JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

A REVIEW OF 3D CONCRETE PRINTING: GLOBAL EVOLUTION AND APPLICATIONS IN THE INDIAN CONSTRUCTION SECTOR.

[1]**Mr. Vaibhav Raju Kondane**
[1]B.E 1st year Civil engineering student
[1]College Of Engineering And Technology, Akola, Maharashtra ,India.

***Abstract* :** *The construction industry is currently undergoing a digital transformation driven by the need for rapid urbanization and sustainable development [1]. 3D Concrete Printing (3DCP), or Additive Manufacturing, offers a viable solution to labor shortages and material wastage by automating the deposition of cementitious layers. This paper reviews the evolution of 3DCP technology, tracing its origins from the 1939 "Wall Building Machine" to modern robotic extrusion systems used in India. The study analyzes the technical workflow of 3DCP, drawing parallels with Fused Deposition Modeling (FDM) processes, and highlights the critical material constraints regarding pumpability and buildability.*

Special emphasis is placed on the Indian context, examining case studies such as the country's first 3D-printed home at IIT Madras and the strategic deployment of military bunkers in Leh at 11,000 feet. While the technology promises significant time savings and potential alignment with national affordable housing schemes like PMAY-Urban, structural challenges remain. A review of mechanical characterization reveals that the interface between printed layers exhibits 11–14% higher porosity compared to cast concrete, resulting in a 22–30% reduction in bond shear strength. The paper concludes that while 3DCP is technically feasible, widespread adoption in the Indian construction sector requires the development of standardized IS codes and improved interlayer reinforcement strategies. Furthermore, the study includes an experiment analysis of slicing parameters using Eiger software to demonstrate the rheological divergence between FDM and concrete extrusion.

***IndexTerms* - 3D Concrete Printing, Additive Manufacturing, Affordable Housing, Automation, Construction Technology, PMAY**.

Introduction :

The global construction industry is currently navigating a "trilemma" of challenges: rapid urbanization, severe labor shortages, and the urgent need for sustainable waste reduction. As traditional manual methodologies struggle to meet the escalating demand for infrastructure, 3D Concrete Printing (3DCP)—scientifically classified as Additive Manufacturing (AM)—has emerged as a transformative solution. Defined by the ASTM F2792-12a standard [8], AM is the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. By eliminating the need for expensive timber or steel formwork, 3DCP offers the potential to reduce material waste by significant margins while accelerating project timelines.

While 3DCP is often popularized as a 21st-century innovation, the concept of automated construction has a distinct historical lineage that predates the digital age. Patent records reveal that the origins trace back to 1939, when inventor William E. Urschel created the "Wall Building Machine" in Indiana, USA [4]. This device utilized a primitive mechanical extrusion system to layer concrete without forms, effectively serving as the precursor to modern automated construction. However, the technology remained dormant for decades until 1995, when Dr. Behrokh Khoshnevis at the University of Southern California developed Contour Crafting [6]. This gantry-based robotic system introduced a trowel-like nozzle attachment that smoothed layers as they were deposited, laying the technical foundation for today's commercial printers.

From a technical perspective, the operational workflow of 3DCP parallels the Fused Deposition Modeling (FDM) process used in industrial polymer prototyping. The process begins with a "Digital Twin"—a CAD model processed through slicing software to generate G-Code coordinates. However, significant rheological differences exist. While polymer printers using materials like Nylon 12 operate with layer heights as low as 0.1 mm for high-precision components, construction printing operates at a macro scale with layer heights typically ranging from 20 mm to 50 mm. This necessitates specialized cementitious mixes that possess high "thixotropy"—the ability to be fluid during pumping but solid immediately upon deposition to support the weight of subsequent layers.

In the Indian context, the technology has rapidly transitioned from laboratory research to strategic on-site application. A landmark achievement occurred in 2022 with the construction of India's first 3D-printed house at IIT Madras, followed by commercial deployment by startups like Tvasta Manufacturing Solutions and infrastructure giants like L&T. Beyond residential use, the technology has demonstrated versatility in extreme environments. In a unique defense application, the Indian Army utilized robotic arm manipulators to construct military bunkers in Leh at an altitude of 11,000 feet, proving that 3DCP can function in sub-zero temperatures where manual labor is inefficient and logistics are constrained.

