

Three-Dimensional Printing of Structural Members with Shotcrete Technique: Design, Construction, and Future Directions

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Abstract. This paper provides a comprehensive review of the current state of 3D printing technology in the construction industry, highlighting the potential applications, benefits, and future directions of this emerging field. The review indicates that 3D printing technology has the potential to revolutionize the construction industry by offering more efficient, precise, and sustainable methods of construction. The technology offers numerous advantages, including the ability to create complex geometries and custom components, improved precision and accuracy, reduction in waste materials, improved worker safety, and potential for use in remote or inaccessible locations. Furthermore, the advent of additive manufacturing, colloquially known as 3D printing, presents prospects for the advancement of novel material compositions, printing methodologies, and cybernetic systems that have the potential to optimize the efficiency and effectiveness of the construction domain. Future research should focus on developing larger printers with more efficient support structures, improving the accuracy and speed of printing, and exploring the potential of using new and innovative materials in the construction process. Additionally, the environmental impact of 3D printing technology should be further examined, particularly in terms of its potential for reducing waste and energy consumption in the construction industry. Overall, the potential utilizations and advantageous outcomes stemming from the implementation of 3D printing technology within the construction sector are momentous. Persistent exploration and innovation within this realm hold the capacity to engender noteworthy strides in construction technology and foster heightened sustainability within building methodologies.

1 Introduction

Three-dimensional printing (3DP) and shotcrete techniques are two innovative technologies that have recently emerged in the construction industry. 3DP is a process of creating 3D objects by layering materials according to digital models. It has been used in various industries, including architecture, product design, and aerospace, due to its ability to produce complex shapes and designs with high accuracy and precision, Shahrubudina et al. [1]. Shotcrete, also known as sprayed concrete, is a method of applying concrete through a hose and spraying it onto a surface. The concrete is applied in a wet or dry mix and is typically reinforced with steel or fiber to increase its strength and durability. Shotcrete has been used in various construction applications, such as tunnels, retaining walls, and swimming pools, due to its ability to conform to any shape and its quick installation process (ACI Committee 506) [2]. In recent years, there has been growing interest in combining 3DP and shotcrete

techniques to create new construction solutions. This integration offers the potential for creating complex shapes and designs with the precision of 3DP and the strength and durability of shotcrete. It also offers the potential for reducing material waste and labor costs, and for creating structures with enhanced sustainability, Lu et al. [3]. The primary objective of this scholarly exposition is to offer an all-encompassing and meticulous examination concerning the amalgamation of three-dimensional printing (3DP) and shotcrete methodologies within the realm of the construction sector. The primary aim of this research is to thoroughly investigate the combination of 3DP and shotcrete technologies in the construction industry. The study seeks to understand the advantages and limitations of both 3DP and shotcrete methods, explore the materials used in these techniques, analyze the design considerations, examine their implementation in construction, and explore potential future applications and opportunities for these technologies in the construction field. By achieving these objectives,

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valuable insights into the integration of 3DP and shotcrete can be gained, paving the way for further advancements and improvements in this exciting area of construction technology.

Through the attainment of these stated objectives, the present review manuscript endeavors to foster an augmented comprehension of the untapped potential embodied by the integration of three-dimensional printing (3DP) and shotcrete techniques within the construction sector. Moreover, it is anticipated that this scholarly endeavor will furnish invaluable perspicacity, thereby enriching the forthcoming investigations and scholarly inquiries aimed at unraveling the intricacies of this burgeoning realm.

2 Three-dimensional printing technology

2.1 Overview of three-dimensional printing technology and its applications

Three-dimensional printing, commonly referred to as additive manufacturing, encompasses a methodical procedure whereby tangible entities are meticulously crafted in a stratified manner, leveraging a digital blueprint as a foundational framework. Although this innovative technological framework has found profound applications across diverse sectors such as aerospace, automotive, and healthcare, it has recently captivated considerable interest within the construction sphere. This heightened attention stems from its discernible capacity to fundamentally transform the conventional paradigms associated with architectural design and the construction process at large. The implementation of three-dimensional printing technology in the construction field enables the fabrication of intricate forms and configurations that would present substantial challenges if conventional construction approaches were to be employed. The applications of this technology in construction include the production of concrete components, building facades, and even entire structures, Jipa et al.[4].

