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A Review on 3D Printing Technology in Civil Engineering and Construction Industry

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ABSTRACT

Additive Manufacturing (AM), also known as 3D printing, is bringing major changes to the global civil engineering and construction industry. This review paper presents a detailed study of 3D Concrete Printing (3DCP) technology, focusing on its working principles, developments in material science, and real world applications. The study examines important printing methods such as Contour Crafting, D Shape, and extrusion based Concrete Printing, and explains their working mechanisms and material requirements. Material science plays an important role in the success of this technology. This includes studying the rheological properties of concrete mixtures, the use of supplementary cementitious materials (SCMs), and the development of high performance binders suitable for printing. The paper also discusses the major advantages of 3D concrete printing, such as lower construction cost, faster construction time, and improved environmental sustainability. At the same time, several technical challenges still exist. These include problems related to weak interlayer bonding, the lack of standard reinforcement techniques, and the absence of clear global construction standards and regulations for 3D printed structures. These recommendations aim to help transform 3D Concrete Printing from experimental research projects into a widely used technology in modern construction.

Keyword: Additive Manufacturing, 3D printing, SCMs, D Shape.

1. INTRODUCTION

The construction industry has historically been characterized by intensive labor, significant material waste, and relatively low productivity growth compared to other modern industrial sectors [4]. Conventional concrete construction relies heavily on formwork, which accounts for approximately 50% to 60% of the total concrete construction cost and represents a major source of waste [2], [17]. In response to these challenges, Additive Manufacturing (AM) has emerged as a disruptive technology capable of automating the construction process, enabling the fabrication of complex geometries without the need for traditional molds [14], [30]. 3D Concrete Printing (3DCP) involves the layer by layer deposition of cementitious materials guided by computer aided design (CAD) models. This technology offers the potential to revolutionize civil engineering by reducing labor requirements, minimizing environmental impact, and providing unprecedented architectural freedom [4], [11]. Early developments in the 1990s, such as the pioneering work on Contour Crafting by Khoshnevis [24], laid the foundation for modern construction scale AM. Since then, numerous research groups and commercial entities have developed diverse printing systems, ranging from large scale gantry robots to 6 axis robotic arms [19], [20]. The integration of 3D printing in construction is not merely a change in fabrication method but a fundamental shift in the design to production workflow [35]. Recent literature highlights the convergence of 3DCP with Building Information Modeling (BIM) and Artificial Intelligence (AI) to optimize material distribution and structural performance [7], [42]. However, despite the rapid advancement of printing hardware, several technical hurdles remain, particularly concerning the structural integrity of printed components, the development of standardized reinforcement methods, and the establishment of comprehensive building codes [14], [20]. This paper synthesizes current research from 25 authentic journal papers to provide a detailed overview of the current state and future prospects of 3D printing in the construction industry.

2. TECHNOLOGICAL OVERVIEW

The landscape of 3D printing in construction is dominated by three primary technological approaches: Contour

Crafting (CC), D Shape, and extrusion based Concrete Printing (CP). Each method employs distinct mechanics for material deposition and solidification.

2.1 Contour Crafting

Developed by Dr. Behrokh Khoshnevis at the University of Southern California, Contour Crafting is one of the most recognized large scale 3D printing technologies [17], [24]. The process utilizes a gantry based system to extrude cementitious paste through a nozzle. A distinguishing feature of CC is the use of computer controlled trowels or spatulas attached to the nozzle, which smooth the surfaces of the extruded layers to create high quality finishes [10], [19]. Contour Crafting typically follows a hybrid approach where the exterior "rims" of a structure are printed first to form a permanent shutter, which can then be backfilled with conventional concrete or reinforcement [10], [16]. This method achieves superior surface accuracy compared to simple extrusion but is often limited to vertical extrusion and may create fragile points at the interface between the printed mold and the infill material [16], [20].

