RESEARCH PAPER

Influence of Circular and Rectangular Geometries on the Mechanical and Buildability Performance of 3D Printed Concrete Elements

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Abstract
Three-dimensional (3D) concrete printing has emerged as an innovative and sustainable construction technology due to its capability for automated fabrication, reduced material wastage, and enhanced geometrical flexibility. Among various influencing parameters, the geometrical configuration of printed elements plays a significant role in determining their mechanical performance and buildability characteristics. This study investigates the influence of circular and rectangular geometries on the performance of extrusion-based 3D printed concrete elements. Experimental investigations were conducted to evaluate printability, dimensional stability, layer deformation and buildability of both geometrical configurations under identical printing conditions and material compositions. The printed specimens were assessed for shape retention, interlayer integrity, failure behaviour and structural efficiency. Results indicated that circular geometries exhibited improved stress distribution and enhanced dimensional stability compared to rectangular specimens, whereas rectangular elements demonstrated higher susceptibility to edge deformation and stress concentration. Furthermore, the study highlights the importance of geometrical optimization in improving the structural and constructional efficiency of 3D printed concrete systems. The findings of this research provide valuable insights for the design and development of sustainable and mechanically efficient 3D printed concrete structures for future construction applications.
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Introduction

The construction industry, often described as the worlds oldest and largest industry is on the cusp of a transformational revolution driven by the rapid evolution of 3D printing technology. Traditionally considered a low-tech sector, the construction market is set to reach a global market size of USD 14.6 trillion and is projected to reach a compound annual growth rate (CAGR) of 11.9% from 2023 to 2030. The global construction industry is increasingly adopting mobile robotic platforms to perform in-situ maintenance and repair of existing building components [1]. Integrating these 3D printing operations into construction supply chains alters traditional resource flows and requires precise simulation to improve productivity [2]. Accounting for approximately 35% of total global energy use and 38% of carbon dioxide emissions, the sector faces immense pressure to adopt more efficient, innovative and environmentally sustainable practices [1, 2]. Construction 3D Printing (C3DP) also known as additive construction has emerged as a ground-breaking technology poised to revolutionize traditional building methods. This computer-controlled process builds three-dimensional objects layer-by-layer through material deposition based on a digital model. This shift toward additive construction is effectively rewriting the industry's established conventions by introducing diverse wall patterns and structural configurations [3]. To successfully realize these forms advanced segmentation strategies and tool path designs are required to manage the strength requirements of complex concrete geometries [4]. Consequently, a systematic framework for material design is vital to ensure that 3D-printed structural components satisfy both architectural and structural standards [5]. This approach must balance structural performance with the need for environmental sustainability and energy saving [6]. The evolution of 3D construction printing (3DCP) from laboratory research to practical full-scale structural applications highlights its growing viability across the sector [7]. In these applications, the internal architecture of the printed components is a primary determinant of their final mechanical properties and durability [8]. Selecting appropriate materials remains crucial to managing the inherent anisotropy and mechanical variations seen in layered residential wall assemblies [9]. This digital approach not only accelerates construction timelines potentially saving over 60% of on-site time but also promotes a circular economy by utilizing local raw materials, recycled aggregates and agricultural waste. Innovation is extending into specialized fields such as the use of real-time admixture control for successful 3D

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printing in dynamic underwater environments [10]. Furthermore, the integration of Building Information Modelling (BIM) with additive manufacturing enhances the precision and energy efficiency of sustainable housing, 3DCP promises greater precision, sustainability and coordination throughout the building execution phase [11]. Establishing a seamless digital workflow from BIM models to printer tool paths is therefore essential for achieving automated industrialization [12]. Technological tools like machine learning are increasingly employed to optimize material ratios and predict the structural behaviour of printed concrete [13]. These digital methods facilitate the use of circular materials such as construction and demolition waste (CDW) in the development of sustainable geopolymer binders [14]. To ensure high-quality execution 3D scanning methodologies are becoming indispensable for verifying geometric accuracy and managing discrepancies in complex structural elements [15]. Additionally, the technology allows for intricate surface texturing through methods such as 3D-printing assisted flexible formwork for precast pavements [16]. Beyond terrestrial applications, novel printing schemes are being developed to construct habitats on the Moon with extremely low binder utilization [17]. A critical focus of current research is the comparative performance of geometric forms, specifically how circular and rectangular designs influence buildability and cost in housing construction [18]. Sustainability assessments indicate that 3D printing offers significant environmental benefits, particularly when building houses in remote areas [19]. As this transformative technology gains momentum, it is crucial to keep up with its constant progression. For that, review papers covering the latest advancements are in continuous demand [20]. The smart manufacturing capabilities of 3DCP provide remarkable shape variety allowing for the construction of sophisticated columns and free-form shells [21]. Low-carbon binder alternatives such as marine clay and limestone replacements are being investigated to further reduce the carbon intensity of these structures [22]. Recycled fine aggregates and powders from construction waste can also be optimized to improve the thixotropy and buildability of cementations mixtures [23]. Comprehensive literature reviews show recurring trends toward low-carbon developments and optimized supplementary cementations materials in the industry [24]. In regions like India, the effectiveness of 3D printing over conventional methods is already being demonstrated through significant reductions in time and labour [25]. Ultimately, as 3D printing technology continues to advance, it is poised to reshape the fundamental ways in which our built environment is designed and constructed [26]. The present research investigation has been carried out with the following primary objectives:

1. To study the working principles and construction methodology of extrusion-based 3D Concrete Printing technology.
2. To prepare printable cementations material using UltraTech Fixoblock block jointing mortar and polycarboxylate-based superplasticizer.
3. To investigate the rheological and printability characteristics of printable concrete material.
4. To conduct a comparative study between circular and rectangular shaped 3D printed concrete structures.
5. To assess how geometry influences printing time, material consumption, buildability, extrudability, layer stability, and structural performance of printed elements.
6. To identify the main defects and practical challenges encountered in extrusion-based 3D concrete printing.
7. To establish the geometry that offers the best combination of structural efficiency and cost-effectiveness for use in automated construction applications.