2.2 Types of three-dimensional printing technology used for construction

Various classifications of three-dimensional printing technology have been harnessed for construction purposes, encompassing fused deposition modeling (FDM), stereolithography (SLA), and selective laser sintering (SLS), among others. FDM is a type of three-dimensional printing technology that uses thermoplastics as the building material and extrudes them layer by layer. This technology has been used for printing building components such as wall panels and roofing systems, Jandyal et al. [5]. SLA is a technology that uses a liquid photopolymer that is solidified layer by layer using a UV laser. This technology has been used for printing complex geometries such as building facades and ornamental details. SLS is a technology that

uses a powder material that is sintered layer by layer using a laser. This technology has been used for printing building components such as structural elements and reinforcement systems, Jandyal et al. [5].

3 Shotcrete technology

3.1 Overview of shotcrete technology and its applications

Shotcrete technology, or sprayed concrete, is a construction method where the concrete mix is sprayed onto a surface under high pressure. Its popularity stems from its flexibility, strength, and durability. This technique can be applied to walls, roofs, and floors, making it versatile for various construction projects, including tunnels, bridges, and swimming pools (ACI Committee 506 [2]). Shotcrete's ability to adapt to different surface shapes makes it ideal for intricate architectural designs and curved surfaces. Its quick installation process and efficiency suit projects with tight schedules. Additionally, shotcrete's high compressive and tensile strength makes it suitable for critical structural elements like bridge abutments and foundations. Its resilience against environmental factors ensures long-lasting performance and reduced maintenance costs.

3.2 Advantages and limitations of shotcrete technology in construction

Shotcrete technology has several advantages that make it a preferred method of construction. One of the most significant advantages is its ability to form complex shapes and surfaces. Shotcrete technology can be applied in hard-to-reach areas, making it ideal for construction in areas with limited access Bernardo et al. [6]. Indeed, shotcrete represents a distinctive technique whereby a cementitious blend is forcefully projected pneumatically onto a target surface. The composition of shotcrete primarily comprises concrete or occasionally mortar, yet the application process itself distinguishes it from conventional methods. This specialized approach enables the achievement of optimal concrete compaction without the need for traditional vibration techniques. Additionally, shotcrete can be used for a variety of construction projects, such as tunnels, swimming pools, and retaining walls (ACI, 506R-16) [7]. Shotcrete also has a high strength-to-weight ratio and can be used to create thin, lightweight structures with excellent durability, Galan et al. [8].

3.3 Types of shotcrete technology used for construction

Within the construction domain, two principal variants of shotcrete technology prevail, namely dry-mix shotcrete and wet-mix shotcrete. Dry-mix shotcrete involves mixing the dry ingredients, such as cement, sand, and aggregate, and then pumping compressed air

through the mixture to spray it onto the surface. This process is often used for small-scale projects or for repairs and maintenance work (ACI, 506R-16) [7]. Shotcrete technology is a versatile and widely used construction method with several advantages, including its strength-to-weight ratio, ability to be applied in difficult-to-reach areas, and durability. However, it also has limitations, including high initial costs, skilled personnel requirements, and the risk of rebound. By understanding the types of shotcrete technology available, project managers and engineers can choose the best method for their specific construction needs.

4 Integration of three-dimensional printing and shotcrete techniques

4.1 Overview of how three-dimensional printing and shotcrete technologies can be integrated:

Three-dimensional printing (3DP) technology has emerged as a promising technique for the fabrication of complex geometries in the construction industry Teizer, et al. [9]. The prospective implications of 3DP technology encompass the potential to curtail construction expenses and timelines, amplify construction excellence and sustainability, and afford the opportunity for personalized building designs. The integration of 3DP and shotcrete technologies can provide several advantages in construction projects.

The 3DP technology can be used to produce a formwork that can be used to apply shotcrete. The 3DP formwork is typically made of lightweight materials such as plastic, which can be easily removed after the shotcrete is applied. This approach eliminates the need for traditional formwork, which can be time-consuming and expensive to install and remove.

Furthermore, 3DP can also be used to print structural components that can be filled with shotcrete. This approach can increase the structural integrity of the building, as the shotcrete reinforces the 3DP printed components. Furthermore, 3DP has the capacity to fabricate bespoke components featuring intricate geometries that would pose challenges when employing conventional construction methodologies.

