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TRADITIONAL VS 3D CONCRETE PRINTING - APPLICATION AND CHALLENGES: A SYSTEMATIC REVIEW

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Abstract
In the years to come, 3-D printing, a disruptive technology, might have significant societal and economic effects. With the use of concrete and other cementitious and binder materials, the technology, which first emerged in the 1980s and was restricted to the production of tiny goods, is now being used in large-scale construction applications. Reducing or eliminating the energy and environmental footprints as well as the socioeconomic impact is recommended. The study comes to the conclusion that 3DP technology seems to be a promising substitute for traditional building methods and the usage of concrete, based on reported global warming potential (GWP) values. The sustainability potential, evaluations, and difficulties of 3DP concrete for built environment applications are all systematically reviewed in this paper. To determine the current trends and research gaps, a thorough and comparative evaluation of linked literature is conducted.
Keywords: 3D-printing, Reinforced cement concrete, Keys challenges, Future research direction, Application.

1. INTRODUCTION

1.1. Brief overview of 3D printing technology

3D concrete printing, or simply concrete printing, refers to digital manufacturing procedures for cementitious materials using one of numerous 3D printing technologies. In complicated projects, 3D-printed concrete increases geometric freedom and minimizes material waste by eliminating the need for formwork. With recent advances in mix design and 3D printing technology over the last decade, 3D concrete printing has evolved tremendously since its inception in the 1990s. 3D-printed concrete has architectural and structural uses such as building blocks, building modules, street furniture, pedestrian bridges, and low-rise residential structures.

1.2. Background

In the construction sector, all facets of the international construction industry are paying close attention to 3D printing, which is revolutionary. We examined three main areas of 3D printers in our study report, taking into account their use in the construction sector. Despite being developed in the early 1980s, it was useless at the time due to its high cost of use. It became somewhat user-friendly in 2000 since it enables design creation on a computer and costs very little because the concrete for 3D buildings is made of waste materials and polymers. All of a sudden, it became feasible and economical for a variety of models, designs, etc.

1.3. Need of Research

Because of its revolutionary potential and the many unresolved issues, research into 3D printing in concrete building is crucial. By combining material preparation, geometric modeling, and structural design, this technology offers benefits including mass customization, less waste during construction, and the capacity to build intricate structures. Significant problems still exist, nevertheless, such as the requirement for a better comprehension of the scaling of mechanical properties, the prediction of failure mechanisms, and the anisotropic mechanical behavior of 3D printed concrete. Enhancing structural integrity also requires the development of efficient reinforcement techniques and the optimization of material properties.

1.4. Challenges

Numerous important obstacles prevent the widespread use of 3D printing in concrete building. To fully realize this unique construction method's potential, these issues—which include material attributes, technological constraints, and industry resistance—must be resolved.

- Hardening and Workability Time: Concrete's special qualities, like its time-dependent compressive strength, make printing more difficult and necessitate careful handling to avoid structural breakdowns during construction.
- Mechanical Properties: The reliability of 3D printed concrete in building applications is limited by a lack of study on its mechanical characteristics and structural reinforcement techniques.
- Printer Design and management: To guarantee quality and stability, improvements in print path planning and environmental management are required, as current 3D printing systems frequently cannot manage large-scale components efficiently.
- Process Optimization: Achieving consistent outcomes in 3D concrete printing is significantly hampered by the necessity for improved printing conditions and the unpredictability of materials.
- Adoption Barriers: A shortage of experienced labor and unfamiliarity with the new procedures are the main reasons for the construction industry's considerable resistance to adopting 3D printing technologies.

1.5. Role of 3D Printing in Concrete Structure

Using three-dimensional printing (3D printing), computer blueprints may be turned into tangible structures. Metal, resins, or plastic are used by 3D printers to produce thin layers. They keep building layers upon layers to create a whole structure.

- **Prototyping**

Pre-construction planning might include prototyping as a crucial component. Prototyping may be streamlined and several prototypes can be built quickly with 3D printing as part of building design and construction.

- **Modeling**

As with prototyping, modeling allows architects to fine-tune the visual elements of the design before building. A 3D printer can help generate a more accurate model based on architectural drawings. Additionally, it can expedite the modeling process and enable architects to rapidly create several models in order to evaluate various design concepts.

- **Layering**

Compared to traditional construction, these projects have the advantages of lower labor costs and more precise construction thanks to computerized planning. These projects are frequently completed significantly more quickly; some homes are constructed in a day (though additional time is required for finishing, fixtures, and additional components). Layering is frequently used by construction businesses to print building components. After that, they transport these components to the building site and install them next to those manufactured using conventional techniques.