The scope of this work is restricted to extrusion-based 3D concrete printing, employing mortar-type printable materials. The study mainly compares circular and rectangular cross-sectional geometries under controlled, laboratory-scale printing conditions. Key process parameters such as nozzle diameter, layer height, printing speed, and material composition are held constant throughout the experimental program. The research focuses on printability characteristics (such as flow behaviour, shape retention, and layer adhesion) and on the structural behaviour of the printed members. The outcomes of this study may support the future optimisation of automated construction systems and inform geometry-driven design approaches in concrete additive manufacturing.

2. Materials and methodology

The performance of 3D printed concrete structures is highly dependent on the rheological and mechanical properties of the printable material. Unlike conventional concrete used in formwork casting, printable concrete must satisfy two contradictory requirements simultaneously. The material must be sufficiently fluid during pumping and extrusion while also possessing enough rigidity after deposition to support subsequent layers without deformation. Therefore, proper selection of materials and careful control of mixture proportions become essential for achieving successful printing operations.

2.1 Materials used in the study

The present research work utilized a mortar-based printable concrete mixture prepared using UltraTech Fixoblock block jointing mortar, phosrock polycarboxylate ether-based superplasticizer, quartz sand and potable water.

Table No 1: Material properties used in 3DPC

Parameter Category	Specification/ Requirement	Target Value/ Range	Test Method/ Standard	Purpose
Cement Type	Portland cement or blended cement grade	OPC Grade 43/53 OR PPC per IS 1489:2015	IS 269; IS 1489; ICC 1150-2026	Ensures consistent hydration and strength development
Maximum Aggregate Size	Fine aggregate only (no coarse aggregate)	≤2.36 mm (d50 ≈ 240 µm)	IS 383; ICC 1150-2026	Prevents nozzle blockage in extrusion-based 3DPC
Fine Aggregate Type	Quartz sand or graded sand	Sand-to-binder ratio: 1.2–2.0	IS 2386; ACI 211; ICC 1150-2026	Optimizes particle packing and dimensional stability
Superplasticizer Type	Polycarboxylate ether (PCE) based	Dosage: 0.5–2.0% by binder weight; 30% SC	BS EN 450; ICC 1150-2026	Reduces water while maintaining flowability
Water-to-Binder Ratio	Controlled water content for strength/buildability	0.28–0.35 (max: 0.45 per codal)	ASTM C230; IS 10262; ICC 1150	Low w/b ensures higher strength, reduced porosity, better buildability
Water Quality	Potable water, free from impurities	pH: 6.0–7.5; Cl^- < 200 ppm	IS 3025; ICC 1150-2026	Prevents adverse chemical reactions affecting durability
Minimum Cement Content	For strength development	≥320 kg/m³	IS 3370; ICC 1150-2026	Ensures adequate strength and durability
Maximum Cement Content	To control shrinkage	≤400 kg/m³	IS 3370; ICC 1150-2026	Prevents shrinkage cracks per codal provisions
Fibre Type (Optional)	Polypropylene or steel fibber's for crack control	0.5–1.5% volume; AC 32/AC 208 compliant	IS 15950; AC 32; AC 208; ICC 1150	Improves tensile strength, crack resistance, and ductility
Batching Consistency	Material proportion uniformity	Batch-to-batch variation ≤5%	ISO 9001; ICC 1150-2026	Ensures reproducible print quality across sessions
Mixing Time	Homogeneity of mixture	5–7 minutes (high-shear mixing)	ICC 1150-2026; Process specification	Achieves uniform printable mixture
Dry Mixing Time	Particle distribution before wet mixing	2–3 minutes	ICC 1150-2026	Prevents segregation and ensures homogeneity

2.1.1 UltraTech Fixoblock Block Jointing Mortar
UltraTech Fixoblock block jointing mortar was selected as the primary cementations material for this study owing to its fine particle size distribution, strong bonding characteristics, and enhanced workability. In contrast to conventional concrete mixes that include coarse aggregates, mortar-based systems are generally favoured in extrusion-based 3D printing, as larger aggregate particles tend to block the nozzle and interrupt the continuity of extrusion. The use of block jointing mortar offers several benefits in additive manufacturing applications. The material shows improved adhesion to underlying layers, smooth extrusion behavior, and stronger interlayer bonding. The absence of coarse aggregates further aids in sustaining a continuous and stable filament throughout the printing process. The relatively fine particle grading also promotes a smoother surface finish and better dimensional accuracy of the printed layers. Since UltraTech Fixoblock is manufactured under controlled factory conditions, it delivers consistent composition and quality, which is crucial for reliable performance in automated construction processes.

Fig 1: UltraTech Fixoblock block jointing mortar bag (40kg)

2.1.2 Quartz Sand

Fine quartz sand having particle size less than 2 mm was incorporated into the printable mixture to improve particle packing density and enhance dimensional stability. Quartz sand also contributes toward reducing shrinkage and improving the mechanical performance of the printed layers. The use of fine aggregate in controlled proportions improves extrusion continuity while maintaining adequate buildability of the deposited layers.

2.1.3 Superplasticizer

A phosrock polycarboxylate ether-based superplasticizer was utilized to improve the flowability and workability of the printable concrete mix. Superplasticizers play an important role in 3D Concrete Printing because they allow reduction in water content while maintaining sufficient fluidity for pumping and extrusion. The admixture improves rheological behaviour, extrusion smoothness and hydration kinetics. It also reduces internal friction between particles, thereby improving pumpability and preventing nozzle blockage. By lowering the water-to-binder ratio without compromising workability, the superplasticizer contributes toward achieving higher buildability and improved structural stability of the printed layers.

2.1.4 Water

Clean potable water free from impurities was used for preparing the printable concrete mixture. Water plays a critical role in cement hydration and significantly influences the rheological characteristics of the printable material. A controlled water-to-binder ratio of 0.28 was maintained throughout the experimental study. Proper control of water content is essential because excessive water reduces buildability and causes layer collapse, whereas insufficient water reduces flowability and results in poor extrusion continuity.

