EPiC Series in Built Environment
Volume 5, 2024, Pages 822–830
Proceedings of 60th Annual Associated Schools of Construction International Conference

A Review of Gypsum-Based Cementitious Materials in 3D Printing

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Three-dimensional printing (3DP), or additive manufacturing AM, creates a three-dimensional item from a digital 3D model. Although it is still in its preliminary stages of acceptance in the construction industry, this automated manufacturing method has gained substantial importance across industries, including the construction industry. 3D printing technology can improve building efficiency for irregular structures by introducing construction automation. This research aims to review the impact of gypsum on the mixture of cementitious material's printability, compressive strength, compressive strength, hydration, and rheological behavior. This study analyses the relationship between construction materials, like cement mortar and other cementitious materials, and their interesting environmental behaviors with gypsum powder for 3D printing in construction. In addition to reviewing various techniques that are used in the construction industry.

Key Words: 3D Printing, Additive Manufacturing, Additive Construction, Gypsum

Introduction

The construction industry has witnessed an increase in the implementation of 3D printing technology. The potential to improve on present building processes is substantial. One such approach presently being investigated in academia and construction practice is the additive manufacturing of concrete (Bos et al., 2016). Compared to traditional techniques, additive manufacturing provides greater precision and convenience by allowing the automated fabrication of construction structures. Additive manufacturing, commonly known as 3D printing, produces items layer by layer directly from a 3D model. In addition, it can develop synchronization between computer software and mechanical equipment, significantly reducing labor consumption and increasing production efficiency (Peng & Unluer, 2023). Using computer-aided design (CAD) software, 3D printing enables the production of complex structures and shapes. This technical development offers a revolutionary approach to building construction, enabling a faster, more efficient, and cost-effective construction procedure (Kantaros et al., 2023).
Additive manufacturing is utilized in constructing structures and is also known as additive construction. Additive construction also allows for highly complex designs, allowing designers and

architects to create freely without being restricted by certain constraints (Ali et al., 2021). This method of construction has been extensively introduced and discussed in several case studies for the full-scale production of homes and other buildings, and it offers benefits like the capacity to create any shape without molds, reducing material waste, construction timeline, project cost, and minimizing construction errors (Kontovourkis & Tryfonos, 2020).

Numerous studies have examined the application of 3D printing in the construction industry. These studies have examined the application of various materials in 3D printing, including clay, concrete, and gypsum-based cementitious materials. This study comprehensively reviews various techniques and materials used in 3D printing. More specifically, it focuses on the advantages and limitations of gypsum-based cementitious materials in 3D printing. The review also offers a detailed overview of the various categories of printers, including the materials used. It highlights the differences between a laboratory setting and the application of large-scale 3D printing in the construction industry.

Methodology

This study employs a systematic literature review, including an in-depth, critical investigation of published literature and books on 3D printing/additive manufacturing techniques and cementitious materials. The primary objective of this review was to thoroughly assess the latest advancements and concepts about Gypsum-based cementitious materials in the context of 3D printing, which involved examining the printing techniques, processes, material properties, and factors that affect the capacity to 3D print using Gypsum-based cementitious materials. A search method utilizing the "title-abstract-keyword" approach was applied to identify relevant literature-reviewed papers from Google Scholar and Science Direct. The articles were selected based on specific criteria for inclusion and exclusion. Nevertheless, following a comprehensive evaluation and cursory examination of gray literature, extended abstracts, and book chapters. Non-English language articles, and inaccessible publications, papers that were irrelevant or of low quality were eliminated. A total of 45 papers were selected, with 19 used for this research.