- **3D Concrete Printing**

Layer by layer, 3D printers create architectural elements and things. In certain cases, a printer can utilize this method to build a whole house from the ground up. These structures often employ 3D printers to create a base and layer concrete for the walls before roofing is added. A modest house was just constructed in Texas by a business that uses concrete printing.

- **Making Specific Components**

3D printers can also produce smaller parts, but cement-based 3D printing may build a whole house or prefabricate parts that builders can assemble on site.

Instead of depending on prefabricated hardware, 3D printing has the advantage of being able to produce unique components that precisely match the requirements of a certain project. By manufacturing these components on-site or close by, transportation expenses can be decreased and delays brought on by transporting extra parts can be avoided.

2. LITERATURE REVIEW

The fragmentation of 3D printing (3DP) in concrete suggests that a thorough examination of the materials and applications in the building industry is necessary. In order to address issues and potential directions for future research, this paper attempts to summarize the technical, socioeconomic, and environmental aspects of 3DP in concrete. The review emphasizes how crucial it is to examine obstacles in order to improve 3D concrete printing's mechanical performance, sustainability, and durability.[1]

The article gives a thorough introduction to 3D printing (3DP) technology, emphasizing its benefits including customization, design freedom, and the capacity to produce intricate forms with little waste. It covers a range of 3DP methods, such as Fused Deposition Modeling (FDM) and Stereolithography (SLA), describing their materials, procedures, and uses in industries like aerospace and medicine. The analysis also points out important obstacles to large-scale production, such as high costs and processing times. Additionally, it tackles problems with properly implementing this technology and knowledge gaps.[2]

The sustainability potential and difficulties of 3D printed concrete in the built environment are methodically examined in this paper's literature study. It draws attention to the necessity of creative approaches in the building industry while highlighting the benefits of digital manufacturing, like material flexibility and design efficiency. Peer-reviewed publications are the main emphasis of the review, which guarantees a strong selection of original research while weeding out papers that don't discuss sustainability in relation to 3D printing. It also points up research gaps, especially with relation to integrating life cycle analysis (LCA) into environmental impact assessments. According to the research, 3D printing technology has the potential to drastically lower the environmental and energy footprints of conventional building techniques.[3]

In this work, concrete 3D printing (3DP) technologies—specifically, extrusion-based techniques for structural load-carrying members—are the subject of a thorough literature analysis. Three phases make up the review's structure: planning, compilation, and analysis. The investigation is guided by certain research questions. While the second question examines the technologies created to increase the tensile and flexural strength of these elements, the first question discusses the difficulties in building load-carrying structures employing 3DP technology. The review points up important subjects such bond strength and reinforcement techniques, emphasizing the necessity for more study to fill in the gaps in the literature. All things considered, the study highlights how 3DP technology is still in its infancy in large-scale building and the need for further development.[4]

The study offers a thorough analysis of large-scale 3D printing concrete (3DPC) technologies, classifying them into three primary categories: monolithic 3DPC on-site, 3D printing formworks, and 3D printing elements. It draws attention to how large-scale and lab-scale 3DPC have different printability requirements, with the latter frequently failing to satisfy the needs of real-world applications because of variables like layer size and pumping distance. Practical issues are also included in the study, such as concrete preparation, reinforcement construction, and environmental and economic optimization. Additionally, it makes recommendations for future lines of inquiry to improve the usefulness of large-scale 3DPC technology in the building industry.[5]

The current level of 3D printed concrete (3DPC) technology is thoroughly reviewed in this study, with a focus on large-scale constructions. It summarizes research from current studies, emphasizing important topics including concrete's rheology, the effects of chemical admixtures, and the function of inclusions and reinforcements in the printing process. Along with outlining technological obstacles and opportunities for environmental and economic sustainability, the writers also go into operating aspects and the viability of 3DPC. The study also examines how aggregates affect printhead obstruction and what nozzle specs are required to avoid clogging.[6]

Both developments and difficulties in the field are highlighted in the literature on 3D printed concrete. New structural designs are required because traditional structural forms frequently fall short of utilizing the special advantages of 3D printing, such as customization and digitization. Although various reinforcement techniques, such as steel bars and fibers, have been investigated, many are still poorly understood, especially in terms of their failure modes and bearing capacities. Furthermore, research shows that, mostly as a result of the interfaces created during printing, 3D printed concrete's mechanical qualities are typically worse than those of cast-in-place concrete. Overall, the actual application of 3D printed concrete in engineering is limited by notable gaps in safety design and structural analysis, despite the possibility of creative applications.[7]

