Journal of Brilliant Engineering 1 (2026) 41083

Brilliant Engineering

journal home: www.acapublishing.com/journals/4/ben

Review Article

# Thermal Performance of Hybrid Concrete in 3D Printing: Simultaneous Use of Normal-Weight and Foam Concrete

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**Keywords**

*Lattice infill,*
*Thermal insulation,*
*Dual-extrusion 3DPC,*
*3D-printable foam concrete,*
*Hybrid 3D printing systems.*

**Abstract**

In recent years, 3D-printed concrete (3DPC) has emerged as a technology attracting significant attention in the construction industry due to its advantages. Especially, the use of 3D-printable foam concrete (3DPFC) offers a remarkable solution for improving the performance of 3D-printed structures, with its benefits such as sustainability, lightness, and thermal insulation. Due to its low thermal conductivity, foam concrete (FC) minimizes thermal bridges, and its lightweight nature lessens the dead load on structures. In hybrid 3D printing systems, using normal-weight concrete (NWeC) for the outer filaments and foam concrete (FC) for the inner cores provides both economic and energy-efficiency benefits. This method acts as a thermal insulator and reduces the need for thermally insulated sheathing. This study addresses the thermal performance of 3DPC systems in a simple and understandable way, focusing particularly on the role of foamed concrete in reducing thermal bridges. Previous studies have mostly focused on a single material or improvements in infill geometry. However, hybrid 3D-printed systems using NWeC and FC together within the same wall have not been sufficiently investigated holistically. In hybrid systems, using NWeC in the outer layers to provide load-bearing capacity and FC in the inner regions to improve thermal insulation stands out as a promising solution offering both strength and energy efficiency. This study brings together current findings on foamed concrete materials, infill and lattice arrangements, and thermal bridge behavior, and discusses the advantages of this multi-material approach.

## 1. Introduction

In the construction industry, 3DPC technology has emerged as a significant innovation recently. The construction industry's requirement for energy efficiency, rapid production, and sustainability has rendered 3D printing an increasingly appealing solution. 3D printing is regarded as a sustainable construction method due to its ability to reduce material waste, eliminate the necessity for molds, and offer design flexibility [1]. Additionally, shortening the construction period reduces the effort and expense associated with façade scaffolding, management personnel, and site equipment [2].Furthermore, this technology improves the quality of construction management by facilitating more efficient planning and, consequently, more effective process control. An increase in labour productivity is also expected. This benefit is particularly evident in the logistical simplification of the construction process, which is achieved by eliminating formwork [1, 3].

Lately, there has been a substantial increase in research in this field as a result of the benefits provided by 3DPC technology in the construction process. Researchers have investigated the fundamental attributes of 3DPC, including its durability, mechanical performance, and printability [4–8]. On the other hand, in some recent studies, different sectional geometries have been proposed for concrete wall elements produced with 3DPC, and comprehensive experimental and numerical studies have been carried out on the axial bearing capacities of these structural elements [9–14].

By eliminating processes that consume energy and emit significant quantities of $CO_2$, 3DPC provides architectural flexibility and reduced construction costs [15, 16]. More importantly, from a thermal-performance perspective, this flexibility enables the deliberate design of wall cross-sections with internal voids and air gaps, which play a critical role in regulating heat transfer through the building envelope. The arrangement, size, and connectivity of these internal voids govern conductive, convective, and radiative heat transfer mechanisms, thereby directly influencing the thermal transmittance of 3D-printed concrete walls [17].

A variety of factors, including insulation, cavity size, and wall infill geometry, influence the thermal performance of 3DPC building envelopes. The thermal behavior of 3DPC envelopes has been the subject of research by numerous researchers.