Despite these advancements, widespread adoption is hindered by structural limitations, particularly anisotropy (directional weakness). Recent mechanical characterization by Rahul et al. (2019) indicates that the interface between printed layers remains a critical weak point. Their data reveals that the "inter-layer" zone exhibits 11–14% higher porosity compared to the bulk material [2]. Consequently, this porosity leads to a 22–30% reduction in bond shear strength, making printed walls susceptible to lateral loads. Furthermore, the integration of the technology into national frameworks like the Pradhan Mantri Awas Yojana (PMAY-Urban) requires the urgent development of standardized Indian Standard (IS) codes to ensure safety and durability in mass housing projects.

History and Evolution of Automated Construction :

While 3D Concrete Printing is often viewed as a recent technological breakthrough, its conceptual roots extend back nearly a century. The evolution of the technology can be categorized into three distinct eras: the Pre-Digital Era, the Prototyping Era, and the Commercial Era.

1) The Pre-Digital Era (1930s)

The concept of layer-by-layer construction was first patented in 1939 by inventor William E. Urschel. He developed the "Wall Building Machine" in Indiana, USA, which used a mechanical ramming process to extrude concrete layers without the need for static formwork. Although this machine successfully built a small structure, the technology was limited by the lack of digital control systems and did not see widespread adoption at the time.

2) The Prototyping Era (1990s)

The modern resurgence of the technology began in 1995 with the work of Dr. Behrokh Khoshnevis at the University of Southern California (USC). He patented "Contour Crafting," a gantry-based fabrication process that integrated a robotic trowel to smooth the surface of extruded cementitious paste. This innovation solved the issue of surface finish and established the kinematic principles used in almost all modern gantry printers today. Simultaneously, in the 1980s and 90s, the development of stereolithography (SLA) and Fused Deposition Modeling (FDM) in the polymer sector laid the software foundation (slicing and G-code) that construction printers would later adopt.

3) The Commercial Era (2014–Present)

The transition from academic labs to commercial job sites occurred around 2014, when the Chinese company WinSun demonstrated the capability to print ten houses in 24 hours using recycled construction waste. This marked the beginning of global interest. In the Indian context, the technology achieved a major milestone in 2022 with the inauguration of India's first 3D-printed house at the IIT Madras campus, constructed by Tvasta Manufacturing Solutions. Since then, the technology has been adopted for diverse applications, ranging from the "Print-to-Home" affordable housing initiatives to specialized defense infrastructure in the Himalayas.

Methodology and Operational Framework :

The operational framework of 3D Concrete Printing (3DCP) is scientifically classified under Material Extrusion, one of the seven categories defined by ASTM F2792-12a. Unlike Binder Jetting or Vat Polymerization, which are often used for high-resolution prototypes, 3DCP involves the continuous deposition of cementitious material through a nozzle. The methodology adopted for this review is categorized into three critical phases: Digital Design, Material Rheology, and Robotic Execution.

The process initiates with the creation of a "Digital Twin" using Computer-Aided Design (CAD) software such as Rhino 3D or AutoCAD. The critical transition from a virtual model to a physical structure occurs during the slicing phase, where the CAD model is divided into horizontal cross-sections to generate G-Code machine coordinates. This workflow parallels the Fused Deposition Modeling (FDM) process used in industrial polymer manufacturing. However, a distinct divergence is observed in the slicing parameters. While industrial printers utilizing materials like Nylon 12 or Onyx operate with layer heights as low as 0.1 mm to 0.2 mm for high precision, construction printing operates at a macro scale. In 3DCP, the layer height typically ranges from 20 mm to 50 mm depending on the nozzle diameter, requiring specialized software settings to manage the toolpath.

Table 1: Comparison Parameters.

