficiency, these methods limit the benefits offered by 3DCP and complicate the construction process [42]. In-process interlayer/vertical reinforcement was addressed by the bar penetration technique in which pre-cut reinforcing steel bars penetrate the freshly 3D printed concrete layers in a repetitive manner, as illustrated in Figure 5 [55]. The bar penetration test was found to be effective for automating reinforcement placement for up to fifty layers of concrete. According to Sanjayan et al. [55], the bar penetration technique causes a reduction in the bond between the bars and the concrete as we move from bottom to top due to the disturbance occurring from repetitive penetrations. To address this issue, a new method was developed by [42] in which bars are simultaneously coated with a cementitious material that will be dragged down while the bar is penetrating the layers to fill up the created voids. Others tested the use of small nails [56], staples [57], or fibers [58] for more flexible designs; nevertheless, these methods are not effective for more than five printed layers as they limit both strength and ductility [56–59]. Developing "in-process" reinforcing techniques that enable both parallel and interlayer reinforcement is essential, and more research is required for large-scale applications.

### *3.3. 3D Printing Using Concrete Extrusion*

In the last decade, Professor Khoshnevis from the University of Southern California developed a new additive manufacturing process called Contour Crafting (CC) [59]. Contour crafting is a computer-aided method by which pre-mix cementitious materials are deposited in a pre-designated position to form layers that solidify after being extruded from a nozzle attached to an arm [15,60]. The extrusion method in 3DCP is similar to that in contour crafting, except that 3DCP allows 3-dimensional freedom and greater control of the product's internal and external geometry due to the relatively smaller resolution of disposition [16]. For a successful extrusion-based 3D printer, several parameters and conditions have to be satisfied, including the rheological properties of the concrete [36,53,61,62]. Generally, there are five issues to consider: workability, deformation, hardened properties, conformity to the designed geometry, and geometrical freedom in design [61]. Pumpability, which refers to the ease at which the fresh concrete moves from the pump to the extrusion nozzle [38], is one of those critical parameters. While pumping, blockages can occur in the hose due to particle segregation caused by insufficient mixing prior to pumping or due to the mix design itself. This makes the process particularly sensitive to blockages and pauses in the system. Rheology also highly affects the extrusion of 3DCP as, for example, materials with higher yield stress and higher viscosity are relatively harder to extrude [61,63,64]. Extrudability describes the process of extruding the fresh concrete mix through the nozzle with, ideally, no cross-sectional deformation and without a noticeable tearing of the printed filaments. According to Buswell et al. [61], there are no adequate tests to assess extrudability as it is currently evaluated by visual inspection. However, Rajeev et al. [64] suggest that numerical simulation tools may be valuable in evaluating the extrudability criteria of 3DCP and in understanding the flow behavior of concrete. The Discrete Element Method (DEM) is one of the currently proposed simulation models that showed good results when compared to the experimental pressure values, yet the model requires more improvements [64]. The 3D concrete extrusion also depends on the continuous deposition of material to ensure a proper bond between layers and an overall homogenous component [61].

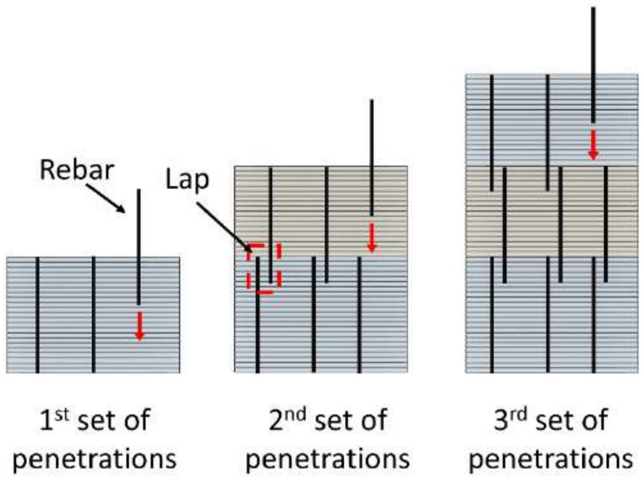


**Figure 5.** Illustration of the steps for the Bar Penetration Technique [55].

Once the material component is satisfied, the extruder assembly and the positioning system became crucial [61]. To illustrate, the extruding system is required to be accurate in depositing the precise quantities of the extruded materials over a pre-determined path [61], along with an accurate positioning system [61,62]. Moreover, the experimental results in [19,53,61,65,66] showed that the length of the extrusion path, the speed at which the nozzle deposits the material, and the shape and size of the extrusion nozzle affect the final 3D concrete-printed product [61]. Elistratkin et al. [65] studied the influence of equipment operation parameters on 3D printing. The authors found that the extrusion process was affected by several factors such as the speed of the nozzle, and the speed of the screw rotation, which resulted in a nonlinear printing process. To elaborate, the investigation showed that a change in the speed of the nozzle can lead to degradation, stretching, and an increase in the yield of the mixture [65]. Due to the inherent thixotropy of concrete, changing the speed of the screw can also affect the viscosity and the dynamics of the mixture, especially when the speed is reduced when printing corners or sharp edges.