The state-of-the-art in 3-D printing concrete is thoroughly reviewed in this study, which also highlights recent developments in materials and technology as well as the field's historical context. It discusses the paucity of research on computational modeling in this area and highlights the necessity of better simulation methods to forecast the performance of materials made of printed cement. In an effort to close the gap between research and real-world construction applications, the review also addresses the development of equipment and the difficulties in creating concrete mixtures that are appropriate for 3-D printing.[8]

This paper's review of the literature focuses on historic buildings that depend on compression for stability. Form, structural principle, materials, and building methods used for walls, roofs, and foundations are the four main vectors that are analyzed. Finding forms appropriate for concrete applications that can be 3D printed is the goal. In the end, the survey creates historically inspired shapes for 3D printing by looking at the materials, construction methods, and structural behavior of ancient buildings. This examination is essential for guaranteeing the qualities of concrete in its fresh state, which impact the printing process's success.[9]

Ref.	Author/Year	Method Used	Objective	Research Gap	Limitation	Conclusions
1	(Rollakanti and Prasad, 2022)	Powder-bed methods involve selective binding of materials, suitable for complex structures	It emphasizes enhancing mechanical performance, durability, and sustainability in 3D concrete printing	Current specifications for printing materials are arbitrary and need standardization	Anisotropic behavior of printed concrete elements.	3DP technology has potential for the concrete construction industry
2	(Dasgupta and Dutta, 2022)	Binder Jetting Method (BJM) for complex concrete designs	Identify technical challenges and opportunities for enhancing benefits	High-performance composite polymers should be explored for structural requirements	Environmental impact increases with energy-intensive processes	The study highlights the potential of 3D printing in construction
3	(Khan et al., 2021)	he stages include planning, compilation, and analysis	To explore technologies for concrete 3D printing of structural elements.	Insufficient research on shotcrete 3D-printed strength aspects.	Layer interfaces act as failure planes, reducing performance.	3D printed formworks save costs but complicate reinforcement integration
4	(Raphael et al., 2023)	Comparison of printability requirements for large-scale and lab-scale 3DPC.	To provide recommendations for future work in 3DPC technology	Exploration of economic and environmental optimizations is still needed.	Heavy gantry systems restrict mobility and flexibility	Economic and environmental optimizations are necessary for practical applications
5	(Xiao et al., 2021)	It categorizes aspects like concrete rheology and printing parameters	To discuss operational parameters and feasibility of 3D printing technology	Further strategies for enhancing tensile strength are needed	Unsuitable mix design can lead to low buildability and weak bonds	Current technology limits construction to low-rise buildings
6	(Souza et al., 2020)	It mentions wrapping GFRP sheets and U-nails as reinforcement methods	To illustrate the application potential of 3D printed concrete	Traditional structure systems do not reflect 3D printing advantages	Inability to embed steel bars during printing. Reinforcement limited to within filaments, not between layers	Mix optimization can reduce carbon emissions in concrete.

7	(Tongji University et al., 2021)	The paper discusses computational materials modeling techniques for cement-based composites	To explore social and economic impacts of 3D printing in construction	Insufficient focus on computational simulations of the 3-D printing process.	Current codes are based on composite concrete-steel systems, limiting innovation	3-D printing in construction is evolving from manual to automated processes
8	(Khan et al., 2020)	Stereolithography and direct energy deposition are also included	To evaluate the impact of 3D printing on various industries	Additional research is required for material	Excessive costs associated with 3D printing technology	FDM is widely used for its low cost and speed

The importance of both fresh and hardened qualities is emphasized as the research examines several facets of concrete mixtures appropriate for 3D printing. It talks about the difficulties with 3D printing concrete, like voids and anisotropy, and emphasizes the necessity of appropriate material combinations that improve printability and mechanical strength. The paper also discusses the potential and difficulties of fiber-reinforced concrete and geopolymer mixtures in 3D printing applications, citing previous research on the subject. It also suggests important research areas for enhancing the quality of printed specimens by choosing the best materials and printing settings.[10]