Parameter	**Traditional Construction (Cast-in-Situ)**	**3D Concrete Printing (Additive Manufacturing)**
Formwork	Required (Timber/Steel) - Time consuming	Zero Formwork – Direct layer deposition
Material Waste	High (due to formwork and cutting)	Low (Exact material placement)
Design Freedom	Limited to straight lines and molds	Unlimited (Curved/Complex geometries)
Labor Requirement	High dependency on manual labor	Low (Automated robotic control)
Construction Speed	Slow (Curing required between steps)	Rapid (continuous extrusion)

Following the digital phase, the success of the printing process depends entirely on the rheological properties of the concrete mix. Unlike standard cast-in-situ concrete, printable mixes must satisfy three contradicting requirements simultaneously: pumpability, extrudability, and buildability. The mix must possess low viscosity under pressure to move smoothly through the hose without clogging or segregating. Conversely, immediately upon deposition, the material must exhibit high thixotropy—regaining viscosity to support its own weight and the weight of subsequent layers without deformation. This "green strength" is critical because, unlike polymer printing where supports are automatically generated for overhangs exceeding 45 degrees, concrete printing typically relies on self-supporting geometric designs to eliminate the need for sacrificial support material.

The final phase involves physical execution using a kinematic system. This is typically performed by either gantry systems, which are utilized for large-scale onsite construction due to their high stability, or robotic arm manipulators. Robotic arms offer greater freedom of movement for complex geometries and difficult terrains. A notable application of this methodology is the use of 6-axis robotic arms by the Indian Army to construct defense bunkers in Leh, demonstrating the technology's capability to operate in environments where traditional logistical setups are unfeasible.

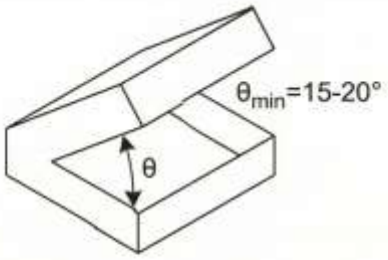

Figure 1: standard design guidelines for additive overhang angle of 40°.In concrete printing ,this constraint is even more critical, as wet concrete lacks the rapid solidification properties of polymers, often limiting overhangs to less than 15° without framework.

Similar to polymer printing guidelines (Figure 1), concrete printing requires strict geometric limits on overhangs because wet concrete cannot support itself at angles greater than 15-20 degrees.

Experimental Analysis of Slicing Parameters :

To validate the theoretical constraints of layer adhesion, an experimental analysis was conducted using slicing software to simulate the toolpath generation.

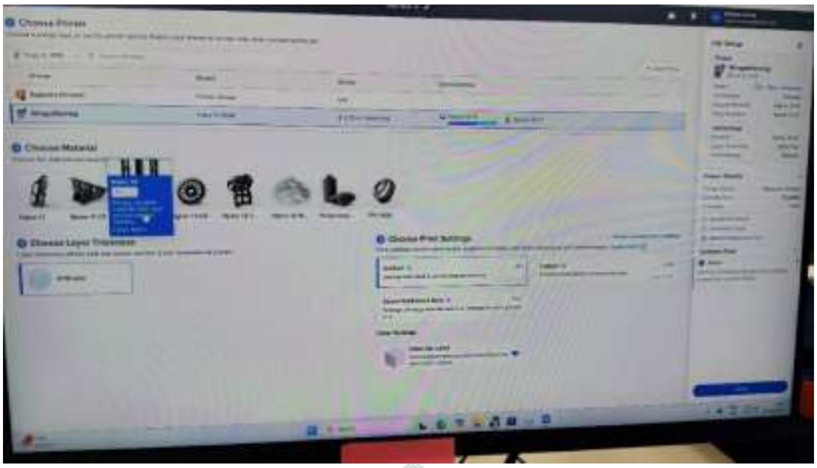

Figure 2: Eiger software interface displaying the material selection (Nylon 12) and layer height setting (0.110 mm). This experimental setup highlights the micron-level precision of FDM printing compared to the macro-scale deposition of concrete[5].

Structural Challenges and Mechanical Integrity :

Despite the automation advantages of 3D Concrete Printing (3DCP), the technology faces significant structural limitations that currently restrict its widespread adoption in high-rise applications. unlike traditional cast-in-situ concrete, which is isotropic (possessing uniform strength in all directions), 3D printed structures are inherently anisotropic. The layer-by-layer deposition process creates distinct interfaces between filaments, introducing planes of weakness that behave similarly to sedimentary rock layers rather than a monolithic concrete block.