2.2 Material Preparation

The preparation of printable concrete followed a systematic digital-to-physical workflow designed to ensure uniformity, rheological stability and extrusion consistency. Initially, dry materials consisting of UltraTech Fixoblock mortar and fine quartz sand were thoroughly mixed for approximately 2 to 3 minutes to achieve uniform particle distribution. Proper dry mixing helps in preventing segregation and ensures homogeneity throughout the mixture. In the next stage, potable water was pre-mixed with the required dosage of polycarboxylate-based superplasticizer to form a homogeneous liquid solution. This solution was then gradually introduced into the dry mixture while continuous high-shear mixing was carried out by Bosch GBM 1600 RE Professional.

Fig 2: Bosch GBM 1600 RE Professional used for mixing concrete

The high-shear mixing process continued for approximately 5 to 7 minutes until a uniform printable mixture was obtained. The resulting material exhibited smooth consistency suitable for extrusion-based printing applications. Priorly a dry run of models prepared on Autodesk AutoCAD 2026 were exported to Simply 3D design i.e. from .dwg format to .stl format and G-code created was conducted setting with initial coordinates at 0,0,0. After preparation, the printable concrete was transferred into a Deltasys E-Forming concrete 3D printer extrusion system.

3. Methodology

The experimental methodology adopted in the present study involved comparative printing and evaluation of circular and rectangular geometries under controlled printing conditions. The study utilized Digital models of circular and rectangular forms were created using Computer-Aided Design software and converted into printable tool paths compatible with the extrusion-based 3D printing system. The preparation of a digital model for 3D Concrete Printing (3DCP) follows a structured workflow that transitions from architectural design to machine-readable instructions. Based on the sources, the process involves modelling, format conversion and slicing to generate the final execution code. First in the process we get 3DPC models is firstly prepared in Autodesk AutoCAD 2026 in .dwg format in 2D modelling then which is to be converted in 3D annotative and drawing format which is measured and

3.1 Model Preparation

3.1.1 Model Preparation in Autodesk AutoCAD

The initial phase of the digital-to-physical workflow begins with creating the architectural design.

- 2D Drafting to 3D Modelling: Designs typically originate as 2D plans in AutoCAD. For 3DCP, these 2D layouts are then transformed into 3D solid models within the software.
- Geometric Considerations: During the modelling phase, it is essential to consider the structural stability of the chosen form. Research indicates that while rectangular geometries are common, circular geometries often provide superior buildability and resistance to overturning forces.
- Dimensional Accuracy: The digital model should explicitly account for the actual width of the extruded filament. For instance, when using a 25 mm nozzle, the printed wall may appear wider than the digital geometry due to material spreading and settlement. To compensate, the model's outer surfaces are typically shifted inward by approximately half the extrude width, ensuring that the as-printed dimensions align more closely with the intended design.

3.1.2 Exporting from .dwg to .stl Format

Once the 3D solid model is finalised in AutoCAD, it must be exported into a format that can be read by slicing software used in the printing workflow.

- STL (Stereo-Lithography) Conversion: The completed 3D solid model is saved or exported as a .stl file. This format is widely adopted as the industry standard for rapid prototyping because it represents only the surface geometry of the object, without storing colour, texture, or internal structure.
- Triangle Meshing: In the STL format, the surfaces of the solid model are approximated using a triangular mesh. Curved or complex geometries are represented as a collection of small, planar triangles, each defined by its vertices and normal vector.
- Accuracy and Faceting: The export settings control the level of triangulation, often referred to as the "poly count." Higher triangle density produces a smoother surface representation but increases file size. It is important to strike a balance: a coarse mesh leads to faceted and visibly stepped printed surfaces, while an overly dense mesh can generate excessively large STL files that may exceed the memory or processing limits of the slicing or printing software.

3.1.3 Slicing and G-code Generation

The STL file is then processed to create the layer-by-layer instructions required by the 3D printer.

- Slicing Software: The STL model is imported into slicing software such as Ultimaker Cura. In this step, the model is intersected with a series of parallel horizontal planes to determine the contour of each individual material layer.

- Parameter Configuration: Technical arrangements are made in the slicer for material assignment, nozzle diameter (e.g., 10 mm or 20 mm), and layer height. These settings ensure the "printability window" is maintained, balancing the flow of material with its ability to support subsequent layers.
- Generating G-code: The final output of the slicing software is G-code, a standardized text file format containing numerical control instructions for the printer.
- Alternative Tools: In some advanced workflows, tools like Autodesk ArtCAM are used to capture G-code data from the architectural designs effectively.

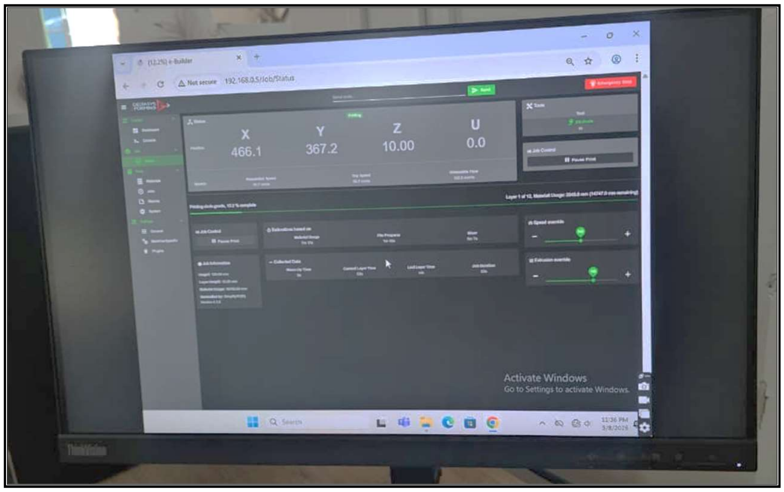

Fig 3: The final output of the slicing software i.e. G-code

3.1.4 Verification and Simulation

Before physical execution, the generated instructions should be verified.

- Path Simulation: The printing path is simulated within the slicing software to check for continuity, corner turns, and potential collisions.
- G-code Verification: Programs like NC Viewer are used to inspect the G-code data and confirm that the printer will follow the intended toolpath without errors.

To ensure reliable comparison between the two geometries, several printing parameters were maintained constant throughout the experimental investigation.