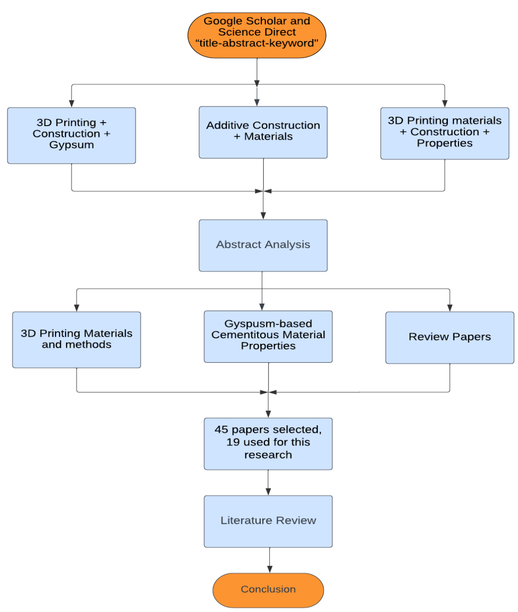

Figure 1. Data selection methodology

Literature Review

Overview of 3D printing materials and techniques used in construction.

3D Printing Materials

Concrete is the predominant construction material on a global scale. Concrete as a building material offers several benefits for constructing buildings and other structures. Firstly, the raw ingredients required for concrete production are inexpensive and easily accessible in almost all locations worldwide. Secondly, previous studies discovered that concrete is primarily used in construction because it possesses high compressive strength, long-term durability, fire resistance, and moldable in various shapes due to its fluid condition before hardening (Bos et al., 2016; Chen et al., 2017). Ali et al. (2022) found that there must be sufficient stiffness and adhesion for 3D concrete printing to be successful and fail-proof. The study stated that 3D printers utilize concrete materials as "ink" or "filament," allowing easy extrusion through the printer, and observed that the 3D printing system's performance relies on the mix ratio and the selection of materials.

The manufacture of Portland cement demands substantial consumption of natural resources, involves high energy consumption, and gives rise to considerable environmental pollution, notably through the release of substantial amounts of CO_2 due to the decarbonization of raw materials (He et al., 2023). 3D concrete printing can yield several advantages in mitigating the environmental consequences of concrete in construction. Adopting additive manufacturing of concrete together with structural optimization can result in a reduction of approximately 50% in environmental impact compared to traditional building methods (Chen et al., 2021). Ultimately, it is possible to incorporate sustainable cementitious materials in additive construction.

Sustainable cementitious materials can significantly impact the rheological behavior of 3D print mixes. Including cementitious materials in printed mixtures improves the thickness, cohesiveness, and flow consistency (Chan et al., 2022). 3D-printed cementitious materials, called printable mortars, comprise three components: binder, fine aggregate, and water. The binders used in printing are ordinary Portland cement, limestone powder, and calcined clay. Substituting a portion of ordinary Portland cement with limestone might accelerate the early-stage hydration, especially when the average particle size of the limestone is tiny. However, by replacing ordinary Portland cement with limestone alone at a rate of more than 10%, the performance and porosity of the cured cementitious material may suffer (Chan et al., 2020).

Gypsum-based Cementitious Materials

Using gypsum in additive manufacturing techniques opens a new avenue for high-value-added gypsum use (Huang et al., 2021). Gypsum was discovered as the most efficient type of sulfate to limit tricalcium aluminate (C_3A) hydration processes, resulting in enhanced workability of concrete material for a more extended period. Hydration of C_3A, the most reactive component of Portland cement, significantly affects the early strength and workability of concrete. Gypsum adds functionality to mortar or concrete by flexing the cement early in hydration. At the initial stage, when mixing cement with water, cement powder reacts with the C3A and hardens. The mixture of gypsum with cement and water forms an Ettringite. This Ettringite begins to form as very fine-grained crystals that create a covering on the surface of the C_3A particles, preventing quick hardening. Gypsum improves the workability of mortar or concrete by keeping the cement flexible at an early hydration stage, slowing down the setting time Bhanumathidas & Kalidas (2019). However, Gypsum is an essential ingredient in cement and a set retarder in ordinary Portland cement (Jia et al., 2021).

Printability. In their study, (Shakora et al., Jan 01, 2019) conducted a flexural strength test to assess the printability of gypsum-based cementitious materials. The results showed that gypsum plays a crucial role as a binder in 3D printing, enhancing the printability of gypsum-based cementitious materials compared to plain cement mortar. This substance's tiny particle size and binding qualities allow for creating accurate and complex layers during the printing process. Chen et al. (2022) mentioned that optimal printing characteristics, including seamless flow, layer binding, and overall print accuracy, may be achieved by controlling the gypsum content in the mix ratio.