The primary structural deficiency lies in the "inter-layer bond." Research indicates that the time interval between depositing subsequent layers—known as the "cold joint" effect—can severely compromise adhesion. Mechanical characterization studies by Rahul et al. (2019) quantified this phenomenon, revealing that the interface between printed layers exhibits 11–14% higher porosity compared to the bulk material. This increased porosity is attributed to air entrapment and moisture evaporation at the surface of the "old" layer before the "new" layer is applied. Consequently, this micro-structural defect leads to a 22–30% reduction in bond shear strength, making unreinforced printed walls highly susceptible to lateral loads such as wind or seismic forces.

Furthermore, the integration of reinforcement remains a complex engineering challenge. Traditional horizontal steel rebar cannot be easily placed during the printing process without obstructing the nozzle path. While some methodologies employ "post-installed" vertical reinforcement—where hollow voids in the printed wall are manually filled with grout and steel bars—this hybrid approach partially negates the speed and automation benefits of the technology. Current research is directed towards developing fiber-reinforced concrete mixes (using glass or basalt fibers) to improve tensile strength, yet the absence of standardized Indian Standard (IS) codes for these new composite materials remains a regulatory barrier for structural engineers.

Case Studies: The Indian Context :

The viability of 3D Concrete Printing (3DCP) in India has shifted from theoretical potential to tangible on-site application, driven by the need for speed in national infrastructure projects and the logistical challenges of remote border areas. Two prominent case studies illustrate the versatility of this technology in the Indian subcontinent.

A landmark achievement in the residential sector was realized in 2022 with the inauguration of India's first 3D-printed house at the IIT Madras campus. Constructed by the deep-tech startup Tvasta Manufacturing Solutions, this 600-square-foot structure utilized a custom-built gantry system to extrude a specialized concrete mix developed indigenously to suit Indian climatic conditions. The primary significance of this project lies in its efficiency; the structure was completed in just five days of printing time, a fraction of the months required for traditional masonry. This serves as a critical proof-of-concept for the Pradhan Mantri Awas Yojana (PMAY-Urban), demonstrating that 3DCP can meet the rigorous timeline and cost constraints required for affordable mass housing schemes.

In the defense sector, the Indian Army, in collaboration with Simpliforge Creations, demonstrated the logistical superiority of the technology by constructing a permanent military bunker in Leh, Ladakh. The project site is located at an altitude of 11,000 feet, where sub-zero temperatures and low oxygen levels render manual labor inefficient and dangerous. Unlike the gantry systems typically used in flat urban terrains, this project utilized a 6-axis robotic arm manipulator, which allowed for precise printing on undulating terrain. This successful deployment highlights that 3DCP is not merely a tool for urban housing but a strategic asset for border infrastructure development, capable of operating in extreme environments where traditional logistical supply chains are unfeasible.

Figure 3 : Robotic arm manipulator constructing a defense bunker in Leh at 11,000ft, demonstrating 3DCP application in extreme climate [7].

Future Scope and Policy Integration :

The future trajectory of 3D Concrete Printing in India is intrinsically linked to the nation's ambitious developmental goals, particularly the Pradhan Mantri Awas Yojana (PMAY-Urban). With a projected shortage of over 10 million affordable housing units in urban areas, traditional construction methodologies—reliant on labor-intensive masonry and timber formwork—are increasingly insufficient to meet the demand velocity. 3DCP offers a scalable solution to this crisis by potentially reducing construction time by 50–70% and material wastage by up to 60%. The technology's ability to utilize indigenous materials, such as industrial by-products like Fly Ash and Ground Granulated Blast-furnace Slag (GGBS), aligns with the sustainability mandates of the National Building Code (NBC), offering a pathway to "green" affordable housing [9,10].