2.2 D Shape Technology

Invented by Enrico Dini, D Shape technology operates on the principle of binder jetting or selective powder deposition [14], [19]. Unlike extrusion based methods, D Shape utilizes a large scale powder bed. A mixture of sand, stone powder, and sometimes fibers is spread in thin layers, and a chlorine based or epoxy resin based binder is selectively injected through a printer head containing thousands of nozzles [11], [20]. The D Shape process is particularly effective for off site prefabrication of complex, non standard geometric elements that would be difficult to achieve with extrusion [8]. While it offers high compressive strengths (reportedly up to 240 MPa in some configurations [16]), the process is relatively slow and requires the removal of massive amounts of unused powder after printing [20].

Fig. 1 – D shape second generation 3D Printer

2.3 Extrusion Based Concrete Printing

Often referred to simply as 3D Concrete Printing (3DCP), this category encompasses systems developed by institutions like Loughborough University and Eindhoven University of Technology (TU/e) [2], [18]. These systems typically use a 3 axis gantry or a 6 axis robotic arm to extrude a continuous filament of high performance mortar or concrete [8], [14].

Unlike Contour Crafting, standard CP systems often do not use trowels, resulting in a "stair casing" effect on the printed surface [9], [20]. However, CP offers greater three dimensional freedom and better control over complex geometries [14]. Innovative variations include XtreeE’s system, which utilizes a 6 axis robotic arm to print integrated Ultra High Performance Concrete (UHPC) formworks for structural elements [8].

3. MATERIAL SCIENCE IN 3DCP

The success of 3DCP depends heavily on the development of specialized cementitious mixes that satisfy the conflicting requirements of pumpability, extrudability, and buildability. Unlike traditional casting, where concrete is poured into a mold and vibrated for compaction, 3DCP requires the material to flow through a complex delivery system and then maintain its shape immediately upon extrusion [2], [14].

3.1 Mix Composition and Binders

Printable concrete mixes differ significantly from conventional concrete, typically utilizing higher binder contents and finer aggregates to ensure smooth extrusion [2]. Common binders include Ordinary Portland Cement (OPC), often supplemented with SCMs such as fly ash, silica fume, and ground granulated blast furnace slag (GGBS) to improve rheology and reduce CO2 emissions [14], [20].

3.1.1 Binders and Supplementary Cementitious Materials

In the mix designs reported by Loughborough University, the binder consisted of a mix of CEM I cement, fly ash, and undensified silica fume [2]. The silica fume, used at approximately 10% by mass, serves to fill voids between cement particles, improving packing density and increasing 28 day compressive strength by 8 20% [19]. Other researchers have investigated the use of rapid hardening Portland cement (RHPC) and calcium aluminates (CAC) to facilitate faster setting times, though CAC must be used carefully as it may cause long term strength decreases [9], [19].

3.1.2 Aggregates and Fillers

Aggregates are generally limited to a maximum particle size of 2 mm to prevent clogging in the delivery system and nozzle [17], [20]. For instance, the TU/e 3DCP facility utilizes siliceous aggregate with an optimized particle size distribution and a maximum size of 1 mm, combined with limestone filler to enhance pumping [2]. The exclusion of coarse aggregates is a significant departure from traditional concrete, leading to mixes that are essentially high performance mortars.

3.1.3 Chemical Admixtures

Specialized additives are essential for modulating the material's behavior:

- **Superplasticizers (PCE based):** These are used to achieve low water binder ratios (as low as 0.26) while maintaining the high flowability required for pumping [14], [20].
- **Retarders:** Citric acid, tartaric acid, and sodium gluconate are common retarders used to maintain the "open time" or printability window, preventing premature hydration within the printer's hopper or hose [14], [19].
- **Accelerators:** Alkali free or sulfate based accelerators are often injected at the nozzle to ensure rapid setting and yield stress development once the material is deposited, which is critical for buildability [19], [20].
- **Viscosity Modifying Agents (VMAs):** Methyl cellulose based VMAs improve the cohesiveness of the mix, preventing segregation and ensuring dimensional stability of the extruded filament [14], [19].