Chamatete and Yalçınkaya (2024) [18] examined the impact of filament width, lattice structure, and granular filler material on the thermal performance of 3DPC building envelopes. AlZahrani et al. (2022) [19] conducted a study on the energy efficiency of infill structures with uniform void-to-concrete ratios. According to Mansouri et al. (2022) [20], the reduction of heat flux can be substantial by dividing large voids into smaller ones. Suntharalingam et al. (2021) [21] observed that the insulation of a building can be enhanced by the trapping of air in complex designs, such as double-row honeycombs or lattice structures. Alkhalidi and Hatuqay (2020) [17] produced economical and energy-effective housing by optimizing the printed-material-to-void ratio. They concentrated on the thermal comfort of 3D printed buildings and determined the thermal transmittance values for different mixtures in different printing configurations. In this study, the lowest value for the thermal transmittance achieved by different wall configurations and printing methods was 0.15 W/m2.K.

Reducing cooling and heating loads in buildings promotes sustainability by reducing fuel consumption and $CO_2$ emissions [22]. Yuan et al. [23] reported that approximately 35% of energy used for air conditioning is met by heat transfer through exterior walls. Due to climate change and

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Received 06 Nov 2025; Revised 07 Jan 2026; Accepted 07 Jan 2026
https://doi.org/10.36937/ben.2026.41083

the increasing reliance on air conditioning to maintain thermal comfort, researching the thermal performance of 3D-printed buildings is of great importance [24]. Buildings now prioritize the development of construction techniques and materials to ensure thermal comfort and lower energy consumption [25].

The building envelope refers to the external surface elements of a building that regulate heat transfer between its interior and exterior environments. The building envelope significantly influences a building's energy efficiency. Both heat transfer through the envelope elements and heat transfer through thermal bridges are involved in the movement of heat across the building envelope. Thermal bridges typically influence the heat flow rate and interior surface temperature [26]. Thermal bridges arise at locations where materials with differing thermal conductivities cross the building envelope, either wholly or partially, leading to a variation in thickness or a difference between interior and exterior regions [27–30]. Capozzoli et al. (2013) indicated that in Europe, thermal bridges can cumulatively increase a building's heating energy requirements by as much as 30% [31].

Most research has concentrated on optimizing the thermal performance of 3DPC envelopes using only NWeC. However, limiting investigations to monolithic NWeC systems may overlook the potential of alternative lightweight materials. In this context, FC is gaining increasing attention for structural applications due to its innovative, cost-effective, and environmentally friendly characteristics [30]. The mechanical performance of FC is strongly governed by its density, making it essential to establish clear correlations between both fresh and hardened densities and its material properties [3]. Despite growing interest in FC-based systems, existing studies have largely focused on the thermal performance of monolithic 3DPC or infill geometries, while a comprehensive review addressing 3D-printable foam concrete and its role in hybrid 3DPC systems remains absent. This paper aims to fill this gap.

## 2. Environmental and Thermal Impact of Foam Concrete

The utilization of FC, in comparison to NWeC, results in enhanced thermal insulation, while maintaining suitable mechanical properties for structural applications. The thermal conductivity and dead load can be reduced by FC as a result of its reduced density [3]. The reduced thermal conductivity of air trapped within the porous cement-based matrix enhances the material's thermal insulation capacity [32].

FC is a lightweight cementitious material characterized by a cellular structure that encloses numerous air voids in a cement-based matrix. FC is characterized as a cellular material that can be produced using simple techniques, including the preformed foam process or the mixed foam process. These processes can be carried out in-situ using standard materials such as binders, water, foaming agents (either synthetic or protein-based), fine aggregates such as sand (generally for densities above 800 kg/m3), additives and other potential inclusions such as fibers. In addition, the wide density range facilitates the customization of the mix design to obtain cement compositions with the required properties depending on the specific circumstances [30]. While low density is advantageous for reducing dead loads and improving thermal insulation, it also introduces rheological and stability challenges during extrusion-based 3D printing, requiring careful control of fresh-state properties. The mechanical properties of FC are primarily related to its density, and it is crucial to correlate both the measured fresh and hardened densities with the specific material properties of FC [3]. Foamed concrete generally provides economic and environmental benefits compared to conventional concrete while demonstrating sufficient mechanical strength and durability, exceptional thermal insulation, and fire resistance, which vary with its density [32–35]. Furthermore, FC has the potential to contribute to a sustainable material cycle by reducing natural resource consumption and managing waste. This allows recycled aggregates and both natural and industrial waste to be used in foam concrete instead of traditional aggregates [36–40]. While FC offers advantages, it also has some disadvantages. Ecologically, FC's higher cement content can contribute more to global warming, potentially making it more ecologically harmful than traditional concrete. From an environmental point of view, foam concrete usually needs more cement to make it strong and stable, which could mean more carbon is stored in the concrete because making cement is a major source of $CO_2$ emissions. So, this brings up the important question of whether better thermal insulation can make up for the higher global warming potential that comes with using more cement by lowering the amount of energy needed to run things. However, FC is recyclable, and recycled FC can be used as filler or insulation granules, reducing material waste and the environmental impact of disposal [3].