However, the transition from experimental prototypes to mass adoption under PMAY schemes depends heavily on regulatory standardization. Currently, the lack of specific Indian Standard (IS) codes for printed concrete creates a legal liability for structural engineers and contractors. For 3DCP to be integrated into government tenders, the Bureau of Indian Standards (BIS) must formulate comprehensive guidelines that address the unique mechanical properties of printed layers, specifically the inter-layer shear strength and ductility. Once these regulatory frameworks are established, the technology is poised to move beyond niche applications to become a primary driver of India's infrastructure growth, enabling the rapid deployment of disaster-resilient housing and strategic border fortifications.

Conclusion :

The evolution of 3D Concrete Printing (3DCP) represents a fundamental paradigm shift in the global construction sector, transitioning the industry from the labor-intensive manual methodologies of the 20th century to the automated precision of the Industry 4.0 era. As demonstrated in this review, the technology has successfully graduated from the theoretical limitations of William Urschel's 1939 prototypes to become a viable commercial reality. In the Indian context, this operational maturity is evidenced by the successful execution of complex infrastructure projects, ranging from the rapid deployment of affordable housing by Tvasta Manufacturing Solutions to the strategic construction of high-altitude defense bunkers by the Indian Army in Leh. These case studies validate 3DCP not merely as a novelty, but as a robust solution capable of operating in diverse and extreme environments where traditional logistics are unfeasible.

However, the widespread mainstream adoption of 3DCP is currently constrained by inherent material and structural challenges that distinguish it from monolithic cast-in-situ concrete. The primary engineering hurdle remains the anisotropy of printed structures, specifically the "cold joint" phenomenon at the inter-layer interface. As highlighted in this paper, the time-lapse between deposition layers results in 11–14% higher porosity and a consequent 22–30% reduction in bond shear strength. This structural deficiency limits the current applicability of the technology to low-rise structures and necessitates the development of specialized chemical admixtures and reinforcement strategies—such as post-installed grouting or fiber integration—to ensure sufficient ductility and resistance to lateral seismic loads.

Ultimately, the future trajectory of 3D Concrete Printing in India depends less on hardware innovation and more on regulatory standardization. For the technology to become a primary enabler of the Pradhan Mantri Awas Yojana (PMAY-Urban), the formulation of comprehensive Indian Standard (IS) codes is imperative. The establishment of standardized guidelines for testing, design, and quality control will legitimize printed structures for government tenders and insurance purposes. If these regulatory frameworks are established, 3DCP holds the transformative potential to bridge India's housing deficit [3], delivering sustainable, disaster-resilient infrastructure at the speed and scale required for a rapidly urbanizing nation.

References :

[1] R. Shaw, K. K. Maurya, and D. Maity, "3D Concrete Printing: A Road Map for future of Automated Construction in India," Journal of The Institution of Engineers: Series A, vol. 102, no. 4, pp. 1-10, 2021.

[2] A. V. Rahul, M. Santhanam, H. Meena, and Z. Ghani, "Mechanical characterization of 3D printable concrete," Construction and Building Materials, vol. 227, p. 116710, 2019.

[3] B. Munshi, "Print-to-Home: 3D Construction Printing for Affordable Housing in India," ResearchGate Technical Report, 2025.

[4] W. E. Urschel, "Wall Building Machine," U.S. Patent 2 331 504, 1939.

[5] Tata Indian Institute of Skills (TATA IIS), "Fundamentals of 3D Printing and Additive Manufacturing: Process Parameters and Design Guidelines," Internal Training Module, Mumbai, 2025.

[6] B. Khoshnevis, "Automated construction by contour crafting—related robotics and information technologies," Automation in Construction, vol. 13, no. 1, pp. 5-19, 2004.

[7] Simpliforge Creations, "Construction of 3D Printed Military Bunkers in Leh at 11,000 ft," Press Release and Technical Overview, 2023

[8] ASTM International, "Standard Terminology for Additive Manufacturing Technologies," ASTM F2792-12a, West Conshohocken, PA, 2012.

[9] Sovetova, M., et al. (2024). Thermal and energy efficiency in 3D-printed Buildings. Energy and Buildings, Elsevier.

[10] Singh, N., Colangelo, F., & Farina, I. (2023). Sustainable non-conventional concrete 3D printing—a review. Sustainability, 15(13), 10121.