Furthermore, 3DCP by extrusion inherently exposes a greater surface area of the concrete, and this, along with the lower w/c ratios commonly adopted, this translates to a higher potential for cracking from dry and autogenous shrinkage [61]. Internal curing, shrinkage-reducing admixtures, and moist curing are different approaches that can be used for this problem. Buswell et al. [61] also showed through Scanning Electron Microscopy (SEM) that the interlayer adhesion may also be weakly bonded due to shrinkage or carbonation. The hydrostatic pressure increases as the build gains height which makes the bottom layers compress under the self-weight of the upper layers. This in turn increases the distance between the nozzle and the underlying layer causing a change in the shape of the filament and possibly affecting layer adhesion or even causing buckling and collapse of the build. Hence, it is desirable to maintain a constant layer height throughout the print [60–62].

### *3.4. 3D Printing Using Foam Extrusion*

Benoit Furet et al. [67] investigated 3D printing polymer foam filled with concrete. The Batiprint3D™ method in this study prototyped a complex wall of two leaves of polyurethane (PU) foam filled with self-compacting concrete in the middle. This technique allowed the inclusion of steel reinforcement in order to comply with the strength capacity required by the used standard. Furthermore, the exterior side of the foam was coated with mortar to be protected from the weather while internally, the foam was covered by plasterboard which complies with all regulations of fire resistance in buildings. The technique can be used to print a PU foam wall with an average width of 80–100 mm with layer heights of about 35 mm and the parameters that need to be adjusted for the print are the flow rates of the isocyanate and polyol components of the PU as well as the speed of the nozzle and its distance from the underlying layer. On the other hand, the self-compacting concrete used in this study allowed it to flow easily in the foam walls without the need for vibration and consisted mainly of cement CEM III 42.5, limestone filler, sand (0–4 mm), gravel (4–10 mm), water, and a set accelerator. For a real-scale demonstration, Yhnova™, which is the structure shown in Figure 6, was evaluated by placing the robot system at the site on a pre-constructed concrete slab [67]. The robot then printed the PU double-skin foam incrementally in 40–110 cm sections such that the concrete can be easily placed. Once the printing and concreting process was done, the exterior and interior walls of the house were subjected to the application of coating and plastering, respectively; followed by the wood frame, roof, doors, windows, and MEP installation. The authors concluded that the Batiprint3D™ construction technique enabled greater freedom of shapes that allowed large, curved geometry and increased the thermal resistance performance by 30–40% compared to the best standards used for conventional construction, hence reducing the negative impact on the environment [67].

**Figure 6.** YhnovaTM: A real-scale demonstrator of 3D printing with BatiprintTM [67].

Yu Zhang et al. [4] conducted a study about the rheological and hardened properties of high-thixotropy 3D printing concrete. The rheology was quantitatively evaluated using a drop table as a pragmatic tool to measure workability over time as well as a concrete rheometer for more accurate measurements. On the other hand, the hardened properties were evaluated through (100 × 100 × 100 mm) cubes for compressive strength, (100 × 100 × 400 mm) beams for flexure and drying shrinkage, and (100 × 100 × 300 mm) specimens for axial compression, all of which were cut from (500 × 500 × 110 mm) printed blocks. After 28 days of curing, the compressive and flexural tests were conducted in three different loading directions T1, T2, and T3, as shown in Figure 7. The high-thixotropy concrete itself had a sand-to-cement ratio (S/C) ranging from 0.6 to 1.5 (0.6, 0.8, 1.0, 1.2 and 1.5). The thixotropy composition (in the percentage of cement mass) was 2% nano-clay and 2% silica fume (SF). The polycarboxylate-based high-range water reducer (HRWR) was 0.26% and the water-to-cement ratio (w/c) was 0.35%. The thickening agent was 0.0125% and the fine aggregate's (river sand) properties were 2.84 fineness modulus and 1 mm maximum particle size.

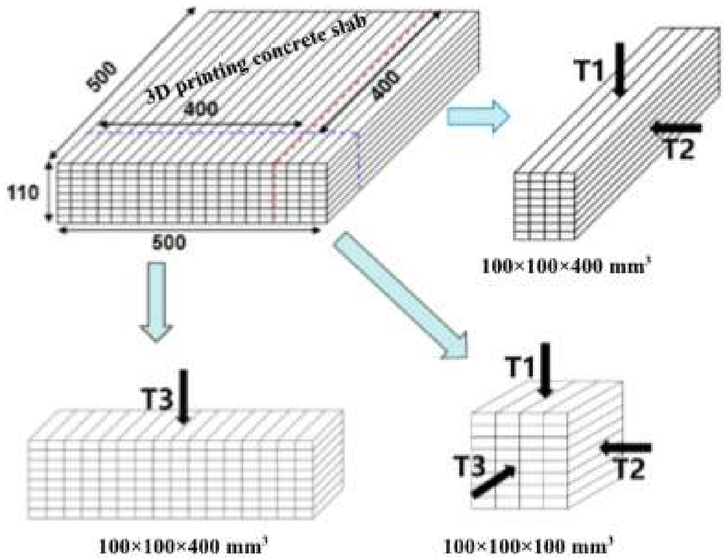


**Figure 7.** Specimens extracted from (500 × 500 × 110 mm) block and loading directions for compression and flexural strength tests [4].