## 3. 3D-Printed Foam Concrete (3DPFC) Applications

In this technique, the dimensions of the filaments and the deposition rate directly influence the economic feasibility of the construction project. The "Concrete on-site 3D-Printing" (CONPrint3D®) concept, which was developed at the Technische Universität Dresden, envisions full-wall 3DCP as an alternative to the method of printing fine filaments and subsequently filling in the mold structures [41, 42]. The typical design of the concrete wall cross-section manufactured in accordance with the CONPrint3D® concept is illustrated in Figure 1(a) By employing printable FC, the manufacturing of the wall elements could be simplified to the printing of the main core, which is FC, and the completion of the inner and outer plastering; refer to Figure 1(b).

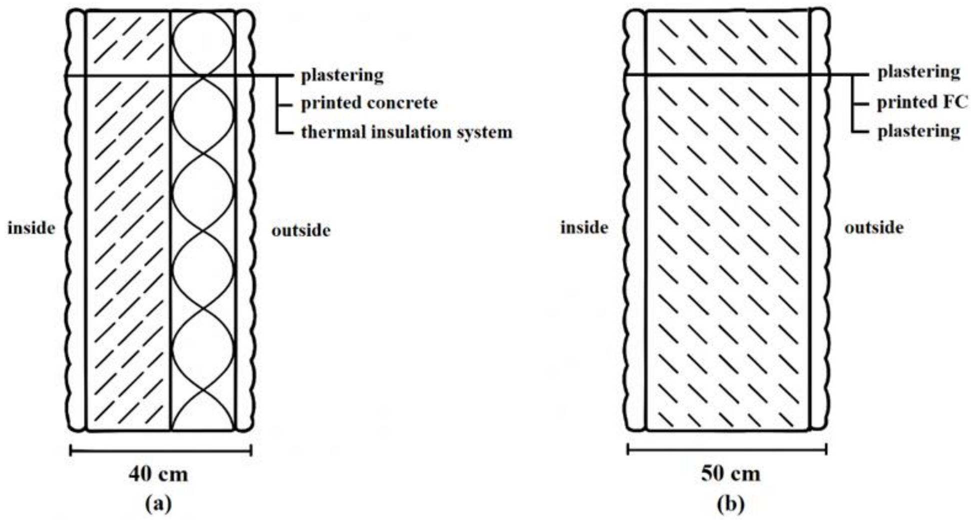


Figure 1. Schematic of wall cross-sections: (a) CONPrint3D® wall with conventional insulation and plastering, (b) entire wall cross-section made of FC with CONPrint3D® technology [3]

Walls printed with FC offer additional advantages over NWeC walls, including enhanced sound insulation and improved fire resistance [32]. In addition, the utilization of FC as a filler material, particularly in 3D printed lattice structures, significantly mitigates thermal bridging effects due to its low thermal conductivity. The lightweight structure of FC also reduces the overall dead load in the structure, enabling the construction of thinner wall sections without compromising thermal performance, thereby enhancing energy efficiency [30].

