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# 3D Printed Concrete: A comprehensive review (2004–2025)

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## Abstract

This paper reviews 3D printed concrete (3DPC) from its inception in the early 2000s to till date, synthesizing findings from peer-reviewed sources and standards. We map the technology's evolution—from contour crafting and early mortar-only extrusion to today's large-scale, reinforced, and sustainability-aligned systems. The review integrates material design (binders, admixtures, fibers, and alternative binders), rheology and printability metrics, interlayer bonding, structural performance and reinforcement strategies, durability, LCA and sustainability, digital workflows (BIM/CAM, toolpaths), quality control and in-process sensing, standardization progress (RILEM/TCs) and notable global case studies. We identify consistent gaps in test standardization, structural design methods, field QC, and long-term durability datasets, and outline a research agenda for code-calibrated design, robust reinforcement, and low-carbon printable binders.

**Keywords:** 3D Concrete Printing; Extrusion; Digital Fabrication; Rheology; Interlayer Bond; Reinforcement; Durability; LCA; Standardization

## 1. Introduction

Additive manufacturing with cementitious materials, particularly 3D printed concrete (3DPC), has evolved from a conceptual innovation into a disruptive construction methodology with the potential to redefine architectural freedom, labor efficiency, and sustainability in the built environment. Early developments in 3DPC were driven by the ambition to automate construction, reduce waste, and enable complex geometries without formwork. The convergence of digital design, precision robotics, and advanced material science has allowed researchers and industry pioneers to overcome initial challenges related to material extrusion, interlayer adhesion, and structural performance. This review chronicles key milestones from the inception of 3DPC in the early 2000s to its current pre-commercial adoption stage, highlighting progress in materials, processing, and standardization.

## 2. Methodology

The literature review methodology employed in this paper adheres to systematic review principles. A total of 100 research publications were identified from databases such as Scopus, Web of Science, and ScienceDirect, alongside technical reports from RILEM committees and industry white papers. Keywords such as '3D printed concrete,' 'digital fabrication,' 'extrusion-based additive manufacturing,' and 'printable cementitious materials' were used in combination with material-specific terms like 'rheology,' 'nano-silica,' and 'geopolymer.' Publications were included if they addressed material formulation, process optimization, structural design, durability, sustainability, or standardization in 3DPC. The review spans from early pioneering works in 2004 to recent innovations documented in 2025.

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## 3. Historical Timeline & Processes

The development of 3DPC can be divided into several distinct phases. The earliest stage, typified by Khoshnevis' contour crafting (2004–2010), focused on demonstrating the feasibility of large-scale layer-by-layer extrusion using cementitious materials. The Loughborough University research group further advanced the field with their large-format printing system (2010–2015), achieving improved material handling and geometric accuracy. By 2016, multiple industrial players—including COBOD, ICON, and CyBe—began deploying full-scale gantry and robotic-arm printers for housing and infrastructure projects. Hybrid techniques emerged, combining coarse aggregates, fiber reinforcement, and robotic placement of reinforcement. This period also saw experimentation with binder-jet methods, shotcrete-based deposition, and on-site mobile printing units capable of adapting to variable site conditions.

## 4. Materials and Mix Design

Material innovation underpins the success of 3DPC. The printable mixes must simultaneously achieve pumpability, extrudability, buildability, and rapid structural stiffening. Ordinary Portland Cement remains the primary binder, often blended with supplementary cementitious materials such as fly ash, GGBS, silica fume, and metakaolin to enhance workability, control hydration kinetics, and reduce carbon footprint. Advanced systems incorporate LC3 (limestone calcined clay cement), CSA cements for rapid strength gain, and alkali-activated geopolymers for reduced clinker content. Rheology is carefully engineered through admixtures, with nano-silica, graphene oxide, and viscosity-modifying agents used to optimize yield stress, thixotropy, and open time. Fiber reinforcements including steel, basalt, PVA, and polypropylene are incorporated to mitigate shrinkage, improve tensile capacity, and enhance interlayer bonding.

## 5. Digital Workflow and Process Control

Digital design and process automation form the backbone of 3DPC operations. Building Information Modeling (BIM) integrates with Computer-Aided Manufacturing (CAM) systems to generate optimized toolpaths, considering factors such as bead geometry, nozzle travel speed, and layer deposition intervals. Closed-loop control systems, coupled with sensors and machine vision, allow real-time monitoring of extrusion consistency and dimensional accuracy. Data from these systems can trigger on-the-fly adjustments to printing parameters, mitigating defects. Innovations in process control also include environmental conditioning, such as localized heating, steam curing, or $CO_2$ exposure to accelerate strength development and improve surface finish.