The controlled parameters included:

- Nozzle diameter: 25 mm
- Printing speed: 50 mm/s
- Layer height: 7–10 mm
- Water-to-binder ratio: 0.27
- Material composition: For the preparation of 10 kg of dry mix, 6.67 kg of UltraTech Fixoblock Block Jointing Mortar and 3.33 kg of quartz sand were used. Approximately 2.7 kg of water and 80–100 g of PCE superplasticizer were added.

Table No 2: Printability Parameters of 3DPC

Parameter Category	Requirement	Target Value / Range	Test Method / Code Name	Purpose of Test
Extrudability	Continuous filament without breaks, tearing, or jamming	Visual inspection: unbroken filament, consistent cross-section	T/CBMF 184-2022; ASTM C1437	Ensures uninterrupted pumping and extrusion through nozzle
Buildability	Maximum printable layers before collapse/deformation	≥40 layers (circular); ≥25 layers (rectangular)	T/CBMF 184-2022; Layer count evaluation	Determines structural stability and maximum printable height
Flowability (Slump)	Workability for pumping/extrusion	140–160 mm (mini-slump)	ASTM C230; IS 959; T/CBMF 184-2022	Ensures smooth pumping without segregation
Flow Table Spread	Material spread under own weight	16.5–24 cm	ASTM C230	Indicates adequate

				workability for extrusion
Open Time	Time window for successful extrusion after mixing	30–60 minutes	T/CBMF 184-2022	Defines usable printing duration before material stiffens
Rest Time	Time between layers before failure	10–30 minutes optimal	T/CBMF 184-2022	Determines maximum layer stacking interval
Shape Retention	Dimensional stability after deposition	Deviation ≤±1 mm from target geometry	ISO/ASTM 52939:2023; 3D scanning	Ensures as-printed dimensions match digital model
Layer Stability	Resistance to deformation under subsequent layers	No slumping or tilting	Visual inspection; ISO/ASTM 52939	Confirms layer can support weight of upper layers

Printing operations were carried out layer by layer while continuously monitoring extrusion continuity, material flow behaviour, structural stability, and dimensional accuracy.

Fig 4: Deltasys E-Forming concrete 3D printer gantry (1m x 1m x 1m)

Circular geometries were printed using continuous curved nozzle vase movement, whereas rectangular geometries involved multiple axis transitions and directional changes at corner regions. After completion of the printing process, the specimens were assessed based on a range of fresh-state and hardened-state properties.

3.2 Tests Conducted on 3D Printed Concrete

A series of experimental tests were carried out to evaluate both the printability and the structural performance of the printable concrete material.

3.2.1 Flowability Test

Flowability is a critical rheological property that governs the pumpability and extrudability of cementations materials intended for extrusion-based applications. In this study, the flowability of the freshly prepared mortar was evaluated in accordance with ASTM C1437 using the standard flow table test. The mortar was placed into a truncated cone mold positioned at the center of the flow table and compacted uniformly. The mold was then lifted vertically, allowing the mortar to spread freely. Subsequently, the flow table was subjected to 25 drops within 15 s, as prescribed by the standard procedure. The diameter of the spread mortar was measured along two perpendicular directions, and the average value was recorded as the flow diameter. To ensure repeatability and reliability, the test was performed in triplicate, and the mean flow diameter was calculated.

Fig 5: Flow test table as per ASTM-C1437

3.2.2 Slump cone Test

The slump cone test was conducted to evaluate the consistency, workability, and deformation characteristics of the fresh mortar, which are essential parameters for extrusion-based 3D printing applications. The test provides an indication of the material's ability to deform under its own weight while maintaining sufficient stability for layer-by-layer construction. Freshly prepared mortar was placed into a standard mini-slump cone positioned on a flat, non-absorbent surface. The cone was filled uniformly and carefully lifted vertically to allow the mortar to spread freely. The reduction in height (slump) was measured immediately after lifting the cone. To ensure the repeatability and reliability of the experimental results, the test was performed three times under identical conditions, and the average slump value was calculated.

Fig. 6: Slump Cone test

3.2.3 Extrudability Test

Extrudability is a key performance parameter for 3D printable cementations materials and refers to the ability of the fresh mortar to be pumped and continuously extruded through a nozzle without blockage, tearing, or interruption. Good extrudability ensures a stable and uniform deposition process, which is essential for producing high-quality printed elements. In the present study, the extrudability of the prepared mortar was evaluated using an extrusion system equipped with a 25 mm diameter nozzle. Freshly mixed mortar was fed into the extrusion setup and continuously extruded under controlled conditions. The extrusion process was visually monitored for nozzle blockage, discontinuity, filament breakage, and surface defects. The time required to produce a 1 m long extruded filament was recorded, and the uniformity of the deposited layer was assessed based on its dimensional consistency and surface finish. The overall extrudability was estimated from the continuity and quality of the extrusion process.

Fig 7: Extruding Process through 3DPC Gantry

3.2.4 Buildability Test

Buildability is one of the most critical fresh-state properties of 3D printable cementations materials and refers to the ability of the deposited layers to withstand the weight of subsequently printed layers without excessive deformation, buckling, or collapse. Adequate buildability is essential to ensure dimensional stability and structural integrity during the layer-by-layer printing process. In the present study, buildability was evaluated by continuously extruding and stacking mortar layers until noticeable deformation or structural instability was observed. The printing process was carried out under identical operating conditions using the developed mortar mix, with each deposited layer having an average height of 10 mm. The maximum number of layers that could be successfully printed while maintaining geometric stability was recorded. The total printable height achieved before any significant deformation or collapse was also measured to assess the load-bearing capacity of the fresh material.

Fig 8: Hardened 3DPC circular and rectangular Models

3.2.5 Initial and Final Setting Time

The setting characteristics of 3D printable mortar play a crucial role in determining its printability and overall performance during extrusion-based construction. An appropriate setting time provides sufficient working duration for material mixing, transportation, pumping, and deposition while enabling rapid stiffening after printing to maintain structural stability. In the present study, the initial and final setting times of the prepared mortar were determined using the Vicat apparatus. Fresh mortar was prepared and placed in the Vicat mould immediately after mixing. The penetration of the Vicat needle was monitored at regular intervals to determine the initial and final setting times. In addition, the total time required to complete the printing operation for each printed geometry was recorded and compared with the measured setting characteristics to evaluate the suitability of the mortar for practical 3D printing applications.