The authors studied five mixes in this study and highlighted that the average spread diameter for the drop table was between 192.5 and 294 mm. It was also observed that as the open time increased, the spread diameter decreased. Furthermore, as the sand-to-cement ratio (S/C) increased, the initial viscosity and initial yield stress increased, while the initial thixotropy decreased. This may be the result of a decrease in nucleation sites in the aqueous suspension. Exceeding the 1.5 S/C ratio caused a reduction in flowability which, consequently, prevented the extrusion of concrete from the nozzle. On the other hand, the mix that had a 0.8 S/C ratio experienced deformation. Therefore, the authors identified an S/C ratio between 1.0 and 1.2 to be optimal in terms of pumpability, extrudability, open time, and the capacity for continuous printing [4]. In terms of compressive and flexural strength, values were more than 44.0 MPa and 8.5 MPa, respectively. The obtained test results varied with the loading direction and the sand-to-cement ratio (S/C). As the sand-to-cement ratio (S/C) increased, the compressive strength increased for all the loading directions whereas the flexural strength decreased. The increase in the (S/C) caused the fresh concrete to be stiff and difficult to print properly. Furthermore, a decreasing trend in terms of compressive and flexural strength was noticed from T1 to T3. The average axial compressive strength, elastic modulus, and Poisson's ratio of the 100 × 100 × 300 $mm^3$ cubes were similar to regular concrete at 35.12 MPa, 36.6 GPa, and 0.28, respectively. Finally, the increase in the sand-to-cement ratio was insignificant in lowering the drying shrinkage, especially before 56 days. The authors also concluded by reiterating their optimism toward 3D concrete printing as a future construction method.

### 3.5. Early-Age Performance of 3D Printed Concrete

Biranchi Panda et al. [21] investigated the early-age mechanical properties of 3D printing concrete and its effect on buildability. The study focused on the use of a high volume of fly ash along with nano-clay particles in a formulation that avoids the use of accelerators. The control 3D printing mix (C-mix) was composed of 60% fly ash, 38% OPC, and 2% silica fume (by mass), and in order to gain early strength, 3% Na–sulphate (wt. of binder) was added to activate the high volume of fly ash. To measure the early-age strength of the mortar, the uniaxial compression test was used to evaluate samples after 5, 30, 60, 120, and 150 min from the time they were mixed with water. The test was applied on (70 × 140 mm) cylindrical samples, chosen such that the effects of particle size were minimized, and a diagonal shear failure was allowed. The deformation of the samples (both lateral and vertical) was measured using 3D optical metrology. The rheology of the samples was also tested after different resting times for up to 150 min, by applying a constant shear rate and observing the time-dependent behavior. After conducting the tests, multiple conclusions were drawn. First, in the uniaxial compression test, the younger cylinders ($t$ = 5, 30, and 60 min) failed by the barreling effect, whereas the older cylinders ($t$ = 120 and 150 min) showed a distinct failure plane. The green strength (unconfined compressive strength), which is the maximum stress after area correction, was hence shown to increase with time. Similarly, the yield stress obtained from rheology testing was also shown to increase with time. The mechanism for this strength gain at the early stage (dormant period) in pozzolanic materials is mainly flocculation and C-S-H bridging [63]. This is followed by rapid hydration after the dormant period which characterizes an exponential increase in static yield stresses. Second, the incorporation of nano-clay increased the green strength which consequently increased the buildability of the printable mortar. This is still limited however by the rate of printing and if the weight of the subsequent layers exceeds the green strength, then plastic failure will take place at the bottom layers and the build will collapse. Adding admixture [68] to the mix can further increase the early-age strength such that the load-bearing capacity of the layers underneath will increase and enable it to withstand the weight of the freshly deposited layers without deforming. Finally, the buildability of any printed structure does not depend solely on the strength of the fresh mortar but also on the structural stability.

## 4. Buildability Measurement and Development

While extrudability refers to the ability to extrude materials easily without altering their original shape, buildability can be defined as the ability to produce layers with adequate strength up to the desired level without signs of excessive deformation or collapse, which is achieved by the high yield strength of fresh materials. This means that the printed layers should be strong enough to overcome the overburden pressure exerted by the subsequent layers [69–71]. Since buildability is related to the height of the printed structure, it can be visually evaluated by printing multiple layers [21,69,72]. However, the inadequate buildability of the printed layers may be attributed to various factors such as the material properties and the geometry of the printed elements. Therefore, for more accurate predictions, adequate models and methods must be implemented. Several studies were conducted to analyze and predict the buildability of printed layers using rheology-based models and mechanical property-based models [63,73–76]. Others [77] combined a modified green compression test (GCT) with material failure models to develop a time-based model for 3D-printed cementitious materials. The model was based on different failure modes at different times because buildability is a function of material properties, which is time-dependent. The models showed an adequate prediction of failure heights of a wall and a hollow cylinder specimen. The authors in [78] investigated the use of several indirect methods used for assessing the buildability of 3DCP including rotational velocity (CRV), unconfined uniaxial compression test (UUCT), constant shear rate (CSR) test, confined uniaxial compression test (CUCT), and fast penetration test. The experimental investigation conducted on extruded samples showed that the material failure predicted by all methods was not consistently accurate, although all methods showed a strong linear correlation. The results also showed that the CRV test adequately predicted the failure only when a geometry factor was applied; otherwise, it underestimated the actual capacity of the 3D-printed samples. The results of the CUCT indicated that the obtained compressive strength was higher than that obtained using UUCT [78]. Both [78] and [79] suggested that the values of strength obtained between the elastic limit and plastic collapse can be used to develop a precise buildability prediction of 3D-printed mortar and concrete.

