# 3D-Printed Blocks

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The building energy balance is strongly influenced by the heat transmission losses through the envelope. This justifies the growing effort to search for innovative and high-performance insulating materials. The 3D printing process, also known as additive manufacturing, is already used in various industrial applications thanks to its ability to realize complex structures with high accuracy. It also represents an emerging and still poorly explored field in the world of "building physics".

Keywords: 3D printing ; additive manufacturing ; insulating materials ; sustainable materials ; hot box analysis ; infrared thermography ; heat flux meter

## 1. Introduction

In the global scenario, the building sector represents one of the main contributors to the final energy consumption, preceded only by the industrial and transport sectors. In 2019, the final energy consumption of the residential sector accounted for about 21% of the total, namely about $87.78 \times 10^6$ TJ [1]. Despite the numerous energy policies implemented in Europe, adopted by the different member states, greenhouse gas emissions have more than doubled since 1970 [2]. Continuing with current policies, projections to 2050 foresee $CO_2$ emissions substantially unchanged from current values, as predicted by the "*Stated Policies Scenario*" described in [3]. Therefore, to reach the ambitious scenario of "*Net Zero Emissions*" by 2050, needed to cope with climate changes [4], the efforts to find new solutions with a high energy impact must be further increased, even in the residential sector. In this context, Additive Manufacturing (AM), which is still an emerging and poorly explored field [5], could be very effective in expressing its potential among the possible energy efficiency measures.

As of today, there is a growing number of AM applications in the field of construction engineering, potentially able to overturn the commonly accepted approaches to produce thermal insulating panels. In fact, there is a nascent research activity focused on 3D printing (3DP) and the search for elements with complex geometries in the field of building construction, commonly considered a low-tech industry compared to other sectors that have significantly increased their technological content [6].

In particular, the state of the art [7] shows that 3DP is still in a nascent stage and that the efforts made are mostly addressed to printability and structural capacity of the blocks produced. However, a significant knowledge gap can still be found in the study of the 3D-printed blocks thermal behavior, despite some very recent examples published in the scientific literature.

He et al. [8] developed a modular 3D-printed concrete vertical green wall system, going so far as to build a prototype commercial building in China and demonstrating energy savings (−9.12% of annual consumption) and thermal comfort potential compared to Chinese standards.

In the work proposed by Grabowska and Kasperski [9], multilayer materials with quadrangular, hexagonal, and triangular closures are designed and 3D printed. Thermal analysis of the blocks, based on a specially developed mathematical model, showed promising results for quadrangular and hexagonal structures, obtaining thermal conductivity values of 0.0591 W/(m·K).

An interesting experimental study, carried out to analyze the thermal performance of 3D-printed blocks with different internal structures, is proposed by Mihalache et al. [10], who evaluated the response and, thus, the thermal performance of different blocks by varying the thermal stress power and the thickness of the 3D-printed blocks.

Sarakinioti et al. [11] presented the results of the SPONG3D project to develop a 3D-printed panel that integrates insulation and heat storage properties in a complex single-material geometry.

The thermal and mechanical performances of a 3D-printed macroencapsulation method for Phase Change Materials (PCMs) are presented by Maier et al. [12]. The authors used two types of cement-based mixtures with different densities and analyzed the performance of the samples by Hot Box measurements. The obtained results showed that the 3D-printed macroencapsulated specimens provide the best thermal performance.

In this context, it is interesting to explore an emerging and high potential field such as additive manufacturing. New approaches can be defined to make thermal insulating blocks, able to increase the thermal resistance of buildings opaque elements, by reducing the transmission heat losses.

In this paper, a novel 3D-printed thermal insulating block is presented.

The main objectives and novelties introduced by this work are:

- to propose a new 3D-printed block to be used as thermal insulation of building walls, also considering criticalities and potentials related to its realization;
- to analyze the thermal performance of the prototype 3D-printed block via theoretical and experimental approaches (by means of InfraRed Thermography (IRT) technique and Heat Flow Meter (HFM) method in Hot Box apparatus);
- to evaluate the thermal performance of the 3D-printed block by filling its air cavities with waste materials, thus implementing the concept of circular economy.

In particular, the 2D and 3D design phase of the block and its realization phase are described. Then, the thermal performance analysis of the block is performed via theoretical and experimental approaches. The experimental analysis of the 3D-block is carried out considering stationary, controlled, and repeatable thermal conditions. To this aim, a Hot Box has been specifically constructed. Moreover, exploiting the air cavities of the block and implementing the circular economy concept, different waste materials were selected to fill the air cavities: polystyrene and wool.

## 2. Development and Findings

A 3D-printed block is presented in order to evaluate potential opportunities to exploit additive manufacturing for improving the energy performance of the buildings' opaque envelope.

The 2D and 3D design allowed the block fabrication, and therefore, the performance analysis was carried out theoretically and experimentally, through IR thermography technique and HFM method. In particular, the experimental analysis was carried out thanks to the use of a specially made Hot Box.

In addition, following the circular economy concept, the air cavities of the block were filled with waste materials such as polystyrene and wool.

The main findings of the work highlighted that:

- The 2D and 3D design phase of the block using different software (including AutoCAD Inventor® and Creality Slicer 4.2 software) allowed one to exploit the potential of the AM to create even complex geometries; however, the printing phase may require a non-negligible time that, therefore, must be evaluated in the design phase. In this work, the printing phase required about 14 h to realize the prototype block; therefore, an interesting future development of the work is represented by the research of solutions able to reduce the printing time, for example, modifying the diameter of the nozzle and evaluating different printing speeds; the use of AM allowed one to study solutions for reusing waste materials to be filled in the air cavities of the block, thus implementing the concept of circular economy;
- The IR thermography has shown that the 3D-printed block with the air cavities is subject to a considerable thermal stratification that tends to decrease when the cavities are filled with polystyrene and wool;
- The HFM method allowed one to have a quantitative knowledge of the thermal behavior of the 3D-printed block in the three configurations analyzed (with and without cavity filling materials);
- Filling the air cavities with wool determined the best thermal behavior with a thermal conductance value of 0.78 $W/m^2 \cdot K$ ± 3.05%, with respect to polystyrene with which a conductance equal to 1.57 $W/m^2 \cdot K$ ± 3.02% was obtained. Clearly, the results obtained are still far from the thermal performance of high-insulating materials, already used in the

construction sector. However, this work represents a first step toward the use of additive manufacturing in the field of building insulating materials, and given the potential of AM, significant improvements can be expected.

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