3.2.6 Casting Time Observation

The total time required to complete the printing operation for each geometry was recorded and compared. Casting time is an important parameter for evaluating construction efficiency and automation benefits.

4. Results and Discussion

4.1 Flowability Test

The measured flow diameters for the three independent trials were 148 mm, 152 mm, and 150 mm, resulting in an average flow diameter of 148 mm. The close agreement among the three measurements indicates good consistency and reproducibility of the prepared mortar mix. The average flow value of 148 mm falls within the recommended range of 140–160 mm for extrusion-based cementations materials, suggesting an appropriate balance between fluidity and cohesiveness. Mortars with insufficient flowability may lead to difficulties in pumping and nozzle blockage, whereas excessively high flowability can result in segregation and poor shape retention after extrusion. The obtained flow diameter indicates that the developed mortar possesses adequate workability to facilitate smooth pumping and continuous extrusion while maintaining sufficient structural integrity to preserve the geometry of the deposited layers. Furthermore, the limited variation between the measured values demonstrates the homogeneity of the mix and the stability of the fresh-state properties. The achieved flowability is expected to contribute positively to extrusion quality by ensuring uninterrupted material delivery and minimizing defects during deposition. Therefore, the developed mortar formulation exhibits suitable rheological characteristics for extrusion-based additive manufacturing and can be considered appropriate for further investigation in 3D concrete printing applications.

4.2 Slump Cone Test

The measured slump values obtained from the three independent trials were 36 mm, 38 mm, and 37 mm, resulting in an average slump of 37 mm. The minimal variation among the measurements demonstrates the consistency and uniformity of the prepared mortar mix.
The average slump value of 37 mm falls within the recommended range of 35–45 mm for 3D printable cementations materials, indicating an appropriate balance between workability and shape stability. A slump value within this range suggests that the mortar possesses sufficient plasticity to facilitate pumping and extrusion while maintaining adequate green strength to support successive layers without excessive deformation or collapse. The observed consistency indicates that the developed mix can be extruded smoothly through the printing nozzle while retaining its geometric profile after deposition. Furthermore, the controlled slump minimizes the risk of material segregation and ensures dimensional accuracy during the printing process. The close agreement among the three trials also reflects the reproducibility of the mix design and confirms its suitability for additive manufacturing applications. Overall, the slump cone test demonstrates that the prepared mortar exhibits the fresh-state properties required for successful 3D concrete printing, providing an optimum combination of flowability, buildability, and shape retention.

4.3 Extrudability Test

The developed mortar exhibited excellent extrusion performance throughout the testing period. No nozzle blockage, tearing, or interruption was observed during extrusion through the 25 mm diameter nozzle, indicating that the material possessed appropriate rheological characteristics for continuous printing. The extruded filament maintained a uniform cross-section and smooth surface texture, reflecting the homogeneous nature of the mortar and its ability to flow consistently under applied pressure. The average time required to extrude a 1 m long layer was approximately 20–25 s, demonstrating efficient material delivery and stable extrusion behavior. Based on the observed continuity, dimensional stability, and absence of extrusion-related defects, the extrudability of the mortar was estimated to be approximately 95%. The high extrudability rating suggests that the developed mix provides an optimal balance between flowability and cohesiveness. Sufficient fluidity enables smooth passage through the nozzle, while adequate cohesion prevents filament rupture and maintains the integrity of the extruded strand. Furthermore, the uniform filament geometry and smooth surface finish indicate that the mortar is capable of producing consistent printed layers with minimal defects, which is essential for achieving dimensional accuracy and structural reliability in 3D concrete printing.
Overall, the obtained results confirm that the prepared mortar possesses excellent extrudability and is highly suitable for extrusion-based additive manufacturing applications. The combination of continuous material flow, absence of nozzle blockage, and stable filament formation demonstrate its potential for reliable and efficient 3D printing operations.

4.4 Buildability Test

The developed mortar demonstrated excellent buildability throughout the printing process. The deposited layers remained stable and effectively supported the weight of the subsequently printed layers without exhibiting significant deformation, lateral spreading, or collapse. The material successfully maintained its structural integrity up to 18 layers, corresponding to a total printable height of approximately 180 mm. The ability to sustain 18 consecutive layers indicates that the mortar possesses sufficient early-age stiffness and green strength to resist compressive stresses induced by the overlying material while retaining the intended geometry. The absence of noticeable deformation during stacking suggests that the rheological properties of the mix provide an appropriate balance between workability and structural stability, enabling continuous printing without compromising dimensional accuracy. Furthermore, the achieved printable height demonstrates that the mortar has adequate load-bearing capacity in its fresh state, making it suitable for the fabrication of multilayered structural components. The successful maintenance of layer geometry throughout the buildability test also indicates good interlayer stability and reduced risk of collapse during printing operations. Overall, the results confirm that the developed mortar exhibits excellent buildability characteristics, with the capability to support multiple deposited layers and achieve a printable height of 180 mm without structural failure. These findings highlight the suitability of the proposed mix for extrusion-based 3D concrete printing applications, where high buildability is essential for producing stable and geometrically accurate structures.

4.5 Initial and Final Setting Time

The developed mortar exhibited an initial setting time of 85 min and a final setting time of 260 min. These setting characteristics provide a balanced combination of workability and early-age hardening required for extrusion-based additive manufacturing. The initial setting time of 85 min offers adequate working time for batching, mixing, transportation, pumping, and continuous extrusion without the risk of premature stiffening or nozzle blockage. This extended open time allows sufficient flexibility during the printing process, particularly for complex geometries or large-scale components that require uninterrupted material flow. The final setting time of 260 min ensures that the deposited layers gradually gain rigidity after placement, promoting dimensional stability and reducing the likelihood of deformation or collapse during the hardening stage. The observed setting behavior is well suited for layer-by-layer construction, where the material must remain workable during deposition while developing sufficient stiffness to support subsequent layers. Furthermore, the recorded printing durations for the fabricated geometries were well within the measured setting window, confirming that the mortar retained its extrudability throughout the printing operation without adversely affecting buildability or interlayer bonding. The combination of an adequate initial setting period and controlled final hardening demonstrates that the developed mix satisfies the practical requirements of 3D concrete printing. Overall, the obtained setting times indicate that the mortar provides sufficient operational flexibility while ensuring timely strength development after deposition. These characteristics, together with its favorable flowability, extrudability, and buildability, confirm the suitability of the developed mix for extrusion-based 3D printing applications.