There are several studies in the literature that utilise the 3DPFC. Research on them has progressed along two main thematic fronts: material development and thermal–structural optimization. Material development studies have primarily focused on improving the printability and stability of FC mixtures. Pasupathy et al. (2022) [43] enhanced the characteristics of 3DPFC by utilizing porous aggregates. Falliano et al. (2020) [44] analyzed the fresh-state characteristics and mechanical integrity of 3DPFC, whereas Cho et al. (2022) [45] explored foam stability. The production of low-density 3DPFC is challenging due to the fact that the porosity of the material increases as the density decreases [46].

Complementary to material development, optimization-oriented studies have explored the use of multiple density levels and novel geometrical configurations to balance load-bearing capacity and thermal insulation. The study conducted by Markin et al. (2021) [3] focused on the development and testing of various foam concrete mixes with densities ranging from 800 to 1200 kg/m³ in order to investigate 3D printing with foam concrete. They assessed the material's cured properties, including thermal insulation, porosity, and strength, as well as its fresh behavior during printing. Printable foam concrete samples with a density less than 1000 kg/m³ are exceedingly uncommon in the literature. Lublasser et al. (2018) [47] and Schmid et al. (2022) [48] reference 3D printing trials that utilize 3DPFC with a density that is less than 600 kg/m³. Parmigiani et al. (2024) [33] 3D-printed structural parts that bear loads and insulate using different FC densities. The samples were tested for strength and thermal conductivity using normal-density concrete for structural strength and ultralight weight concrete for void filling and insulation. Normal-density and ultralight weight foamed concrete have different mechanical properties. The compressive strength of normal-density FC (3DPFC-800) is 7.04 MPa, making it suitable for load-bearing applications. In contrast, ultralight weight FC (ULFC-300) has a compressive strength of 1.43 MPa, which is appropriate for its thermal insulation rather than structural role. The results show that each material's structure balances durability and insulation for specific building functions. Multifunctional components can also improve energy efficiency and beautify façades in new construction or façade renovations.

Thermal–structural optimization through lattice design has been specifically addressed by Chamatete and Yalçınkaya (2024) [30] conducted an investigation into the thermal bridging mitigation capabilities of 3D-printed foam concrete walls in order to enhance the energy efficiency of buildings. They also evaluated the insulation performance of six distinct lattice designs. Insulation efficiencies of up to 94% were demonstrated by walls that lacked direct connections between the exterior and interior surfaces. They observed that the thermal transmittance value is significantly influenced by the contact area between the webs and the interior walls. The primary determinant of thermal bridging in foam concrete walls is the contact area of the webs with the interior surfaces, which is determined by various lattice structures. Structures that separate the exterior and interior skins or reduce the web contact areas demonstrated superior thermal performance. By effectively reducing thermal bridges, innovative lattice designs, such as double-row structures, significantly enhance insulation efficiency.