Several case studies have demonstrated the successful integration of 3DP and shotcrete technologies in construction projects. For example, the construction of a three-story office building in Dubai, which was built using 3DP technology and shotcrete. The building's columns, beams, and walls were all printed using 3DP technology, and shotcrete was applied to reinforce the structure. The building was completed in just 17 days, and the construction cost was significantly lower compared to traditional construction methods, Puzatova et al. [10].

5 Materials used in three-dimensional printing with shotcrete technique

There are various types of materials used for three-dimensional printing with the shotcrete technique, including cementitious materials, admixtures, fibers, and aggregates. Cementitious materials, such as Portland cement, are commonly used as the binder in shotcrete mixtures due to their high compressive strength, good adhesion, and high durability. Studies have explored the use of various types of cementitious materials in three-dimensional printing with shotcrete techniques. For instance, a mix of high-alumina cement and fly ash to improve the flowability and early-age strength of the shotcrete mixture for a printed structure. Other researchers, such as Safdar Reza et al. [11], have also investigated the use of different types of fibers, including steel fibers, glass fibers, and carbon fibers, in shotcrete mixtures for three-dimensional printing.

5.1 Properties and characteristics of these materials

In 3DP with the shotcrete technique, the materials used play a key role in determining the overall performance and durability of the printed structures. The properties and characteristics of these materials are critical factors that need careful consideration during the construction process. Extensive research has been conducted to explore the impact of various materials and additives on the properties of shotcrete mixtures, aiming to optimize their mechanical and structural performance. One important material used in shotcrete mixtures is silica fume, a byproduct of the silicon and ferrosilicon alloy production. Krishnaraja et al. [12] demonstrated that incorporating silica fume into the shotcrete mixture significantly enhances the compressive strength and durability of the printed structure. Silica fume improves the microstructure of the concrete by filling the voids between cement particles, leading to increased density and reduced porosity. This results in a denser and more durable material with higher resistance to chemical attacks and weathering. Additionally, the increased strength of the shotcrete mixture with silica fume ensures better load-bearing capacity and structural stability, making it suitable for various construction applications.

Furthermore, the use of steel fibers in shotcrete mixtures has been investigated to improve its tensile strength and ductility. Pham et al. [13] demonstrated that the inclusion of steel fibers in the shotcrete mixture leads to enhanced crack resistance and improved post-cracking behavior. Steel fibers act as reinforcement within the concrete matrix, bridging microcracks and preventing their propagation. This reinforcement mechanism enhances the tensile strength of the shotcrete, making it more resistant to cracking under applied loads. The increased ductility of the material allows it to deform without catastrophic failure, ensuring better overall performance in seismic and dynamic loading conditions.

6 Design considerations for three-dimensional printing member with shotcrete technique

In order to ensure a successful implementation of the three-dimensional printing with the shotcrete technique, several crucial factors necessitate careful consideration during the design phase. These include factors related to the printing process itself, as well as those related to the structural design of the printed member. Some of the primary considerations include the material properties of the shotcrete mixture, the accuracy and precision of the printing process, the strength and stability of the printed member, and the overall durability and resistance to environmental factors such as moisture and chemicals, Holt et al. [14].

One of the challenges is the limited accuracy and precision of the printing process. While advances in printing technology have improved the accuracy and precision of three-dimensional printing, there are still

limitations to the level of detail and complexity that can be achieved, Žujović et al. [15]. The primary objective of this study is to undertake an exhaustive and systematic literature review (SLR) that delves into the far-reaching ramifications of cutting-edge three-dimensional printing (3DP) technology on the realms of architectural design and construction. In addition, the printing process itself can be slow and time-consuming, which can limit its practical applications in large-scale construction projects, Wu et al. [16]. Indeed, the essence of this paper lies in its comprehensive examination of the foundational concept and distinctive attributes underpinning three-dimensional printing (3DP) within the construction sector. Furthermore, it seeks to evaluate the diverse applications of 3DP technology in the construction domain while concurrently engaging in a thorough exploration of the manifold challenges encountered in its implementation within the industry. Table 1 summarizes the characteristics of 3D printing technologies [20].

Table 1. Summary of the printing processes, printing materials, and some general characteristics of different 3D printing technologies [20].