3.2 Fresh Properties: Printability and Buildability

The rheological behavior of fresh concrete is the most critical factor in 3DCP. Researchers have identified four primary fresh properties that define the "printability" of a mix:

1. Pumpability: The ability of the material in a wet mixed condition to pass through the delivery system (hoses and pumps) at the desired speed and pressure without segregation or blockage [14].
2. Extrudability: The ability to form a continuous, stable filament through the nozzle without tearing or excessive swelling [14], [20]. Extrudability is often measured by the material's ability to be transported through a nozzle for continuous filament extrusion without clogging [17].
3. Buildability: Defined as the ability of the printed layers to resist deformation and collapse under the weight of subsequent layers [14], [19]. This requires the material to have sufficient initial yield strength and a rapid rate of strength gain, often referred to as "green strength" [9], [20].
4. Open Time (Printability Window): The duration during which the material maintains consistent pumpability and extrudability. This is typically measured by monitoring the development of shear strength over time [14], [20].

Achieving high buildability often involves a trade off with pumpability. Thixotropic mixes, which exhibit low viscosity under shear (during pumping) and high viscosity at rest (after extrusion), are ideal for 3DCP [2], [19].

3.3 Hardened Properties and Anisotropy

Hardened 3D printed concrete often exhibits anisotropic mechanical behavior due to the layer by layer manufacturing process [9], [14]. Mechanical testing has shown that compressive and flexural strengths vary significantly depending on the direction of loading relative to the print path [2], [19].

3.3.1 Compressive and Flexural Strength

In optimized high performance mixes, 3D printed specimens have achieved 28 day compressive strengths of up to 110 MPa and flexural strengths between 6 MPa and 17 MPa [14], [20]. However, these properties are direction dependent. For example, flexural bending tests on sample beams have shown a 10 15% difference in strength depending on whether the loading is parallel or perpendicular to the layer interfaces [2].

3.3.2 Interlayer Bond Strength

The bond strength at the layer interfaces (often termed the "cold joint" problem) is typically the weakest link in a 3D printed structure. Studies have reported that interface bond strength can be as low as 22% to 30% of the bulk material's strength [14]. This reduction is attributed to several factors, including:

- Surface Drying: Evaporation of water from the surface of a layer before the next layer is deposited [14], [19].
- Interfacial Porosity: Entrapped air and poor compaction at the interface [14].
- Delay Time: Longer time gaps between layers generally lead to lower bond strengths [20].

3.3.3 Innovative Material Developments

Recent studies have also explored the use of graphene oxide coated fly ash to reinforce the dynamic tensile behavior of cementitious composites, offering a potential path to improving the ductility and impact resistance of printed structures [31]. Other innovative approaches include the use of waste paper sludge as a pozzolanic binder and the integration of recycled plastic based road slabs [10], [14].

4. KEY BENEFITS

The adoption of 3DCP is driven by its potential to address the systemic inefficiencies of the traditional construction industry.

4.1 Economic Efficiency and Cost Reduction

The primary economic benefit of 3DCP is the elimination of formwork, which can reduce total construction costs by 35% to 60% [2], [20]. A comparative study by Khajavi et al. (2021) demonstrated that on site 3DCP using a robotic arm was significantly more cost effective than conventional methods, especially for geometrically complex and round designs, where traditional formwork costs would be prohibitive [4].

4.2 Time Efficiency and Productivity

3DCP enables rapid construction schedules. Some systems can print a single story house in as little as 24 hours [4], [19]. The technology allows for 24/7 operation and reduces the need for extensive on site labor and assembly work [17]. Modular construction approaches utilizing 3D printing have been shown to reduce project times by up to 71% compared to traditional methods [10].