4.6 Casting Time Analysis

The casting time required to print a single layer was significantly influenced by the geometry of the printed element. The circular 3D concrete printing (3DPC) specimen required only 19.4 s to complete one layer, whereas the rectangular specimen required 25 s. This corresponds to a 22.4% reduction in printing time for the circular geometry. The shorter casting time of the circular specimen can be attributed to the continuous and uninterrupted printing path. Since the nozzle follows a smooth curved trajectory, there is no need for frequent deceleration and acceleration during printing. In contrast, the rectangular geometry contains four corners where the print head must reduce its speed to maintain dimensional accuracy, thereby increasing the overall layer deposition time. These results indicate that circular geometries can enhance printing productivity and reduce construction time in large-scale additive manufacturing applications.

4.7 Material Consumption

The quantity of material required for a single printed layer also varied with geometry. The circular specimen consumed 366.39 gram of printable concrete, while the rectangular specimen required 430.1 gram. Consequently, the circular geometry achieved a 14.8% reduction in material usage. The lower material consumption observed in the circular specimen is primarily related to its geometric efficiency and smoother deposition path. The rectangular geometry requires additional material accumulation at corner regions to maintain dimensional stability and continuity of the printed filament. Such localized material deposition increases the overall material demand. Therefore, the circular configuration offers a more resource-efficient solution, contributing to reduced material costs and improved sustainability.

4.8 Cost Evaluation

The economic assessment showed that the circular specimen achieved a cost score of 12, representing the optimum performance among the evaluated geometries, whereas the rectangular specimen achieved a cost score of only 2. The higher cost efficiency of the circular geometry is directly related to its reduced printing time and lower material consumption. Since material cost and machine operating time constitute a substantial portion of the total printing cost, improvements in these parameters translate into significant economic benefits. Furthermore, the elimination of printing defects and collapse-related failures reduces the need for rework and material wastage. These findings suggest that adopting circular geometries in 3D concrete printing can improve overall project economics while maintaining structural performance.

4.9 Surface Quality and Defect Formation

Surface quality observations indicated that the circular specimen produced uniform and defect-free layers with smooth printing paths. No visible joint defects, discontinuities, or surface irregularities were detected throughout the printing process. In contrast, the rectangular specimen exhibited noticeable material accumulation at corner regions, leading to uneven layer deposition and localized surface defects. The corners acted as critical zones where changes in nozzle direction affected extrusion consistency. These regions are also susceptible to stress concentration, potentially compromising both aesthetic quality and structural performance. The absence of corners in the circular geometry eliminated these issues and resulted in a more homogeneous printed structure. This improved surface finish can reduce post-processing requirements and enhance the overall quality of printed concrete components. The experimental results clearly demonstrate that the circular 3D concrete printing geometry outperformed the rectangular geometry in all evaluated parameters. The circular specimen achieved faster printing, lower material consumption, superior extrusion consistency, enhanced buildability, improved surface quality, and greater cost efficiency. The continuous curved printing path minimized nozzle speed variations and prevented corner-related defects, while the uniform stress distribution contributed to higher structural stability. Therefore, from both engineering and economic perspectives, circular geometries represent a more effective design configuration for large-scale 3D concrete printing applications and offer substantial advantages in terms of printability, buildability, sustainability, and construction efficiency.

Fig 6: Freshly 3D printed circular and rectangular models

4.10 Defects in 3D Concrete Printing

Several types of defects can arise during 3D concrete printing, often due to unsuitable material properties, improper printing parameters, or unfavourable environmental conditions. Layer separation is one of the most frequently observed defects in printed concrete, occurring when the bond between successive layers is weak or incomplete. Surface cracking may appear as a result of rapid moisture loss, drying shrinkage, or inadequate curing regimes. Layer collapse is another common problem, typically associated with insufficient buildability, where the deposited material cannot adequately support subsequent layers without excessive deformation or failure. Nozzle dragging may disturb previously deposited layers and affect dimensional accuracy. Corner bulging is generally observed in rectangular geometries because of material accumulation during directional changes. Air voids may also develop within the printed structure due to improper extrusion or entrapped air. Uneven extrusion results in dimensional inconsistency and poor surface finish quality.