Bos et al. [80] developed a discrete lattice model to assess the buildability performance of 3D-printed concrete. The model incorporated various components such as printing velocity, time-dependent stiffness and strength, non-uniform gravitational load, and localized damage. The lattice model was used to predict the failure of a square and a cylinder structure and the results were compared to those obtained experimentally. A 10% relative difference and 41% overprediction were observed for the square structure and cylinder structure, respectively. Chang et al. [81] studied the use of rotational rheometry, unconfined uniaxial compression tests, and direct shear tests to evaluate different 3D printable cementitious mortars. The study concluded that determining the friction angles of specimens is critical in predicting buildability. This is because the test showed that a correlation is only applicable by assuming significant friction angles which are related to Mohr–Coulomb failure behavior. Hence, the authors suggest combining rheometry–shear and uniaxial compression test results could be a valid approach, although extensive research is needed. Another study performed by Muthukrishnan et al. [82] explored technologies for developing buildability in 3DCP. The authors tested enhancing the printed concrete buildability by adding additives during the initial mixing, although it affects the pumpability parameter. They have also tested adding some set-on-demand interventions at the print head. This was performed by mixing heating, accelerators, ultrasonication, or magnetorheological control at the print head. The previous process increased the yield strength of the printed concrete immediately after extrusion and thus promoted buildability without affecting pumpability [82].

In addition, Qiang Yuan et al. [15] provided a feasible method for measuring the buildability of fresh 3D printing mortar. In this study, the development of specimen deformation was monitored by a designed deformation monitoring device at different loading intervals. Penetration resistance and a calorimetric test were also utilized to describe the structural build-up in the mortar. The material used in preparing the printable mortars were Portland cement (PC), polycarboxylate high-range water reducer (HRWR), attapulgite (AG; used to enhance the structural build-up), and sodium gluconate (SG). The mortar specimens were subjected to flowability, rheological, deformation tests, penetration resistance measurement, and calorimetric tests. After performing the tests, numerous conclusions were drawn. First, both AG and SAC increased the dynamic yield stress and plastic viscosity of the mortars, although SAC did so to a lower extent. These parameters helped enhance the extrusion performance of the mortar and reduce the chances of early-age cracks. Second, the fast-hydrating SAC significantly improved the structural build-up and the penetration resistance while the combination of SAC and attapulgite caused a notable increase in the growth rate of the static yield stress [83]. Third, as the interval time increased, the deformation values gradually decreased. Furthermore, the addition of attapulgite and SAC decreased the deformation significantly [83]. Attapulgite addition improved the thixotropic performance and shape stability. In this study, twenty layers were printed in order to evaluate the buildability by determining the maximum deformation. All the mix designs experienced large deformations despite no collapse taking place even at a low rate of yield stress growth. To reduce these deformations, either the layer cycle time should be reduced, the layer thickness should be reduced, or the rate of yield stress growth of the mortar should be increased. It was concluded that the combination of SAC and AG was the most effective for increasing the structural build-up rate [83]. The growth of penetration resistance was also found to be directly proportional to the growth of static yield strength making the penetration resistance an effective method of measuring the structural build-up of 3DCP mortars.

Yu Zhang et al. [30] studied the fresh properties of a novel 3D printing concrete mortar such as its buildability, rheology, workability, green strength, open time, and heat of hydration on different mixtures. Some mixtures incorporated nano-clay (NC), while others incorporated silica fume (SF), as a partial cement replacement at a content of 2%. A high-range water reducer (HRWR) was added to improve the workability of the mixtures due to the high demand for water caused by the additive materials. Where a thickening agent (TA) was used, the material exhibited dough-like rheological properties. To maintain a sufficient open time, a retarder agent (RA) was added to verify the thixotropic property of the nano-clay. Since there is no recognized standard for evaluating the buildability of concrete, the height of the layers built and visual deformation or collapse were used to estimate the fresh concrete's buildability. In addition, for more accurate prediction, the green strength test was used to assess the buildability of freshly printed concrete. Compared to the control mixture, the silica fume mix, nano-clay mix, nano-clay, and RA mix had higher build-ups. The incorporation of both silica fume and nano-clay resulted in the highest build-up; therefore, it is the optimum mixture additives in terms of buildability [30].

## 5. Large-Scale 3D-Printed Structures

According to Puzatova et al. [84] and Wangler et al. [85], the main challenge of implementing automation in real-life applications is the automatic tools. This is because large-scale construction projects require extremely large components that require customized tools such as robotic arms. The authors in [86–92] affirmed that the layer-by-layer extrusion technique is the most widely used technology in the construction industry. Wang et al. [92] concluded that this technology is suitable for large-scale construction projects and can be functional for the most used materials in construction, which are concrete and steel. The authors in [93–96] suggest that these two materials can be combined to construct reinforced concrete 3D-printed structures. Puzatova et al. [84] evaluated the current additive manufacturing printers including robotic arm printers, portal-type printers, and gantry 3D printers. The authors noted that the gantry 3D printers are the most suitable for large-scale mass construction. This is attributed to their configuration that allows the construction of buildings without any size restrictions. However, all printers were found to be inapplicable for printing concrete that contains coarse aggregates. Since the incorporation of coarse aggregates is desired for optimum economics and performance, it is necessary to optimize the 3D printing technology for printing with mix designs containing large aggregates.