3D printing technologies	The printing process	Printing materials	Cost index	Printing time index	Accuracy index: Smallest feature (µm)
Stereolithography	Using a UV laser beam to harden the liquid polymer and lowering the perforated platform to manufacture multiple layers.	Liquid photosensitive resins	200-400	100-120	1-366
Fused deposition modeling	Printing material is supplied to the printer head to deposit the material into the layers.	Acrylonitrile butadiene styrene (ABS); Elastomer; Wax; Metal	100	100	260-700
Inkjet powder printing	Printer head is employed. Printing material in powder form is deposited. Afterward, binder is sprayed, heated, and dried. The complete product is cured in an oven.	Polymers; Metal	40-80	20	350-500
Selective laser sintering and Selective heating sintering	Printing material in powder form is deposited. Afterward, it is consolidated using a focused laser beam. The procedure is repeated from layer to layer.	Nylon-based materials; Rapid steel; Sand form	200-400	100-120	45-100
Contour crafting	Printing material is squeezed out from the nozzle and then toweled. The gantry system is computer-controlled and moves with the nozzle.	Ceramics materials; Concrete	N/A	4 mins/m ²	N/A

7 Construction and implementation of three-dimensional printing member with shotcrete technique

The integration of 3D printing in the construction sector has garnered significant interest owing to its capacity to produce intricate and personalized structures with greater efficiency and cost-effectiveness compared to conventional construction techniques. The combination of 3D printing with shotcrete, a sprayable material composed of cement, water, and aggregates, has shown promising results in producing strong and durable structures suitable for a wide range of applications. A study by Hossain et al. [17] demonstrated the potential of using a 3D-printed mold and shotcrete to construct reinforced concrete structures. This study explores the effects on the labor market resulting from the adoption of 3DP in the construction sector. While 3D printing with shotcrete offers many benefits, there are also several challenges and limitations associated with this technique. For example, in a study by Buchanan and Gardner [18], the researchers identified challenges such as the lack of design guidelines and the need for better material properties. This paper, a comprehensive review of present metal additive manufacturing (AM) methodologies, existing research endeavors, initial applications within the construction field, as well as its utilization in other advanced technological domains, has been conducted. Furthermore, this study explores the multitude of prospects and obstacles that lie ahead for the broader implementation of metal AM in the construction industry. A potential functionally graded AM beam is forming an integral component of a hybrid structure [21].

8 Potential advancements in technology and materials

Perkins and Skitmore [19] provided a comprehensive review of 3D concrete printing technology and its future prospects. They noted that one potential advancement in this technology is the use of new and innovative materials, such as self-healing concrete or concrete that can absorb pollutants from the air. Another potential area of advancement is the development of new printing techniques that can increase printing speeds and improve the accuracy of the final product. According to the proponent of the contour crafting method, remarkable advancements in building speed can be achieved through its utilization. Projections indicate that the contour crafting method has the potential to complete the construction of an entire house within a few hours instead of the traditional timeline spanning several months [19].

In addition to the use of new materials, the recycling of construction waste into printable materials could be a promising approach to reduce environmental impact and material cost, Shahrubudin et al. [1]. Advances in materials science and technology could also lead to the creation of new materials that are better suited for 3D printing, such as composite materials that are both lightweight and strong.

9 Conclusions

The present review paper has delved into the technology of 3D printing with shotcrete in the construction industry, discussing its various facets, including the materials used, the printing techniques involved, and the potential benefits and applications of this technology. By conducting an extensive examination of the existing literature, this research paper has underscored the transformative potential of 3D printing in conjunction with shotcrete techniques within the construction sector. Notably, it has emphasized how this integration can facilitate the fabrication of intricate geometries and bespoke components, surpassing the limitations of conventional construction approaches. Furthermore, this amalgamation holds promise for enhancing construction efficiency, mitigating waste generation, and bolstering worker safety standards.

In light of these findings, recommendations for future research in this area include the continued development and improvement of printing techniques and materials, as well as the exploration of new applications for 3D printing in the construction industry. To advance the knowledge in this field, additional research endeavors are imperative to ascertain the long-term durability and performance of structures built employing this technology. Furthermore, there is a pressing need to identify the most cost-effective and sustainable methodologies for incorporating 3D printing with shotcrete in the construction domain. These areas of investigation will pave the way for informed decision-making, ensuring the successful implementation of this innovative approach while optimizing longevity, functionality, and eco-friendliness. In conclusion, the potential for 3D printing with shotcrete to revolutionize the construction industry is significant. While this technology is still in its early stages, continued research and development in this area could lead to significant advancements in construction technology and more sustainable building practices. The implications and potential impact of 3D printing with shotcrete for the construction industry are vast, making it a technology worth watching closely in the years to come.

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