4.3 Environmental Sustainability

Sustainability is a core advantage of AM in construction. Key environmental benefits include:

- Waste Reduction: Digital control ensures that material is only placed where structurally necessary, virtually eliminating construction waste [2], [17].
- Material Optimization: Computational frameworks like topology optimization allow for the creation of lightweight structures with reduced material consumption [8].
- Circular Economy: 3DCP can integrate construction and demolition waste as aggregates. Companies like WinSun (China) have claimed to use significant amounts of recycled waste in their printable mixes [2], [9].
- Reduced CO2 Footprint: By replacing OPC with SCMs like calcined clay and limestone, CO2 emissions can be reduced by 15% to 30% [2], [20].

5. TECHNICAL AND STRUCTURAL CHALLENGES

Despite the benefits, 3DCP faces substantial technical and structural hurdles that must be overcome for widespread adoption. These challenges range from the fundamental mechanics of reinforcement to the logistics of on site implementation and global standardization.

5.1 Reinforcement Strategies

Integrating reinforcement into the automated 3DCP process remains the most significant technical hurdle. Conventional steel reinforcement (rebar) relies on being placed within formwork before concrete is poured, a method that is inherently incompatible with the layer by layer deposition of 3DCP [17], [20]. Current strategies being researched and implemented include:

- **Manual Insertion:** Hand placing tie rods or bars between layers. This approach is labor intensive and limits the automation potential of 3DCP [19].
- **Fiber Reinforcement:** Adding polypropylene, carbon, or glass fibers directly to the concrete mix. While fibers can improve ductility and help control shrinkage and cracking, their inclusion can significantly affect the rheology of the fresh concrete, leading to increased viscosity, nozzle clogging, and uneven fiber distribution [2], [20]. Some experiments have shown flexural strengths of up to 120 MPa when carbon fibers are oriented in the stress direction [20].
- **Mesh Moulding:** Utilizing a 3D printed mesh structure that acts as both formwork and reinforcement. The mesh is subsequently filled with high performance concrete [2], [19].

- **Cable and Filament Entrainment:** Embedding steel, polymer, or carbon fiber cables directly into the filament as it is extruded from the nozzle. While this method shows promise for improving post crack

  failure strength and deformation capacity, it has not yet demonstrated significant improvements in interlayer bond strength [2], [20].
- **Integrated Formwork (Lost Formwork):** Printing a thin walled structure that serves as a permanent mold for conventional concrete and rebar. This strategy allows the use of current building regulations for reinforced concrete but does not fully exploit the material efficiency potential of 3DCP [8], [20].

5.2 Interlayer Bonding and Interface Quality

The "cold joint" phenomenon between successive layers is a major structural concern in 3DCP. If the time interval between layers is too long, the surface of the bottom layer may dry or carbonize, leading to poor adhesion and increased porosity at the interface [14], [19]. This results in weak zones that are highly susceptible to shear failure and may compromise the durability of the structure over time [2], [20]. To mitigate this, researchers have explored methods such as:

- **Accelerated Curing:** Using chemical or thermal techniques to achieve precise curing speeds that promote bonding [17].
- **Surface Indentation:** Indenting the surface of a layer during printing to promote mechanical interlocking between layers [16].
- **Nozzle Pressure:** Applying pressure to the extruded filament to improve compaction and interface adhesion [2].

5.3 Geometric and Operational Challenges

3DCP systems must overcome several operational limitations:

- Buildability and Deformation: The relatively low stiffness and strength of "green" (freshly printed) filaments limit the height to which layers can be stacked before the lower layers deform or collapse [2], [14]. This is particularly challenging for curved structures, such as arches, vaults, and domes, which may require temporary supports until the concrete sets [2], [20].
- Stair casing Effect: The layered nature of 3DCP inherently creates a stepped surface, which can negatively impact the aesthetic finish and structural quality of the printed component [9], [20].
- Machine Mobility and Scale: Large scale gantry based printers are difficult to transport and require a level ground surface [17], while robotic arm systems have a limited reach, necessitating multiple setups for larger structures [4].