Gosselin et al. [97] conducted research about the potential and buildability of large-scale 3D printing of multifunctional structural elements using ultra-high-performance concrete. The research focused on acquiring the rheological and setting characteristics of the material that allows for an optimum layer length and path cycle time. Since the paths are essentially three-dimensional, the tangential continuity method (TCM) was adopted due to its suitability for large-scale AM. The advantage of this method is that it prevents geometrical gaps between two layers. The developed printable mortar consists of Portland cement (30–40%), crystalline silica (40–50%), silica fume (10%), and limestone filler (10%). The prepared mortar was armed with the appropriate rheological properties for pumping, early-age mechanical strength for structural build-up, and workability for the acceleration of the printing process. Two structural wall elements were demonstrated in this study as examples and proofs of concept. First, a multifunctional wall element was designed for the rehabilitation of the damaged structure. The designed structural element would act as an external supporting wall. The geometry of the structure was optimized to reduce the amount of heat flowing through the whole structural element by reducing the contact area between the two sides of the wall without sacrificing its structural performance. Second, an acoustic dampening wall element was designed to perform structurally and acoustically. The varying geometry of the wall tubes acts to dampen the acoustic waves passing through them and provides a level of soundproofing to the wall. Besides the wall geometry, the soundproofing will also depend on the properties of the material. Figure 8 shows both 3D-printed structural walls [97].

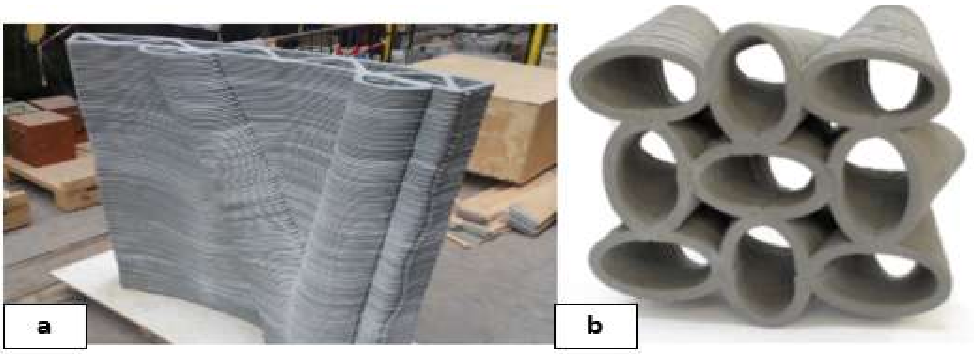


**Figure 8.** Structural wall elements. (**a**) Multifunctional wall element, (**b**) acoustic-dampening wall element [97].

The two examples illustrate the feasibility and buildability of AM for the applications of architecture and construction. However, there are also numerous limitations in concrete-based AM. For instance, the need for support in the production of large-scale 3D printed structures. Using a generic 6-axis robotic arm can enable complex geometries compared to an overhead crane [98]. In conclusion, despite the importance of reducing cost and time of construction, the main interest of AM is adding value to the structural element performance through the clever use of geometry. Xu Zhang et al. [99] studied large-scale 3D printing by a team of mobile robots. In this study, to overcome the limitation of the size of the printed structure due to the reach of the robotic arm, a team of multiple mobile robots was utilized. Each of the mobile robots was made up of a holonomic mobile platform, a mini 6-axis robotic arm, a stereo camera, and a pump. Two concrete mix designs were prepared to meet rheological requirements (viscosity and yield stress). The first mix design was ordinary concrete that consisted of OPC, fly ash, silica fume, river sand, and water, whereas the second mix design was a fiber-reinforced concrete that consisted of OPC, fiber, sand, water, fly ash, silica fume, and superplasticizer. The two mixed designs were used by robotic printers as shown in Figure 9 [99].

**Figure 9.** Concurrent printing of a large structure by two mobile robot printers [99].

The locations of the robots were first optimized and then followed by the programming of the trajectories using OpenRAVE such that the robots can ensure the material is delivered accurately and without any collisions. Then, once the print process is completed, the robot printers return to their home station. In this study, the two mobile robots concurrently printed a structure that was 1.86 × 0.46 × 0.13 m which is beyond the reach of either individual robot. Compared to existing 3DCP methods, the study suggested that this proposed system has several advantages such as enhanced scalability, greater time efficiencies, and a more practical on-site approach due to the increased mobility of the system. However, the motion of the robots should be carefully planned in order to avoid collisions and optimize material delivery. Additionally, to make sure that the parts printed by the robots are perfectly aligned, the precision of the robot localization must be high. The coordination of the robots' mixing and pumping system is also crucial such that the material delivery is continuous and synchronized.

## 6. Integration of BIM into 3D Construction

Building Information Modelling (BIM) is a digital version of a facility such that its physical and functional properties are stored in an easy-to-access, visualize, share, and understand format. It greatly helps in forming reliable and well-informed decisions regarding the entire life cycle of the facility from conception to demolition [100]. Nowadays, BIM software platforms are used for designing and carrying out many construction projects worldwide. BIM offers a variety of benefits such as automated checking of compliance with different building codes, automated cost estimation [101], scheduling [102], clash detection between different disciplines [103], and energy analysis and simulations [104]. Furthermore, it improves energy efficiency, reinforces sustainability, reduces life cycle cost, and generates less design coordination errors. BIM is also used for maintenance, cost analysis, and operation throughout the building life cycle.