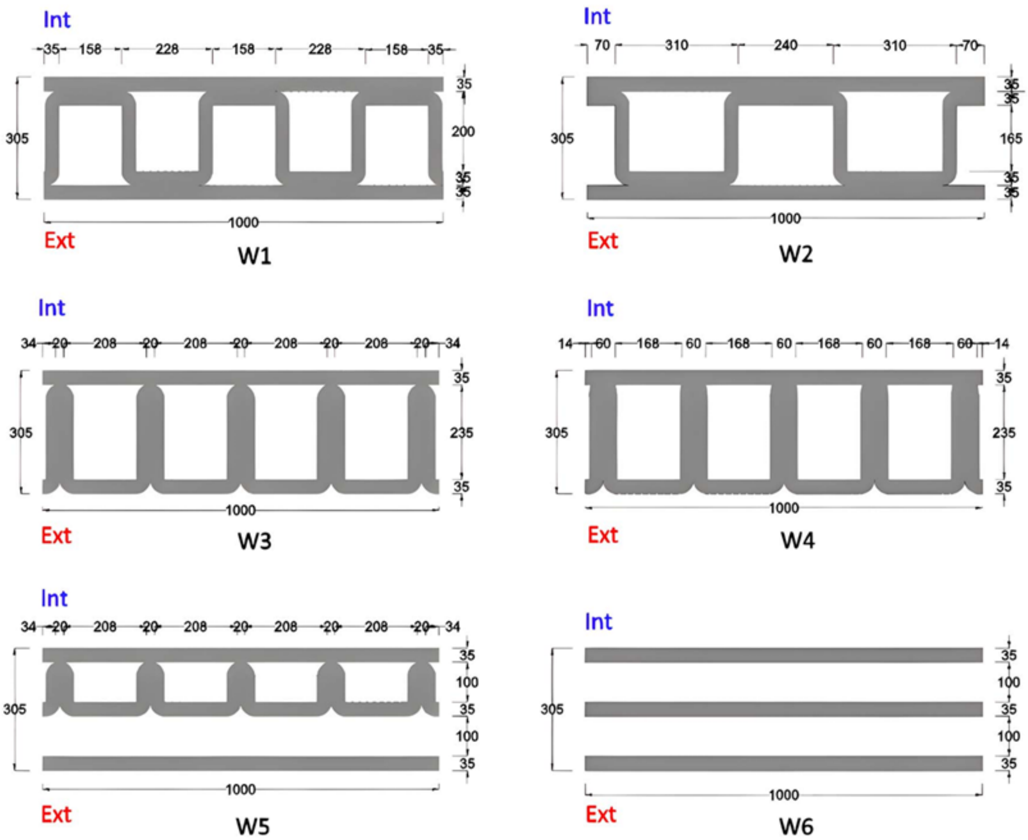


Figure 2. Six distinct lattice designs studied by Chamatete and Yalçınkaya (2024) [30]

## 4. Hybrid 3D Printing and Research Proposals

Traditionally, the literature has focused on printing high-strength, uniform mixtures; however, today, hybrid 3D printing systems are gaining prominence to enhance both structural and functional performance. According to Bayat and Kashani (2025) [25], double-skinned 3D-printed walls with air gaps can reduce heating energy consumption by 12% compared to traditional masonry walls. Different wall geometries significantly altered the building's thermal insulation by modifying the transfer of heat through the envelope. The investigation demonstrated that thermal resistance is enhanced in comparison to standard masonry walls by configurations such as double-skinned walls with air gaps and infill layers. In general, the thermal insulation performance of a building can be significantly enhanced by the design of wall geometries that incorporate air gaps and optimize material distribution using 3D printing techniques. This leads to a decrease in heat transfer and an increase in thermal resistance.

From this perspective, the concurrent printing of NWeC and FC, as shown in Figure 3, can enhance structural and thermal performance. This hybrid approach, which can utilize distinct wall cross-section geometries, facilitates the development of novel building components. In particular, NWeC can be used for the outer filaments, while FC can be used for the inner filaments. Similarly, the load-bearing sections under pressure can be filled with NWeC, while the non-load-bearing sections can be filled with FC. This application reduces material waste, controls heat transfer, and reduces thermal bridges.

In such systems, NWeC can be strategically employed in the outer filaments or load-bearing regions to ensure structural integrity, while FC can be placed in the inner filaments or non-load-bearing zones to enhance thermal insulation. This material differentiation enables optimized material use, reduces thermal bridging, and improves heat flow control without the need for additional insulation layers.

