

3D Concrete Printing: Optimizing the Design of Interlocking 3D Printed Concrete Blocks for Fast and Sustainable Construction

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Abstract. In a world where construction faces environmental challenges and high labor demands, optimizing sustainable methods is crucial. 3D Concrete Printing (3DCP) stands out as an innovative, efficient technique, eliminating molds, reducing waste, and enhancing design flexibility while significantly improving construction speed and cost effectiveness. This study explores interlocking 3D printed concrete blocks as an alternative to traditional modular construction, minimizing mortar dependency for rapid, precise assembly and increasing structural stability. Experimental validation examines geometric accuracy, mechanical strength, and printing efficiency, proving that 3DCP blocks can match or surpass conventional ones. Customizable thermal, acoustic, and mechanical properties, enhanced by specialized concrete mixtures and reinforcements, expand its construction applications. By bridging automation and sustainability, this work demonstrates 3D printed modular construction's potential for cost-effective, scalable, and eco-friendly building solutions, particularly for rapid housing, disaster relief, infra-structure development, and customized architectural projects.

Keywords: 3D Concrete Printing, Modular Construction, Interlocking Blocks, Additive Manufacturing, Sustainable Building, Construction Automation, Mortar-Free Assembly.

1 Introduction

Modular construction is an ancient building technique that involves assembling structures using prefabricated and standardized elements manufactured off-site and assembled on-site. Modular systems have been an essential component of construction since the time of ancient civilizations, when they used big blocks of stone, and are still used today in concrete masonry units (CMUs) [1, 2]. Due to its inherent benefits including cost effectiveness and assembly speed, this method is still widely used today. Compared to traditional cast-in-place techniques, modular construction increases productivity, enables quicker project completion

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by using repetitive components and can improve thermal, mechanical and acoustic performances in construction [3-5].

Modular block construction is widely used, but it faces limitations that affect sustainability and efficiency. Conventional blocks require expensive, inflexible molds, limiting design and personalization. Mortar used in assembly adds curing time and increases labor and material costs. Additionally, mortar-dependent systems are prone to long-term maintenance issues such as joint deterioration and cracking. These challenges highlight the need for more flexible and efficient solutions [6-8].

In recent years, 3D concrete printing (3DCP), a technology that combines the age-old expertise in concrete manufacturing with the fascinating processes of 3D printing (3DP), also known as additive manufacturing (AM), has emerged as a transformative technology in the construction industry [9], offering a promising alternative to conventional modular block production. 3DCP drastically cuts down on production time and material waste by allowing the direct fabrication of complex and personalized concrete elements without the use of molds. Interlocking forms and geometries that were previously hard to accomplish using conventional methods are now created thanks to the accuracy and adaptability of AM techniques [10, 11]. Consequently, 3DCP creates new opportunities for designing modular systems that can be quickly assembled without the need for mortar, enhancing productivity and sustainability.

This study investigates the design optimization and manufacturing of interlocking 3D printed concrete blocks for fast, eco-friendly building. The proposed modular system reduces the need for mortar through smart assembly techniques that enhance structural stability and ease of installation. The study explores the possibility of creating blocks in a range of sizes and shapes without molds, allowing for on-demand customization while maximizing the use of materials and construction time. The ultimate goal is to use creative 3DCP applications to further modular building solutions.

2 Literature Review

2.1 Concrete modular and interlocking construction blocks systems

In the building industry, modular construction has been used widely due its efficiency, effectiveness-cost, and project timelines acceleration ability. Modular traditional systems depend on prefabricate CMUs or concrete elements precast, which are manufactured off-site and assembled onsite. These systems preserve structural integrity while lowering labor costs and speeding up construction [1-3].

In literature, many scientific studies are focusing on designing CMUs with inter-locking masonry techniques [12-16], a new approach that uses mechanical connections with specified geometries and shapes like tongue-and-groove connections and dry-stacked blocks. These techniques have been developed to increase stability and reduce the amount of mortar used, which makes construction more efficient.

2.2 3DCP in construction: State of the art

3DCP's historical background dates back to the mid-1980s with the introduction of contour crafting, an extrusion-based method for automated concrete fabrication. Later developments included powder-based printing like D-Shape and more adaptable extrusion methods such as Concrete Printing. Advances in robotics, material science, and digital fabrication further accelerated 3DCP's progress. Its applications now range from small architectural elements to

full-scale buildings, demonstrating im-proved design flexibility, cost reduction, and minimized construction waste [9, 10, 17, 18].