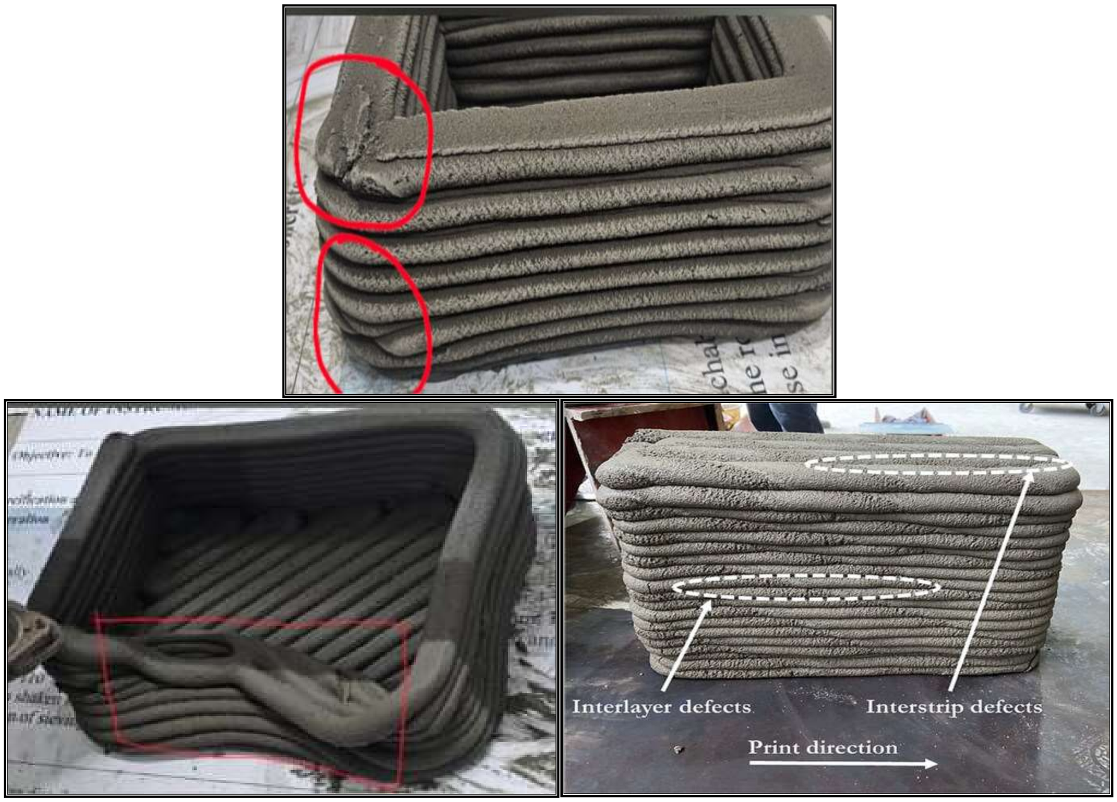

Fig 7: Defects in 3DPC

4.11 Challenges in 3D Concrete Printing

Despite the numerous advantages of 3D concrete printing, several technical challenges remain associated with the technology. One of the primary challenges is maintaining appropriate rheological properties of the printable concrete mix, including adequate flowability, buildability, and early-age structural stability. Poorly balanced rheology can lead to nozzle blockage, loss of shape fidelity, or layer collapse, thereby affecting both print quality and structural performance. The material must possess sufficient flowability for extrusion while simultaneously retaining its shape after deposition. Another significant challenge is interlayer bonding. Weak bonding between successive layers may reduce structural integrity and overall strength of the printed element. Nozzle blockage is also a common problem in extrusion-based printing systems. Improper mix proportions or insufficient flowability may interrupt the printing process. Dimensional accuracy becomes difficult to maintain during continuous printing operations, especially for geometries involving sharp corners and directional changes. The incorporation of reinforcement into 3D printed concrete structures presents another significant challenge. Automated methods for placing reinforcement within printed elements are still in the developmental stage and not yet fully mature for routine use. Moreover, the lack of widely accepted design codes and the limited number of large-scale field applications currently restrict the broader adoption of 3D concrete printing technology.

Conclusion

The present study successfully developed and evaluated a mortar mix suitable for extrusion-based 3D concrete printing by assessing its key fresh-state properties. The average flow diameter of 148 mm and slump value of 37 mm confirmed that the mix possessed adequate workability and consistency for smooth pumping and extrusion. The mortar exhibited excellent extrudability, achieving approximately 95% extrusion efficiency through a 25 mm nozzle without blockage or filament deformation. Furthermore, the material demonstrated superior buildability by successfully supporting 18 printed layers with a total height of 180 mm without significant collapse or deformation. The measured initial and final setting times of 85 min and 260 min, respectively, provided sufficient working time for mixing and printing while ensuring timely hardening after deposition. Overall, the developed mortar exhibited a well-balanced combination of flowability, extrudability, buildability, and setting characteristics, making it highly suitable for 3D concrete printing applications. The findings indicate that the proposed mix can produce stable and dimensionally accurate printed elements, thereby demonstrating its potential for additive manufacturing in the construction industry. However, further investigation of hardened mechanical properties, durability performance, and the development of standardized testing procedures and design codes is necessary to enable its widespread structural application and commercialization.

Future Scope

Although the developed mortar exhibited satisfactory fresh-state properties for 3D concrete printing, further research is required to address several limitations. At present, there is a lack of dedicated Indian Standard (IS) codes and standardized testing procedures for evaluating the printability of 3D printable cementations materials, highlighting the need for the development of comprehensive guidelines and specifications. In addition, the hardened properties of the printed mortar, including compressive strength, flexural strength, tensile strength, interlayer bond strength, shrinkage, and long-term durability, require detailed investigation to establish its structural reliability. Future studies should also focus on optimizing mix design, evaluating large-scale printed components, and assessing the long-term performance of 3D printed structures under different environmental conditions to support their practical implementation in the construction industry.