Recently, the focus on integrating BIM with additive manufacturing in construction has increased. There are numerous algorithms developed for 3D printing in construction using BIM. Omid Davtalab et al. [104] proposed a perspective of utilizing BIM in AM in construction projects as shown in Figure 10. Printing 3D structure projects start with 3D modeling—a function of the architectural and structural analysis and design—using CAD software. After that, the 3D model is sent to software called POCSAC in order to extract some data and send them to different units. The 3D model is sliced into layers of a specific thickness, and then POCSAC carries out the toolpath optimization of the sliced 2D layers. Then, numerical control (NC) commands (or G-code) are sent to the robot to control its movement and material mix proportioning commands are sent to the automated material preparation unit to prepare the mix.

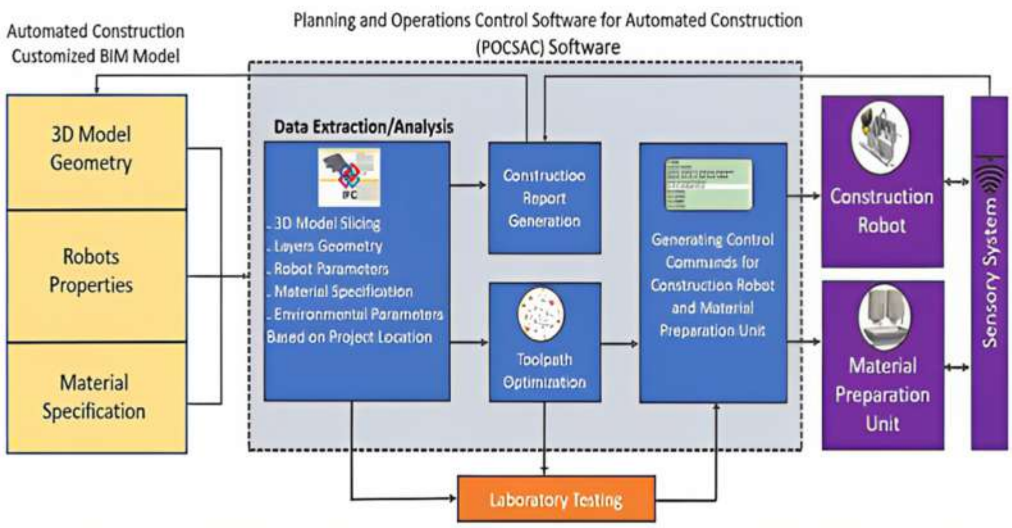


**Figure 10.** BIM-integrated 3D concrete printing framework [104].

Prior to 3D printing of the structure, the designed concrete mixture is laboratory tested. POCSAC reports three main groups of data for mixture design stage. The initial BIM model contains the concrete's mechanical and durability properties along with the environmental conditions of the project site but this information will not be extracted by the software. On the other hand, during the toolpath optimization, the interlayer time gap is calculated and then reported by POCSAC. During the construction process, POCSAC documents a lot of detailed significant environmental and process data by a sensory system. These data are a future reference. For instance, the formation of any cold joints due to a delay in layer deposition can be studied and referenced from POCSAC reports even years after construction. Another BIM-based automated construction system was developed by Ding et al. [105]. The basic procedure of AM technology, as shown in Figure 11, decomposes a three-dimensional model into lamellar files of a certain thickness in a certain direction of the model (usually Z direction), transforms the three-dimensional model into several approximately two-dimensional profiles, then amends the lamellar files and generates NC programs, and finally imports the NC programs to the Computer Numerical Control (CNC) system so that the CNC system controls the material regularly and accurately, stacking up to achieve automatic construction.