Compressive Strength. Concrete and mortar compressive strength is a standard measure to evaluate their durability. In research conducted by Liu's team, the compressive strength of 3D-printed gypsum-based geopolymer concrete varied from 20 to 50 MPa, and the bending strength ranged from 7 to 20 MPa, depending on the gypsum type and curing circumstances Liu et al. (2023). An excessive quantity of gypsum can result in a reduction in strength due to the production of gypsum crystals, weakening the structure's integrity. Determining the ideal gypsum concentration is crucial to attaining the intended compressive strength in a gypsum-based cement mixture (Wolfs, 2015).

Hydration. Gypsum undergoes an exothermic hydration process in many phases, forming strength and setting qualities in the material. Gypsum undergoes hydration by dissolving its crystals in water, forming calcium and sulfate ions. Subsequently, calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$), also known as gypsum, is formed (Bhanumathidas & Kalidas, 2019).The distinctive characteristic of gypsum is its capacity to regulate the solidification time of cement-based mixes. It is a retarder, impeding the hydration process and inhibiting rapid solidification. Controlled hydration is essential in 3D printing, enabling adequate material extrusion and layer deposition time. Furthermore, formulations with a high gypsum concentration can demonstrate enhanced long-term strength due to slow and regulated hydration, resulting in a more compact and enduring structure as time progresses (Bobby & Singamneni, 2014).

Rheological Behavior. The hydration process impacts the rheological qualities of the cementitious mortar, which in turn impacts its flow characteristics and viscosity. The rheological characteristics of a cementitious mortar refer to its ability to flow. Effective management of hydration kinetics is crucial for preserving the stability of the mortar and avoiding problems like sedimentation or clogging throughout the printing process. Gypsum can add thixotropic properties to the mortar. Consequently, the viscosity of the mortar diminishes under the influence of shear tension, only to rebound once the shear stress is eliminated (Peng & Unluer, 2023).

Factors Affecting the 3D Printability of Gypsum-based Cementitious Materials

Gypsum offers a range of advantages as a 3D printed material, including lightweight, fire resistance, accessibility, recyclable qualities, and cost-effectiveness. However, using Gypsum-based cementitious materials in 3D printing presents many challenges and constraints. Although gypsum-based cementitious materials' fast-setting characteristic makes it excellent for 3D printing applications, it is restricted by their low mechanical properties, which may cause the structure to collapse during the ongoing printing process (Jia et al., 2021).

Peng and Unluer (2022) stated that the rheological characteristics of cementitious materials might be complicated, posing challenges in attaining the intended flowability and printability. The composition, particle size distribution, and water-to-binder ratio affect the material's flow properties. Attaining a smooth and consistent flow of material is essential for the effective distribution of layers and the overall strength and stability of the printed item. According to research by Chen et al., another obstacle that arises from the restricted printability of Gypsum-based material is the setting time. Gypsum has a very rapid setting time, leading to potential nozzle obstruction during printing (Chen et al., 2021)

Furthermore, the inadequate compressive strength of gypsum-based materials weakens the structural strength of the printed products. In addition, using cementitious materials in 3D printing is associated with some limitations due to sustainability and environmental implications. Studies reveal that cement manufacture is a significant source of carbon dioxide emissions. Therefore, using cementitious materials in 3D printing requires continuous measures to mitigate the environmental impact of their manufacturing and application. The hurdles and limits indicate the necessity for more study and advancement to overcome the technical and environmental limitations of mixing Gypsum and cementitious materials in 3D printing (Peng & Unluer, 2023).