3DCP consists of three key units “Fig. 1”: a pumping unit, a printing unit (3D print-er), and a control unit [9, 19]. The pumping unit is responsible for moving the mixed concrete to the printing head. The printing unit, which can be either a gantry-based system or a 6-axis robotic arm [20], precisely deposits the material in a controlled manner to build structures layer by layer. Finally, the control unit plays a crucial role in converting the virtual 3D model into machine instructions by generating the re-quired toolpath for the printer’s movement.

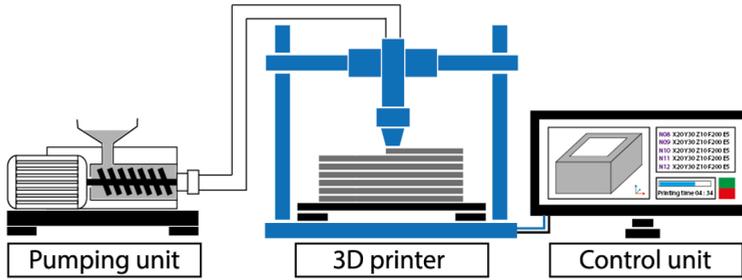


Fig.1. The 3D Concrete Printing (3DCP) process

2.3 Gap analysis: Problem Statement

Conventional modular systems still have a number of limitations despite the developments, including the requirement for standardized molds, expensive shipping, and restricted flexibility to accommodate complex geometries. Block assembly using mortar necessitates more labor and takes longer to complete because of curing procedures. Furthermore, the design flexibility required to effectively create customized structures is lacking in traditional prefabrication methods [6-8, 21, 22]. These draw-backs emphasize the need to investigate cutting-edge approaches, like 3DCP, to im-prove modular construction techniques.

One of the main limitations of traditional techniques is actually addressed by employing 3DCP, which makes it possible to fabricate modular concrete blocks without the use of molds. Complex interlocking geometries can be directly printed using additive manufacturing, guaranteeing exact fit and mortar-free assembly. By allowing on-demand customization of block shapes and sizes, this method not only maximizes material usage and cuts down on construction time, but it also increases the adaptability of modular systems. As a result, 3D printed interlocking blocks present a viable substitute for quicker, more environmentally friendly, and more effective building solutions.

3 Materials and Methods

3.1 Concrete for 3D printing

Unlike traditional concrete, printable concrete must offer a balance between buildability and flowability [23]. The material should be sufficiently fluid to extrude smoothly through the nozzle while retaining enough structural integrity to support subsequent layers. Additionally, in order to guarantee appropriate layer adhesion without deformation or collapse during printing, controlled setting times are essential [23, 24].

In 3DCP, the main concrete’s mixture property is rheology as the 3DCP process necessitates conflicting rheological requirements in order to guarantee the balance between buildability and flowability. It requires high workability during the pumping phase before

extrusion, but also needs low workability and high thixotropy after extrusion for better buildability of concrete [25].

3.2 Design methodology for interlocking mechanisms

With carefully engineered geometries, interlocking printed blocks ensure stability, alignment, and load distribution during mortar-free assembly. Tongue-and-groove, dovetail, and pin-and-hole systems are common interlocking patterns that improve structural integrity and make assembly easier. These designs eliminate the need for traditional binding materials, speeding up construction while maintaining strength.

The modular block designed in this work as represented in the “Fig. 2” is developed to meet key technical specifications, ensuring easy printing, assembly, and structural resistance. The geometry is optimized for extrusion without complex support structures, making it suited for layer-by-layer printing. The interlocking features facilitate accurate and fast assembly, reducing construction time while improving stability. The design must use a flexible parametric approach that allows the block's dimensions to be changed without affecting the interlocking mechanism as a whole in order to accommodate changing construction needs. This flexibility guarantees effective material use and maximizes performance in a variety of building situations.

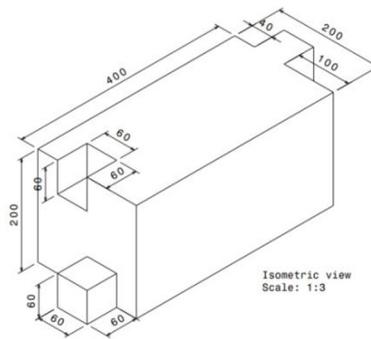


Fig.2. The concrete block CAD model and dimensions

3.3 3D printing process

Structure optimization. One of the key advantages of 3DCP is the topology optimization integration, which refines the block structural design based on mechanical force distribution by analyzing load paths and stress concentrations to remove excess material while preserving or even increasing strength [26, 27]. As a result, stronger and lighter structures can be made, saving materials and increasing productivity. As shown in "Fig. 3", topology optimization guarantees only necessary material is deposited, improving stability, durability, and resource efficiency.