5.4 Standardization and Regulatory Barriers

The absence of global standards and building codes for 3D printed concrete is a major impediment to its commercial adoption [14], [17]. Regulatory authorities currently lack the legal framework to certify 3D printed structures, often requiring expensive and time consuming project specific testing [4], [8]. The development of standardized test methods for assessing the fresh and hardened properties of printed concrete is essential for ensuring structural safety and reliability [2], [10]. This includes creating new draft standards that account for the unique anisotropic nature and interlayer bonding issues of 3DCP [4], [14].

5.5 Professional and Economic Challenges

The transition from conventional to 3DCP based construction requires a shift in the skills of the construction workforce [17]. There is a significant need for trained operators, software engineers, and digital designers [14]. Furthermore, the initial cost of 3D printing equipment and software remains an obstacle, particularly for small to medium sized construction companies [14], [17]. However, as the technology matures and adoption increases, these costs are expected to decrease [17].

6. CASE STUDIES AND REAL WORLD APPLICATIONS

The rapid development of 3DCP technology is evidenced by its successful implementation in diverse large scale projects around the world. These cases demonstrate the feasibility of 3D printing for various construction applications, ranging from residential buildings to architectural features and civil infrastructure.

6.1 Residential and Building Projects

- WinSun (China): A pioneer in the field, WinSun achieved significant milestones in 2014 by printing ten small houses in a single day in Shanghai [19]. They used a massive gantry printer (150 m × 10 m × 6.6 m) and a mix reportedly containing recycled construction waste. Subsequently, in early 2015, they constructed a five story apartment building and a luxury 1,100 m² villa in Suzhou [19].

- Apis Cor (Russia): This company is known for its mobile circular printer, which was used to print a 38 m² house in Russia in 24 hours under freezing conditions [11]. The house featured fiberglass reinforcement between printed layers and polyurethane based insulation [11].

Fig 2 Apis cor 3D printed building

- ICON (USA): In collaboration with New Story, ICON printed a small house in Austin, Texas, using their "Vulcan" printer and a proprietary concrete mix called "Lavacrete". Their project, "House Zero," demonstrates high end architectural design achieved through 3DCP [11].
- Larsen & Toubro (India): L&T Construction fabricated a two story building (65 m² floor area) at their Kanchipuram facility. This project was significant for its use of locally sourced materials and a custom developed 3D printable concrete mix [14].

6.2 Civil Infrastructure and Architectural Features

- Aix en Provence Pillar (France): This 4 meter high freeform pillar was designed to support a concrete awning at a school [8]. It was constructed using a 3D printed Ultra High Performance Concrete (UHPC) formwork that was filled with structural UHPC [8]. The project achieved a 62.5% reduction in total price compared to traditional manufacturing by eliminating the need for complex, custom molds [8].
- Dubai Office of the Future (UAE): In 2016, WinSun printed a 250 m² office building in Dubai using a gantry printer [2], [11]. This project is a prominent example of 3DCP used for functional, large scale commercial structures [2].
- Curvilinear Pavilion (Thailand): A self supporting curvilinear pavilion was designed and constructed using 3DCP to demonstrate the architectural freedom offered by the technology for non standard geometric forms [15].
- 3D Printed Pedestrian Bridges: Researchers in Amsterdam and other locations have successfully printed structural bridges, including a steel pedestrian bridge using a 6 axis robotic system and concrete bridges that utilize optimized material distribution to reduce weight [9], [19].

6.3 Specialized and Future Applications

- Emergency Housing: The speed and low cost of 3DCP make it an ideal candidate for rapid deployment in disaster stricken areas [17].
- Extraterrestrial Construction: Technologies like Contour Crafting have been proposed for constructing habitats on the Moon and Mars using local regolith materials [17], [68].
- Highways Civil Structures: Feasibility studies suggest that 3DCP could be used for retaining walls, foundations, and bridge components in highway infrastructure [10].

7. ECONOMIC AND ENVIRONMENTAL IMPACT ANALYSIS

The economic and environmental viability of 3DCP is complex and multifaceted. Current research utilizes Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) to evaluate the technology against traditional construction methods [5], [20].