The study examines the development and efficacy of 3D printing technology in the building sector, emphasizing its benefits over conventional techniques. It talks about how additive manufacturing has grown significantly over the last three decades and how it affects cost effectiveness and design optimization. The study highlights how important it is for the construction sector to adjust to new technology, especially given the push to innovate. Furthermore, it contrasts the time and expense of building a single-story home with traditional techniques, demonstrating the possibility of lower labor and material costs.[11]

The potential of additive manufacturing to transform concrete construction is discussed in the study along with the new technology known as 3D Concrete Printing (3DcP). It examines current approaches like pre-installed and post-installed reinforcements and draws attention to the difficulties with reinforcement techniques, especially in the interlayer direction. In order to provide continuity between layers, the authors present a novel in-process technique for inserting mesh reinforcement during layer deposition. The study also looks at the qualities of the materials that were employed, such as the features of different silica sands and steel reinforcing mesh. In general, the research highlights the necessity of efficient reinforcement techniques to improve the structural soundness of 3DcP buildings.[12]

The paper gives a thorough introduction to 3D printed concrete, emphasizing the technology's quick development and possible uses in building. It talks about how conventional concrete constructions can't handle the special qualities of 3D printing, such customization and digitization. The literature study highlights the need for more research on the bearing capacity and failure modes of 3D printed components by examining a variety of reinforcing techniques. With the help of successful case studies, it also classifies appropriate structural forms for 3D printing, such as hollow, tree, arch, and structure-functional forms. The ultimate goal of the paper is to direct future investigations toward tangible, sustainable solutions.[13]

In example, geopolymer materials—which are made by alkaline activating silicon-aluminum raw elements like fly ash and metakaolin—are gaining popularity as sustainable substitutes for Ordinary Portland Cement (OPC). Compared to OPC, these materials offer lower energy usage and CO2 emissions. According to research, geo-polymerization can improve concrete's durability and mechanical qualities, making it a good choice for building. Nevertheless, little is known about how to optimize concrete-geopolymer hybrids, particularly with regard to their mechanical and physical characteristics when 3D printed. According to studies, adding geopolymer can make these hybrids more environmentally friendly by enhancing fire resistance and lowering toxic leachates.[14]

3. PROBLEM STATEMENT

Rapid urbanization and industrialization present the construction sector with a number of difficulties that impede its growth, such as a lack of experienced workers, resource depletion, and safety concerns. Reinforcement procedures are necessary because concrete 3D printing (3DP) technology is unable to provide printed structural elements with sufficient tensile and flexural strength. Material selection and design guidelines are made more difficult by the absence of recognized standards and specifications for 3DP technology in concrete building. The usage of Ordinary Portland Cement (OPC) and transportation are the main causes of 3DP's significant environmental effect, underscoring the need for more environmentally friendly products and procedures. Because present formulations frequently lack coarse particles, increasing reliance on cementitious ingredients and potentially increasing carbon emissions, it is imperative that concrete compositions be optimized for 3DP.

It can be difficult to integrate reinforcement into intricate 3D printed formworks, especially when it comes to maintaining structural integrity in a variety of climates.

4. FUTURE SCOPE

- The development of comprehensive material design schemes and rheology control methods is critical to improving printability and economic feasibility, guaranteeing that 3DCP can be used effectively in large-scale projects.
- The establishment of common building norms and regulations for 3D printing procedures is critical. This includes developing design standards, calculating methods, and construction processes to aid widespread adoption.
- More research is needed to investigate the bond strength and anisotropic behavior of 3D printed concrete parts, which are major obstacles to adopting this technology into traditional construction procedures.
- Exploring creative building methodologies and structural designs optimized for 3DCP can increase project performance and efficiency.
- Engaging public and private institutions, particularly academia, is critical for joint efforts to address current hurdles and promote 3D printing technology in building.
- The integration of sophisticated materials, such as nano-clays and fibers, should be further investigated to improve the rheological qualities and overall performance of 3D printed concrete.

5. CONCLUSION

3D concrete printing (3DCP) outperforms traditional construction technologies in terms of efficiency and cost-effectiveness, especially for geometrically complicated constructions. The technique is known for its sustainability, as it generates little waste and allows for new designs that improve environmental performance. The development of concrete-geopolymer hybrids has showed promise in producing ecologically friendly building materials, with optimal compositions resulting in increased mechanical capabilities. Large-scale 3DCP deployment remains challenging, notably in terms of reinforcement techniques and the necessity for specific mix designs to attain desired structural strength. There is an urgent need for additional research to address the limits of present analytical models and improve the automation and accuracy of 3DCP systems.

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