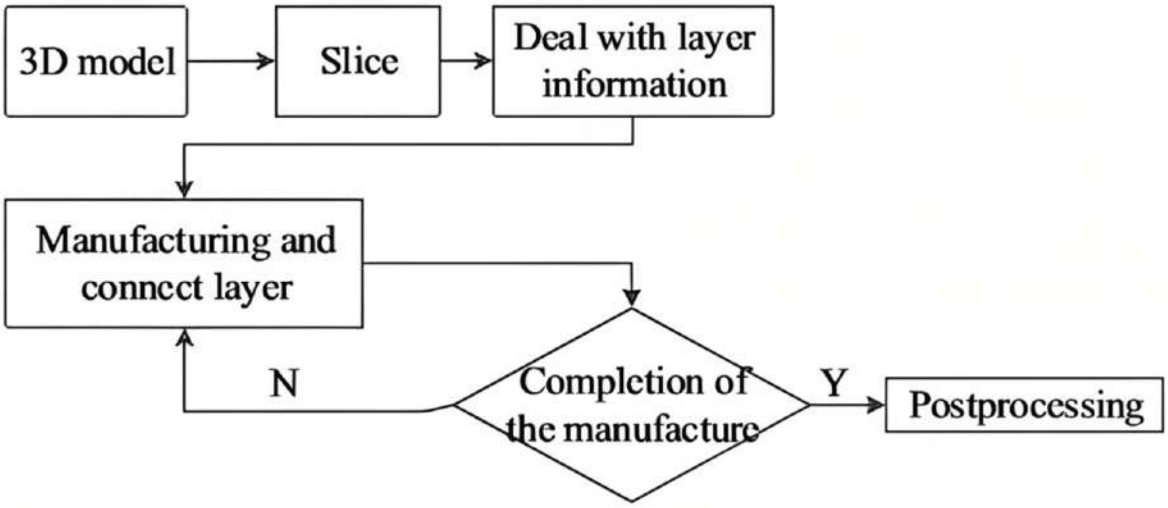


**Figure 11.** The basic procedure of AM technology [105].

The proposed system consists of two main core parts: the NC program-generating system and NC program execution setup. The first main core part converts the BIM model layer data which are sliced by manual operation to specific CNC codes. These codes drive the second main core part to automatically 3D print the building components according to the designed BIM model. Figure 12 demonstrates the framework of the proposed BIM-based automated construction system. Mehmet Sakin and Yusuf Kiroglu [100] presented a framework for utilizing BIM for 3D printing sustainable houses. The process starts with designing a 3D model. If the designed 3D model is not in an STL file format, then it should be converted to an STL file. The model must be sliced and converted to layers that are readable by the 3D printer. After that, the 3D printer processes the materials and then layers the material according to the design. Figure 13 illustrates the BIM-based 3D printing of a sustainable house system. Building Information Modeling (BIM) adds great value to conventional and automated construction in terms of improving the efficiency throughout the life cycle of the structure. However, there has not been any comprehensive investigation into implementing BIM in automated construction [105]. Therefore, further investigation is required to develop the optimal BIM-based 3D printing system that addresses all the significant aspects of AM in construction.

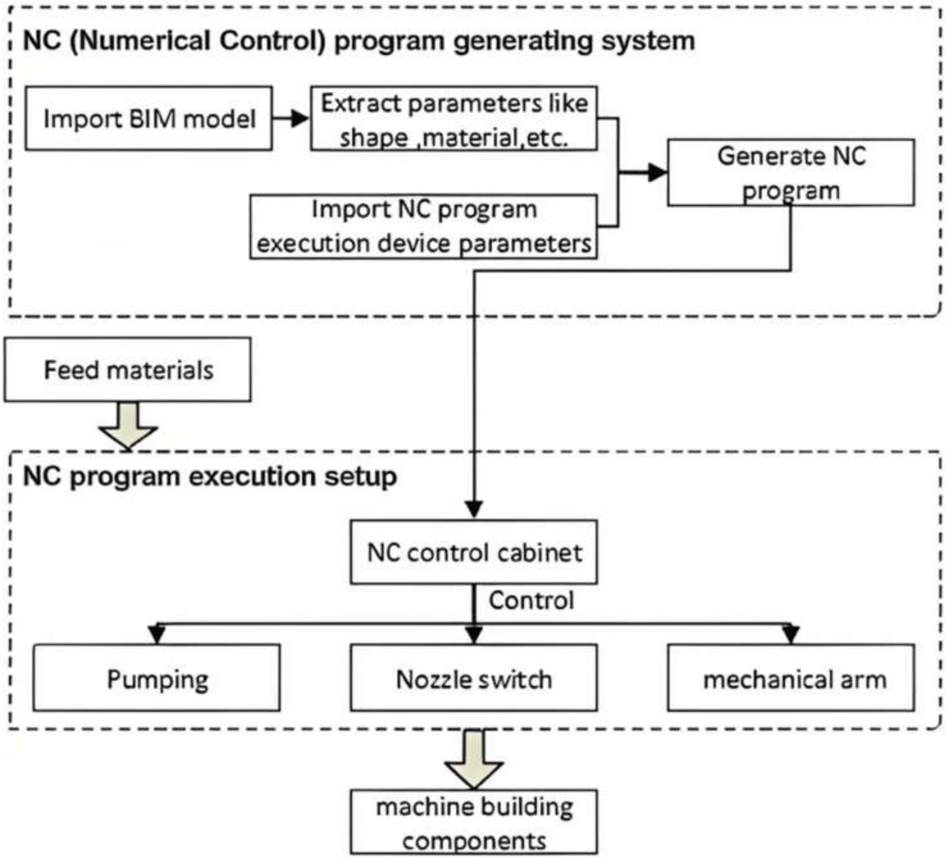


**Figure 12.** BIM-based automated construction system [105].


**Figure 13.** BIM-based 3D printing of sustainable houses system [100].

## 7. Challenges Associated with 3DCP

In terms of challenges, since 3D printing technology is still in the development phase, there are multiple challenges encountered by the implementors of this technology around the world. Some of these challenges include:

- Developing a concrete mix design with thixotropic rheological behavior that is unsegregable, pumpable, extrudable, buildable, and printable in an exposed environment with various weather conditions.
- Developing a concrete mix design with a small coarse aggregate size that has sufficient mechanical properties to avoid clogs inside the 3D printing machine.
- Developing a concrete mix design with proper tensile properties that allows eliminating or diminishing steel reinforcement.
- Developing a concrete mix design entirely from the materials available locally without the need of acquiring overseas products.
- There are no codes or standards to follow for AM in the construction of buildings.
- Constructing a multi-story building entirely by the 3D printer without using conventional construction methods or other structural systems is still in development.
- 3D printers require skilled operators, careful handling, and proper cleaning.
- There are still no standardized tests to evaluate concrete's buildability and interlayer bonding.
- Applying the building regulations issued by governmental entities such as green buildings regulations for thermal insulations issued by the Dubai Municipality.