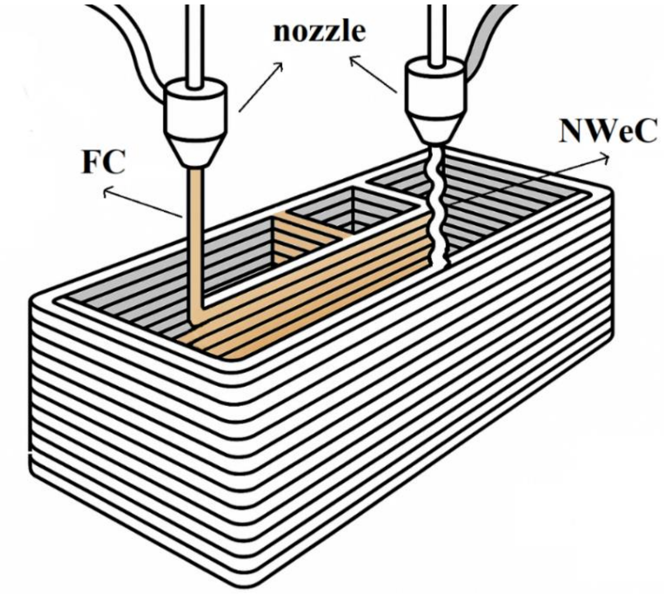


Figure 3. The concurrent printing of both NWeC and FC

For example, in a two-nozzle 3D printer system, one nozzle prints the outer filaments with NWeC while the other simultaneously prints FC just inside these filaments, which can be used as a highly effective method for thermal insulation. It is crucial that the FC fully adheres to the outer filaments without gaps. This way, the FC provides insulation by being embedded within the wall, eliminating the need for a separate insulation layer. In other words, foam concrete functions as a thermal insulation material and, because it requires less aggregate than NWeC concrete, is less expensive. Additionally, the behaviour of the transition zone in hybrid systems between NWeC and FC, the impact of the cross-sectional area geometry of 3D-printed hybrid concrete walls on thermal performance, the levels of greenhouse gas emissions, and the potential for recycling should each be evaluated separately.

Although little research has been conducted on hybrid 3D printing with NWeC and FC, studies on multi-material 3D printing in related fields can still provide useful information. Earlier research on multi-material extrusion-based printing has pinpointed numerous significant challenges, such as nozzle design and synchronization, material compatibility, variations in setting and hardening behavior, and bond strength at the interface of dissimilar materials. These problems are crucial for hybrid concrete systems, and they must be carefully addressed to ensure that the structure and thermal performance are effective.

Accordingly, the key research questions identified in this paper—namely the behavior of the transition zone between NWeC and FC, the influence of cross-sectional geometry on thermal performance, the life-cycle greenhouse gas emissions of hybrid wall systems, and the recyclability of multi-material components—constitute the core contribution of this review. Addressing these issues will be important for advancing hybrid 3D-printed concrete systems from conceptual designs to practical, energy-efficient building applications.

## 5. Conclusion

This study highlights the promising potential of hybrid 3D printing systems to enhance the thermal performance and energy efficiency of buildings by combining additive manufacturing technologies and materials. In particular, the strategic use of NWeC and FC in 3D-printed wall systems can enhance insulation efficiency by minimizing thermal bridging and reducing heat transfer across the building envelope.

This review has synthesized the existing knowledge on the thermal performance of 3D-printed concrete building envelopes. The current literature indicates that, while substantial progress has been made through infill geometry optimization, lattice design, and air-gap configurations, the application of monolithic 3D-printed foam concrete remains an emerging and promising approach for thermal insulation in 3D-printed structures.

Nevertheless, the reviewed studies reveal a clear gap in the effective integration of structural and thermal functions within a single 3D-printed wall component. In particular, the simultaneous use of NWeC to provide structural integrity and FC to enhance thermal insulation has not yet been comprehensively investigated within hybrid 3D printing systems, underscoring the need for integrated material strategies that extend beyond purely geometric or monolithic solutions.

To address this gap, this paper proposes a hybrid, multi-material 3D printing approach in which NWeC and FC are placed within the wall cross-section according to their respective structural and thermal roles. Such systems are expected to significantly improve insulation efficiency while maintaining adequate load-bearing capacity. Future research should focus on key challenges, including the behavior of the transition zone between dissimilar materials, the influence of cross-sectional geometry on thermal performance, life-cycle greenhouse gas emissions, and the recyclability of hybrid components.

## Declaration of Conflict of Interests

The author declares that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## How to Cite This Article

Mütevelli Özkan, İ., G., Thermal Performance of Hybrid Concrete in 3D Printing: Simultaneous Use of Normal-Weight and Foam Concrete, Brilliant Engineering, 1(2026), 41083.
https://doi.org/10.36937/ben.2026.41083