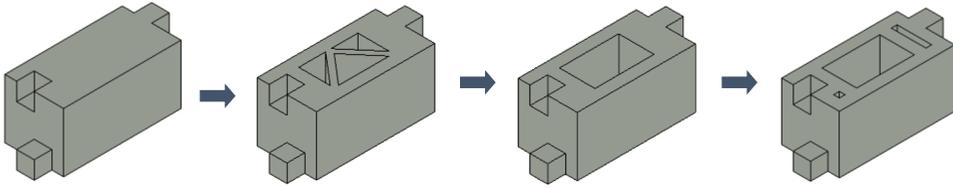


Fig.3. Optimization of the concrete blocks structure

Printer setup. The efficiency of the printing process relies on printer size and workspace organization. Larger gantry or robotic arm-based printers can produce multiple blocks simultaneously, enhancing productivity. To maintain continuous workflow, a moving plank or pallet system is needed to shift printed blocks away from the printing zone, allowing them to set before handling and enabling uninterrupted production.

Temporary supports are needed during printing for the interlocking overhanging features. These supports prevent deformation or collapse during the extrusion be removed after printing. Material waste is reduced while maintaining geometric accuracy and appropriate interlock formation through support placement.

Nozzle design. The nozzle design is crucial for ensuring printing precision and adaptability [28]. To suit various block dimensions, it must be adjustable and handle different extrusion diameters. The proposed design includes a threaded mounting system for quick nozzle size changes, with 20 mm used as the reference diameter for optimal flow and bonding.

Additionally, trowels are integrated near the nozzle to enhance geometric accuracy and dimensional tolerance [28]. These elements help in shaping and smoothing each printed layer, ensuring uniform layer height and consistent interlocking features. By fine-tuning the nozzle shape, extrusion rate, and trowel geometry, the printing process achieves high precision, reducing defects and ensuring seamless block assembly.

Assembly process. The interlocking mechanism minimizes or eliminates mortar use by enabling fast, easy assembly. Designed features ensure block stability and alignment without adhesives. Additionally, columns and other structural components have specified geometries to match the interlocking joint shape, enhancing strength and load distribution “Fig. 4”. This efficient, modular process is scalable, adaptable to various designs, reduces labor time, and boosts construction efficiency.

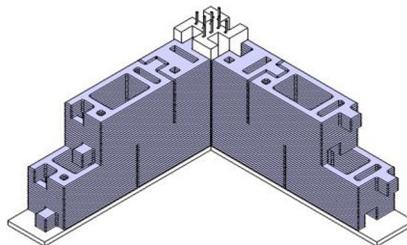


Fig.4. Printed blocks and columns Assembly

4 Results and Discussion

4.1 Prototyping and testing

Path optimization. Path optimization algorithm is employed to determine the short-est possible toolpath while ensuring smooth, uninterrupted extrusion. The algorithm prioritizes linear movements and eliminates redundant passes, preventing revisiting the same point twice [27, 29]. As a result, for a 400×200 mm concrete block, the optimized toolpath for layers containing the interlocking features covers a total distance of 2640 mm “Fig. 5”, while the section without interlocking extends to 2780 mm.

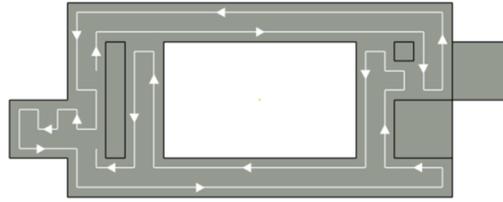


Fig.5. The printing path of a 400×200 mm concrete block

Extrusion flow rate, printing speed and time. In 3DCP, the extrusion flow rate (Q_E) and printing speed (V_{Pr}) are interconnected, requiring calibration to ensure consistent material deposition [30]. Equation (1) defines the relation between these parameters, where S_E represents the extrusion section, V_E the extrusion velocity, and S_{Layer} the printed layer section:

$$S_{Layer} \times V_{Pr} = S_E \times V_E = Q_E \quad (1)$$

For our system, the pumping unit delivers a flow rate of 2.2 l/min (36000 mm³/s). Given that the nozzle diameter is 20 mm, the printed layer section (S_{Layer}) is estimated to be 180 mm². Using Equation (1), V_{Pr} is approximately 200 mm/s, ensuring optimal balance between flow rate and printing speed. Once the printing speed (V_{Pr}) is determined, the next step is to calculate the total printing time (T_{Pr}) required for creating a single block. The printing time depends on the number of layers (n) and the total toolpath length per layer (Di_{Pr}). The relationship is given by Equation (2):

$$T_{Pr} = \sum_1^n Di_{Pr} / V_{Pr} \quad (2)$$

The number of printed layers (n) is determined using Equation (3), where H represents the total block height and h is the thickness of each printed layer.

$$n = H / h \quad (3)$$

Table. 1 presents the flow rate Q_E values and printing times (T_{Pr}) for the reference block, comparing two nozzle configurations (20 mm and 40 mm). This comparison highlights the impact of nozzle size on printing efficiency, where a larger nozzle diameter reduces the print time but affect layer resolution and geometrical precision.

Table 1. Calculating the printing speed depending on the nozzle extrusion diameters.

Printing speed : VPr = 200 mm/s			
Nozzle diameter (mm)	Layers height h (mm)	Flow rate QE (l/mm)	Printing time TPr
40	10	2.2	4 min 30 s
40	20	4.4	2 min 15 s
40	10	4.4	2 min 15 s
40	20	8.8	1 min 8 s

The values of QE and TPr are approximate.

Post printing tests. After the printing, multiple tests are conducted to validate the printed blocks quality. The first step is to verify geometric and dimensional accuracy. In addition, mechanical tests are performed to evaluate the strength of the blocks. Shear tests measure the interlocking mechanism's resistance to lateral forces, while compression tests evaluate the load-bearing capacity. These tests are necessary to verify the blocks structural performance for use in actual construction projects.

4.2 Comparison with traditional methods

Time and material savings analysis. Actual modular construction depends on pre-cast molds, raising costs, production time, and material waste. Mortar use also slows assembly due to curing time. In contrast, 3DCP removes the need for molds, optimizes material usage, and greatly reduces construction time, offering a more cost-effective and sustainable alternative.

Thermal, Acoustic, and Mechanical Behavior. The layered structure of 3D printed blocks improves thermal insulation by trapping air pockets, while acoustic properties can be tuned by modifying layer thickness and geometry. Customized concrete mix-es further enhance thermal and acoustic performance [31-34]. Mechanically, 3DCP blocks can achieve high compressive and shear strength, with integrated reinforcements and high-performance additives enhancing structural reliability and adaptability to various construction needs [23, 35, 36].

Modular Scalability / Different Shapes/Sizes. In contrast to traditional blocks, which need unique molds for every variation, 3DCP enables on demand blocks fabrication with different sizes and shapes. The method is perfect for a range of construction needs, from complex architectural structures to small-scale housing, because of its modular scalability, which permits flexible design adaptations.

5 Conclusion

This study demonstrates the potential of 3DCP to revolutionize modular construction by enhancing the design and manufacture of interlocking concrete blocks. Unlike traditional methods using molds, 3DCP enables fabrication of complex geometries, reducing material waste, production time, and increasing design flexibility. The pro-posed design produces structurally reliable and adaptable blocks allowing rapid and mortar-free assembly while maintaining mechanical strength and geometric accuracy.

This study demonstrates the printing efficiency attained through nozzle design, toolpath strategies, and extrusion parameter optimization. Post-printing tests verify the printed blocks

resistance, strength, and dimensional accuracy. Optimized concrete mixtures can also be used to customize the thermal and acoustic performance, and the incorporation of reinforcement improves the structural dependability of these blocks.

Overall, 3DCP based interlocking modular blocks offer a scalable, cost-effective, and sustainable alternative to traditional block construction. They allow for customized, mold-free units, making them ideal for complex structures and rapid housing. Future research will focus on enhancing materials, automation, and deployment at scale to accelerate adoption in the construction industry.

Acknowledgements. I express my gratitude to IRESEN's funding for my participation in the International Colloquium on Mechanical and Civil Engineering 1st edition (ICMCE'2025) held at the Faculty of Science and Technology of Fes, from 22nd to 23rd April 2025 to pre-sent some of our 3D concrete printer project results during this event.

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