3D Printing Methods

Traditional construction methods have several obstacles, including operating in harmful environments, a scarcity of experienced labor, safety concerns, material wastage, and difficulties in transportation management. Consequently, the ability to implement automated additive construction systems on-site will enable addressing these issues as quickly as possible, encouraging interest in these technologies (Ali et al., 2022). Puzatova and his team conducted a study comparing the traditional construction approach with the 3D printing method using a CONPrint3D printer. Comparative analysis between the 3DP approach and the traditional construction method revealed that using a printer to build a single floor of a structure is 25% more cost-effective. The printing process involves the participation of only two individuals: a machine operator who has received specialized training and a qualified professional worker. Hence, using 3D printing in construction enables the rapid construction of homes, especially in situations requiring immediate attention (Puzatova et al., 2022).

Currently, 3D printing in construction offers a wide range of applications. The primary techniques used in concrete 3D printing include D-shape, contour crafting, and extrusion-based concrete printing (Ali et al., 2022; Chen et al., 2021; Peng & Unluer, 2023; Puzatova et al., 2022; Raphael et al., 2023; Wolfs, 2015). Among these technologies, extrusion-based concrete printing is the most prevalent, with a rapidly growing number of research projects conducted globally (Chen et al., 2021; Raphael et al., 2023). However, compared to other methods, the drawback of the extrusion-based 3D printing method is restricted mobility and the necessity for assembly/disassembly at each building site (Peng & Unluer, 2023).

Direct Material Extrusion 3D Printing

The computer is set up with a design model that is prepared with 3D software such as Fusion 360 and Cura. The design model file is saved on the computer in an "STL" format as shown in Figure 2 (Shahzad et al., 2021). The direct material extrusion method is a specific 3D printing process characterized by its level of detail. The direct material extrusion 3D printing method is divided into four distinct phases: pumping, extrusion, building, and curing (Huang et al., 2021).

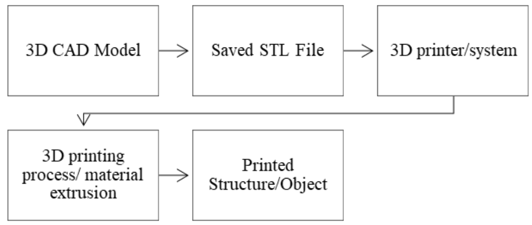

Figure 2. Typical 3D printing process (Shahzad et al., 2021).

Pumping Phase. Pumping gypsum-based cementitious material in a 3D printer tube requires a meticulous approach to guarantee uniform flow and precise placement of the material when printing. The mix is pumped into a tube attached to the bottom of a hand loader mounted to a table on another side of the set-up. Once the printer tube is mounted on the printer motor in the start position. The STL file is transferred to a 3D printer's interfacing software to initiate printing using the information of parameters saved in "STL" files .

Extrusion Phase. 3D printers are used to facilitate the extrusion of the material. During the pumping and extrusion phases, materials must possess high fluidity, low dynamic yield strength, and no setting to prevent blockage in the conveying pipe or extrusion head. The printing process necessitates workability, including the printed specimens' structural integrity, consistency, and three-dimensional accuracy (Peng & Unluer, 2023). The aggregate particle size is crucial since an enormous particle size might obstruct the nozzle. On the other hand, very tiny particle sizes might cause an increase in the hydration heat of the cement. As a result, choosing an adequate aggregate particle size is critical and depends on the size of the nozzle employed (Ali et al, 2022).

Building Phase. During printing, the materials are ejected through the nozzle of the 3D printer layer by layer to build a shape, forming layers that gradually form a structure. The buildability of the cementitious material refers to its capacity to support the weight of an extruded layer and subsequent layers without altering its shape. The more layers it can sustain without deformation, the more its buildability improves (Teixeira et al., 2023).

Curing Phase. Subsequently, the material is left to undergo a curing stage when it solidifies and gains strength. In the latter two phases, the substance would undergo solidification. Compared to the preceding and subsequent phases, the material must quickly transition from liquid to solid (Huang et al., 2021).

Gantry System 3D Printing

Gantry concrete 3D printing is an extrusion-based concrete printing technique with excellent accuracy and easy linear axis control. The benefit of gantry printers is the larger print area, which allows for constructing relatively small structures in general and using concrete with coarse aggregate (Puzatova et al., 2022). Most 3D printing systems used in educational institutions and the construction industry utilize both 3-axis- and 4-axis (small-scale) gantry-based systems and 6-axis robotic deposition configurations (large-scale).