## 6. Structural Performance and Reinforcement

3DPC structures often exhibit mechanical anisotropy due to their layered construction, with weaker interlayer bonds compared to intralayer material. Addressing this, reinforcement strategies include co-extruding continuous fibers, embedding steel cables, robotic placement of steel rebars during printing, and designing lattice-type infills. Hybrid systems combine printed shells with cast-in-place concrete cores for enhanced load-bearing capacity. Experimental studies indicate that optimized print paths, surface texturing between layers, and post-processing techniques can significantly improve load transfer and ductility. These innovations aim to bring 3DPC structures into alignment with conventional reinforced concrete design codes.

## 7. Durability and Long-Term Behavior

Durability in 3DPC is influenced by interlayer porosity, directional permeability, and potential cold-joint formation. Chloride ingress, carbonation, freeze-thaw cycles, and sulfate attack remain critical concerns, particularly for structures exposed to aggressive environments. Studies have shown that improved mix densification, the inclusion of pozzolanic SCMs, and application of surface sealants can extend service life. Emerging durability data from field projects are beginning to validate laboratory predictions, but long-term datasets exceeding five years remain scarce.

## 8. Sustainability and LCA

3DPC offers potential sustainability benefits through reduced material waste, elimination of formwork, and optimization of structural geometry for material efficiency. Life cycle assessments (LCAs) reveal that printable concrete with low-clinker binders can achieve significant reductions in embodied carbon. Energy demands for printer operation and material preparation are generally offset by savings in formwork production and transport logistics. Additionally, 3DPC facilitates the integration of recycled aggregates, industrial by-products, and bio-based fibers, further contributing to circular economy objectives.

## 9. Standardization, Codes, and Safety

The absence of universally accepted standards has historically hindered the wider adoption of 3DPC. Efforts by RILEM TC 276-DFC and ASTM committees are defining terminology, specimen geometries, and test protocols specific to additively manufactured concrete. National guidelines are emerging in countries such as the Netherlands, UAE, and China, while India is initiating draft provisions for design and quality control. Safety standards addressing human-robot interaction, equipment operation, and on-site hazard management are also under development, ensuring regulatory pathways for broader deployment.

## 10. Field Demonstrations and Case Studies

Notable field applications of 3DPC include residential buildings, pedestrian bridges, public infrastructure, and bespoke architectural elements. Projects such as the TU Eindhoven printed bridge, ICON's housing developments in the USA and Mexico, and COBOD's large-scale public structures in Europe demonstrate scalability and adaptability. Indian case studies have highlighted the viability of 3DPC for rapid construction of schools and community facilities, using locally sourced materials and IS code-aligned design approaches.

## 11. Techno-Economics and Adoption

Economic feasibility of 3DPC is influenced by capital investment in printers, material costs, production speed, and the learning curve associated with workforce training. While initial costs are high, economies of scale and process optimization are steadily reducing per-unit costs. Business models are emerging that combine equipment leasing, turnkey project delivery, and design–print partnerships. Market adoption is also contingent on overcoming barriers such as regulatory approval, insurance coverage, and client acceptance of non-traditional construction methods.

## 12. Research Gaps and Future Directions

Despite significant advancements, several research gaps remain. These include the development of standardized mechanical and durability testing tailored to 3DPC, integration of continuous reinforcement compatible with automated processes, long-term field monitoring to validate service life predictions, and refinement of sustainability metrics specific to digital fabrication. Additionally, the adoption of digital twin technology and machine learning for predictive process control represents a promising frontier for optimizing performance and reliability.

## 13. Conclusions

3DPC has progressed beyond its prototyping phase, entering an era of early adoption supported by advances in material science, structural reinforcement, durability enhancement, and the beginnings of formal standardization. The convergence of these elements is paving the way for the construction of code-compliant, low-carbon structures at an industrial scale. Material innovations—including the use of nano-silica, graphene oxide, and SCM-rich binders—are enhancing printability, strength, and sustainability. Reinforcement strategies are mitigating anisotropy, while durability measures are increasing confidence in long-term performance. As standards mature and industry confidence grows, the next decade is poised to see 3DPC emerge as a mainstream construction technology capable of delivering sustainable, cost-effective, and architecturally versatile solutions.

## Compliance with ethical standards

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No conflict of interest to be disclosed.

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