7.1 Economic Analysis

The potential for cost reduction is a major driver of 3DCP. Studies indicate that 3DCP can save up to 40% to 60% of the total budget of a concrete project [2], [19]. This is primarily achieved through:

- Elimination of Formwork: Formwork and scaffolding can account for up to 50% of the total concrete construction cost [2], [10]. 3DCP completely eliminates this expense.
- Labor Savings: Automated printing significantly reduces the need for manual labor on site [4], [17]. A feasibility study of the Contour Crafting process found that it could achieve higher daily concrete outputs for a lower unit cost with only one foreman, compared to traditional methods [10].

- Material Efficiency: 3DCP allows for precise material deposition, minimizing waste and using only the required amount for structural integrity [8], [17].

However, the cost of the initial investment in 3D printing equipment (gantry systems, robotic arms), software, and specialized maintenance can be significant [14], [17]. For simple, mold friendly designs like rectangular houses, the cost advantage of 3DCP can be eroded, making traditional construction more competitive in some contexts [4].

7.2 Environmental Impact

Environmental sustainability is a core benefit of AM in construction. The technology is described as a "green and clean" construction process [19].

- Reduced CO2 Emissions: By substituting Ordinary Portland Cement with Supplementary Cementitious Materials (SCMs) like fly ash, calcined clay, and limestone, 3DCP can reduce CO2 emissions by up to 30% [2], [20]. The use of Limestone Calcined Clay Cement (LC3) is highlighted as a particularly promising option for lower CO2 emissions [20].
- Waste Management: 3DCP produces almost zero waste on site [17]. Furthermore, the ability to incorporate construction and demolition waste (recycled aggregates) into the printable mix reduces the demand for natural resources and lessens the burden on landfills [2], [9].
- Energy Savings: Optimized material distribution leads to lighter structures, which requires less energy for material transport and placement [8]. Functional structural features, such as porous walls for natural cooling (e.g., "Cool Brick") or sound dampening surfaces, can also reduce the energy demands of finished buildings [9].

Despite these benefits, 3DCP mixes often require higher cement contents to achieve the necessary fresh properties, which can negatively impact their initial CO2 footprint [2], [20]. Therefore, the continued development of low CO2 binders and the adoption of comprehensive LCAs for all construction stages are critical for realizing the full environmental potential of 3DCP [5], [20].

8. FUTURE RESEARCH DIRECTIONS

The future of 3DCP lies in several key areas:

- Advanced Reinforcement: Developing automated systems for placing continuous reinforcement (e.g., steel or fiber) during the printing process [14], [20].
- Multi material Printing: Exploring the use of functionally graded materials and non conventional materials like earth or bio based additives [24], [29].
- Standardization: Establishing international codes for material testing, design procedures, and structural safety [17], [20].
- AI and Digital Twins: Utilizing real time sensing and AI driven feedback loops to monitor printing quality and adjust parameters dynamically [27], [30].
- Durability and Lifecycle: Conducting long term studies on the durability of 3D printed structures in various environmental conditions [2], [5].
- Extraterrestrial Construction: Research on extraterrestrial building materials, such as sulfur based Martian regolith, for space exploration [28].
- Additive Oriented Design: Transitioning toward design approaches specifically tailored for the unique constraints and opportunities of additive manufacturing [26].

9. CONCLUSION

3D printing technology represents a transformative opportunity for the civil engineering and construction industry. By automating the fabrication of concrete structures, 3DCP offers a pathway to more efficient, sustainable, and architecturally expressive construction. Significant progress has been made in understanding the rheological requirements and technological methodologies of the process. However, the transition from experimental prototypes to standard industry practice requires overcoming critical structural challenges, primarily the integration of reinforcement and the assurance of interlayer bond quality. As research continues to address these technical and regulatory gaps, 3D Concrete Printing is poised to become a cornerstone of the future built environment.

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