- Precise localization of the 3D printers under different terrain conditions.

## 8. Summary and Conclusion

This review article explained the general 3D concrete printing process performed by different printing systems that are available in the market. The paper also reviewed the materials that could enhance the performance of 3D concrete structures as suggested by research. An overview of 3D concrete-printed reinforcement, extrusion methods, and early-age performance of 3D-printed concrete was performed. This could help in setting up a laboratory to assess and evaluate the fresh properties of the 3D concrete printing mix designs to achieve printability and buildability requirements. The paper also explored existing buildability measurement techniques and the potential of implementing BIM into 3D construction. The main points of this review article are:

- ❖ The 3D concrete mix design undergoes various stages of mixing, pumping, and extruding before it produces a 3D structure. However, in order for the 3D concrete mix to be successfully printed, it needs to have certain printability requirements such as pumpability, extrudability, buildability, interlayer bonding, open time, and segregation prevention. All these printability requirements are dependent on the workability (flowability) of the mix design. The concrete should exhibit thixotropic rheological behavior in which the viscosity is reduced and regained through the printing stages in order to have a flowability that allows printability to be achieved. It is recommended to incorporate calcined clay, nano-clay, fibers or ECC, and pozzolanic materials into the mix design to improve the concrete's thixotropic rheological properties, mechanical properties, durability, and sustainability.
- ❖ The implementation of AM in construction offers a wide range of advantages including reductions in cost, labor, formwork, construction time, waste, and emissions. It allows flexibility in changing the design of the structure, printing complex and customized shapes for aesthetics, and utilizing the geometry of the printed structure to improve the performance in terms of thermal insulating and soundproofing with less amount of material required. AM allows improvement of efficiency and safety at the construction site and support of damaged structures by allowing structural rehabilitation by using 3D-printed elements.
- ❖ There are different systems of 3D printing such as gantry-based systems, cable-suspended platforms, swarm approaches, and mobile robotic arms. The selection of any of those systems is dependent on different factors: the 3D structure, budget, and project site, among other factors.
- ❖ In comparison to conventional construction, additive construction offers a reduction in cost, labor, and time, and an elimination of formwork and reinforcement. It offers the flexibility of changing the design and combining 3D printing with other construction systems. To date, additive construction faces a lot of obstacles that slow down its full utilization. For instance, developing a 3D concrete mix design with thixotropic rheological behavior that is pumpable, extrudable, and printable in an exposed environment. It should also have sufficient mechanical properties regardless of its small coarse aggregate size and has proper tensile properties to reduce or eliminate steel reinforcement.
- ❖ There is a need for a fully operational 3D laboratory to assess the quality of 3D mix designs in terms of hardened and rheological performance. The focus of this research was directed at fresh properties due to the fact that fresh properties play a larger role in achieving printability requirements. There are six parameters that were suggested to be tested in the 3D laboratory which are workability (flowability), rheological properties (yield strength, plastic viscosity, thixotropy), green strength, buildability, penetration resistance, and hydration heat. Some of these tests lack standardization and can be used for research purposes due to their value in indicating the quality of the 3D mix design. Other parameters still lack testing methods such as interlayer

bonding. It is suggested that the 3D laboratory include a temperature controller to mimic the printing process in an exposed environment.

- ❖ Additive construction can be integrated with Building Information Modeling (BIM) to achieve higher performance throughout the life cycle of the 3D structure from the construction stage to demolition in terms of design, cost, scheduling, energy, and maintenance. In this research, three different algorithms developed for integrating BIM with 3D concrete printing were discussed. The three BIM-integrated additive construction frameworks share a lot of similarities and few differences because their development was for slightly different purposes. However, this integration has not been investigated in depth because it is still in its early stages. Therefore, BIM-integrated additive construction systems still need to be studied in depth in order to develop a system that covers all the significant aspects that can be used as a reference for any 3D construction project.

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## Abbreviations

| | |
|---|---|
| 3DCP | 3D Concrete Printing |
| AG | Attapulgite |
| AM | Additive Manufacturing |
| BIM | Building Information Modelling |
| CAD | Computer-Aided Design |
| CC | Contour Crafting |
| CNC | Computer Numerical Control |
| CSR | Constant Shear Rate |
| CUCT | Confined Uniaxial Compression Test |
| DEM | Discrete Element Method |
| GCT | Green Compression Test |
| HRWR | High-Range Water Reducer |
| MCF | Mineral-Impregnated Carbon Fiber |
| NC | Nano-Clay |
| NC | Numerical Control |
| PC | Portland Cement |
| PU | Polyurethane |
| RA | Retarder Agent |
| RHA | Rice Husk Ash |
| SCM | Supplementary Cementitious Materials |
| SEM | Scanning Electron Microscopy |
| SF | Silica Fume |
| SG | Sodium Gluconate |
| TA | Thickening Agent |
| TCM | Tangential Continuity Method |
| UUCR | Unconfined Uniaxial Compression Test |

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