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References

1. Kathrin Dörfler a, Gido Dielemans a, Stefan Leutenegger b, Selen Ercan Jenny c, Johannes Pankert d, Julius Sustarevas e, Lukas Lachmayer f, Annika Raatz f, Dirk Lowke g, “Advancing construction in existing contexts: Prospects and barriers of 3d printing with mobile robots for building maintenance and repair”, Cement and Concrete Research 186 (2024) 107656
2. Ramani Ayyagari a, Qian Chen a,b,*, Borja García de Soto a, “Quantifying the impact of concrete 3D printing on the construction supply chain”, Automation in Construction 155 (2023) 105032
3. Habibelrahman Hassan a, Edwin Rodriguez-Ubinas b,*, Adil Al Tamimi a, Esra Trepci b, Abraham Mansouri c, Khalfan Almehairbi d, “Towards innovative and sustainable buildings: A comprehensive review of 3D printing in construction” , Automation in Construction 163 (2024) 105417
4. Nan Zhang *, Jay Sanjayan , “Concrete 3D printing and digital fabrication technologies for bridge construction”, Automation in Construction 179 (2025) 106485
5. Ofer Asaf a,∗,Arnon Bentur b, Pavel Larianovsky b, Aaron Sprecher , “From soil to printed structures: A systematic approach to designing clay-based materials for 3D printing in construction and architecture”, Construction and Building Materials 408 (2023) 133783
6. Zengfeng Zhao a,b, Chenyuan Ji a,*, Jianzhuang Xiao a,b,*, Lei Yao a, Can Lin a, Tao Ding a,b, Taohua Ye a, “A critical review on reducing the environmental impact of 3D printing concrete: Material preparation, construction process and structure level”, Construction and Building Materials 409 (2023) 133887
7. Alireza Hasani *, Sattar Dorafshan, “Transforming construction? Evaluation of the state of structural 3D concrete printing in research and practice” , Construction and Building Materials 438 (2024) 137027
8. Mohamed El Aabbas a,*, Mustapha Mahdaoui b, Mohammed Ahachad a, Brahim Mazian c, Issam Aalil d, Mustapha Ouardouz a, “Advancing sustainable construction: Terracotta component development through extrusion-based 3d printing with local clay”, Construction and Building Materials 442 (2024) 137549
9. Katy Bradford a,* , Russell Gentry b, Lola Ben-Alon c, Kimberly Kurtis a, “Construction 3D printing material selection: Minimizing cost and carbon footprint of residential wall assemblies” , Construction and Building Materials 493 (2025) 143150
10. Onur Ozturk , Caleb Lunsford , James Strait , Sriramya Duddukuri Nair *, “Breaking barriers in underwater construction: A two-stage 3D printing system with on-demand material adaptation” , Cement and Concrete Composites 164 (2025) 106306
11. Mehmet Sakin*, Yusuf Caner Kiroglu Hasan Kalyoncu, “3D Printing of Buildings: Construction of the Sustainable Houses of the Future by BIM”, Mehmet Sakin et al. / Energy Procedia 134 (2017) 702–711 703
12. Rodrigo García-Alvarado a,*, Pedro Soza b, Ginnia Moroni a,c, Fernando Pedreros a, Martín Avendaño a, Pablo Banda a,d, Cristian Berríos a, “From BIM model to 3D construction printing: A framework proposal”, Frontiers of Architectural Research 13 (2024) 912e927
13. Songyuan Geng a,b, Qiling Luo a,b, Kun Liu c, Yunchao Li c, Yuchen Hou c, Wujian Long a,b,*, “Research status and prospect of machine learning in construction 3D printing”, Case Studies in Construction Materials 18 (2023) e01952
14. Shoukat Alim Khan a,*, Muhammad Jassim a, Husyin Ilcan b, Oguzhan Sahin c, İsmail Raci Bayer d, Mustafa Sahmaran b, Muammer Koc a, “3D printing of circular materials: Comparative environmental analysis of materials and construction techniques”, Case Studies in Construction Materials 18 (2023) e02059
15. Evgenia Spyridonos a,*, Vanessa Costalonga a,b, Jan Petrš a,c, Gabriel Kerekes d, Volker Schwieger d, Hanaa Dahy a,e, “Enhancing construction

accuracy with biocomposites through 3D scanning methodology: Case studies applying Pultrusion, 3D Printing, and Tailored Fibre Placement", Case Studies in Construction Materials 22 (2025) e04499

16. Xingyu Chen a,1, Yuhong Wang a,2,*, Xingyi Zhu b, Wei Sheng a, Long Yee Chan a, "Design and construction of high-performance surface textures for precast concrete pavements: A flexible formwork and 3D printing assisted texturing method", Case Studies in Construction Materials 22 (2025) e04576
17. Zifan Geng a,b,* , Zhiwen Wu a, Xiangyu Wang b , Lizhi Zhang a, Wei She a, Ming Jen Tan b,*, "A novel 3D printing scheme for lunar construction with extremely low binder utilization", Additive Manufacturing 99 (2025) 104657
18. Çağatay Takva a,b,*, Semahat Merve Top c, Berru İzel Gökgöz d, Şeyma Gebel b, Zeynep Yeşim İlerisoy b, Hüseyin İlcan e, Mustafa Şahmaran e, "Applicability of 3D concrete printing technology in building construction with different architectural design decisions in housing", Journal of Building Engineering 98 (2024) 111257
19. Motalebi Arash , Khondoker Mohammad Abu Hasan , Kabir Golam *, "Assessing the environmental impact of building houses in remote areas: 3D printing vs. traditional construction techniques", Journal of Building Engineering 102 (2025) 111968
20. Badr Saad Alotaibi a,*, Abdulsalam Ibrahim Shema b, Abdullahi Umar Ibrahim c, Mohammed Awad Abuhussain a, Halima Abdulmalik b, Yakubu Aminu Dodo a, Cemil Atakara d, "Assimilation of 3D printing, Artificial Intelligence (AI) and Internet of Things (IoT) for the construction of eco-friendly intelligent homes: An explorative review", Heliyon 10 (2024) e36846
21. Xiaonan Wang a,b, Wengui Li a,*, Yipu Guo a, Alireza Kashani a, Kejin Wang c, Liberato Ferrara d, Isabel Agudelo e, "Concrete 3D printing technology for sustainable construction: A review on raw material, concrete type and performance", Developments in the Built Environment 17 (2024) 100378
22. Harn Wei Kua * , Anqi Shi 1, Vignesh Kajandran , Charlene , Tiam Weng Mark Lam , Abhimanyu Goel , De Hui Alwin Wong , Peak Kee Lim , Layla Harris Kasee , Xi Wen Ong , Ghasan Fahem Huseien , Alexander Lin , "Toward sustainable construction 3D printing: limestone and non-calcined recycled marine clay as partial cement replacement", Cleaner Engineering and Technology 29 (2025) 101074
23. Rafael Robayo–Salazar , Armando Vargas , Fabio Martínez , Ruby Mejía de Gutiérrez *, "Utilization of powders and fine aggregates from the recycling of construction and demolition waste in the 3D printing of Portland-based cementations materials", Cleaner Materials 11 (2024) 100234
24. Mehran Khan *, Ciaran McNally **, "Recent developments on low carbon 3D printing concrete: Revolutionizing construction through innovative technology", Cleaner Materials 12 (2024) 100251
25. Abhishek Pandit1, Aditi Kumari2, "Effectiveness of 3D Printing In Construction Industry over the Old Conventional Method Regarding", Volume 6 , Issue 6 , June – 2021 International Journal of Innovative Science and Research Technology ISSN No:-2456-2165
26. Alyssa Morrison, "The Future of Building: The Potential Impacts of 3D Printin", (2024). Honors Theses and Capstones. 799. https://scholars.unh.edu/honors/799