This system has three main components: a printing setup, a control device, and a material transfer system. Chen et al. (2022) stated that for the 3 or 4-axis setup, the new mortar mixture is combined in several batches and then transported either manually or automatically through a connecting hose to

the feeder of the material conveying pump. This method is commonly used in small-scale applications, such as printing material fabrication and other experimental operations. Large-scale construction 3D printing, on the other hand, is a proficient construction method that can reduce the need for costly formwork when manufacturing a variety of distinctive curved and complex buildings (Shahzad et al., 2021). The gantry 3D printing technique is used in this extensive 3D printing constructing method as shown in Figure 3. A continuous system, such as an inline mixing machine, is required for a seamless system that effectively synchronizes with the pump while performing large-scale construction 3D printing (Chen et al., 2022). The mixture flows toward the head of the printer to the nozzle due to the pump's pressure, which comprises various components that allow the mix to be printed precisely at the configured position, speed, and angle.
The concrete material is extruded from the nozzle and deposited onto the print surface. The distance between the printer head and the print surface significantly affects the shape and characteristics of the printed structure (Bos et al., 2016). Wolfs (2015) also noted that the time needed to complete the printed structure depends on the specified layer size and configured printing speed. After being extruded from the nozzle, the material should soon achieve the required stiffness. Overall, the operation of 3 and 4-axis gantry-based deposition systems is likely to be less challenging compared to 6-axis robot arms.

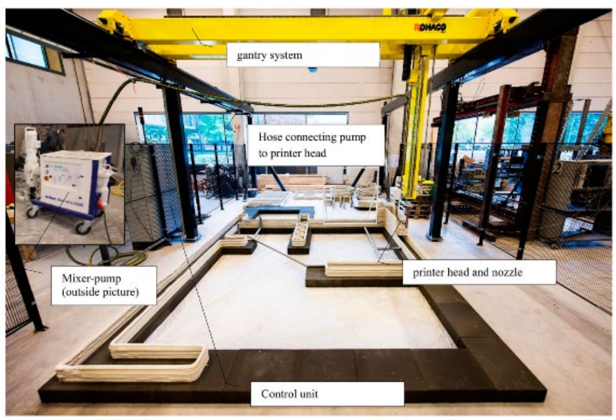

Figure 3. Gantry 3D Printing System (Bos et al., 2016)

Conclusion

Using 3D printing or Additive manufacturing techniques in construction offers numerous advantages. These include the automation of building processes, which leads to savings in time and materials, the ability to create complicated curved designs, and eliminating worker exposure to hazardous environments. Therefore, 3D printing possesses notable benefits and possibilities that can facilitate the advancement of the eco-friendly building construction industry. Extrusion techniques remain the predominant approach to 3D printing in the construction industry. Several printing factors, such as material flowability, extrusion speed, time intervals, nozzle distance, printing environmental conditions, and nozzle types, alter the interlayer bond strength of printed cementitious materials. Traditional construction engineering has several obstacles, including operating in adverse settings, a scarcity of experienced labor, safety concerns, material wastage, and transportation logistics. Consequently, having the ability to implement automated additive construction systems on-site will have a great impact on overcoming these issues. Gypsum provides a multitude of benefits as a 3D printing material, such as its lightweight nature, fire-resistant properties, accessibility, recyclability, and cost-effectiveness. Nevertheless, the utilization of gypsum-based cementitious materials in 3D printing comes with a host of challenges and limitations.

Limitation and Future Studies

Further research and development are required to address the technical and environmental challenges of combining Gypsum and cementitious materials in 3D printing for construction. These difficulties and restrictions highlight the need for additional study and progress. Many researchers advocate rheology and hydration control as effective for achieving predefined on-demand settings. Hence, adding retarders and accelerators in the material mix will control the setting time of Gypsum. Also, there are no standards for 3D printing yet; standards are essential requirements.

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