Influence of 3D microstructure for improving the thermal performance of building façades

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Abstract. The thermal performance of a building is highly dependent on the heat transmission through the envelope. On the other hand, additive manufacturing has been increasingly used in several industrial applications due to its possibility to produce complex structures. However, most studies of the 3d printing process focused on mechanical performance. This study aims to evaluate how the internal 3D-printed microstructure affects thermal performance. Twelve infill patterns were analysed, including Gyroid, Grid, Hilbert curve, Line, Rectilinear, Stars Triangles, 3D Honeycomb, Honeycomb, Concentric, Cubic, and Octagram spiral. Using fused deposition modelling (FDM), the samples were printed with polyethene terephthalate-glycol (PET-G) thermoplastic filaments. Thermal tests were conducted using a calibrated hotbox, following the recommendations of ASTM C1363-11:2014. The results obtained show a variation of 70% by changing the internal microstructure using fix infill density of 25%. Concentric, Gyroid and Hilbert curve achieved the best thermal insulation properties.

1. Introduction

The energy renovation of buildings is a primary concern and objective at the European level, essential to support the energy transition to reach carbon neutrality by 2050. An effective way to decrease the amount of CO_2 emissions in the lifecycle of the building is to reduce its energy needs [1]. Improving thermal insulation is a cost-effective solution to increase building energy efficiency [2]. On the other hand, the EU building energy renovation rate has been slow – under 1% per year [3]. According to the European Commission's "Renovation Wave Strategy" to achieve carbon neutrality by 2050, this rate should be at least double the current one. Although, it is estimated that the required renovation rate should be at 3% [4].

On the other hand, more than 300 million tons of plastic are produced each year globally, and Europe is the second-largest producer of this material. In contrast to the amount produced, only a small percentage is recycled. In Europe, only 14% of post-consumer plastic waste is recycled [5], while the rest is incinerated, placed in landfills, or mismanaged. The mismanagement of plastic waste is the most impactful since it contaminates oceans, lakes, rivers, and soils through its degradation to microplastics [6]. Thus, it is urgent to reduce plastic waste while defining strategies to integrate existing plastic waste into value chains for reuse, upcycling, and downcycling.

The research and development of new technologies are essential to address both issues discussed previously. This development could establish the necessary know-how to facilitate the integration of plastic waste in the construction value chain. Research is being conducted regarding this integration of plastic waste as building components [7,8]. Though, there is space for further research on the integration of plastic waste into the building renovation industry. One approach to this topic would be the local recycling of post-consumer plastic into 3D printing filament by a replicable open-source machine [9].

Local recycling proposes a low to zero-emission recycling process of post-consumer plastic. Nonetheless, this recycling method requires that its material is integrated into the value chain of a 3D-printed product.

The use of recycled plastic and renewable materials has notably emerged from scientific literature as a relevant topic to the research [10,11]. Regarding the increase in research involving recycled plastic, developing new solutions for additive manufacturing (AM) using polymer composites based on waste resources can help European Union achieve a circular economy. By controlling the internal geometry and different combinations of infill percentages, 3D printing allows the optimisation of thermal conductivity and creates lighter components.

However, few studies were conducted evaluating the influence of microstructure on thermal performance [12]. Existing studies make use of printing configurations which are not ideal for civil construction, usually with an extrusion nozzle with a diameter of 0.4mm. Larger nozzle diameters reduce the printing time and often allow for a larger area of contact between layers, which results in increased layer adhesion, but it also could reduce the plastic depositing precision, resulting in a layered finish that is not desirable for some industries. Although the construction sector uses a lower precision rate than other industries (e.g. mortar rendering in building façades), it allows the usage of a large extrusion nozzle to be compatible with the construction sector.

Using Fusion and Deposition Modelling (FDM) method, this study evaluates the thermal performance of 12 specimens 3D printed with a 1.75mm PET-G thermoplastic filament in an industrial 3D printer, Builder Extreme 1500 Pro. Different configurations of core topologies were tested in the laboratory to investigate thermal resistance variation inherent in 3D printing configuration. The hot box test method was used to measure the thermal resistance. Based on the results, the microarchitecture of the 3D printing configuration was investigated, aiming to achieve an optimised configuration for thermal resistance. The experiment was carried out with high print speeds and a 1.2mm nozzle – above the 0.4mm used in current literature.

2. Material and methods

2.1 Specimen preparation

All the samples were printed using the industrial 3D printer model Builder Extreme 1500 Pro with Polyethylene terephthalate glycol (PET-G) filament. The CAD models were developed in the Sharp3D software since it is a professional and robust tool for 3D modelling and digital prototyping. The chosen slicing software for exporting the g-code was PrusaSlicer, version 2.4.0, due to its internal library of 3D geometries. The slicer software settings were adjusted to the material and printer characteristics to obtain consistent panels without printing defects. The printer nozzle diameter of 1.2mm was heated to 250^{o}C, and the printing bed was set at 60^{o}C. Printing and printer-bed temperatures were selected according to previously developed temperature testing and were limited by printer capacity. The print layer height used was 0,45mm for the first layer, followed by 0,6mm for the rest of the print. The extrusion width was set to 1,26mm, 105% of the nozzle diameter. The print speed was set at 45 mm/s in the first layer, followed by 75 mm/s during the rest of the print. Travel speeds in the X and Y axis were set to 800 mm/s, according to the maximum value of the 3D printing. Additional values, such as retraction value and printer head acceleration, were defined in previous tests ensuring minimal stringing, ghosting, and other printing defects.

The polymer selected was PET-G due to its low thermal conductivity, hygrothermal performance, UV radiation resistance, and good mechanical strength when compared to other materials available [13,14], which are some of the performance criteria generally required for energy renovation of facade panels. Moreover, it was opted not to use recycled plastic in this experiment to avoid possible sources of contaminations that could interfere with the results' reliability. Nevertheless, recycled plastics could be used to 3D-print the renovation panels after defining the best geometry configuration.

For example, recycling PET into 3D-printing filaments has been identified as a key milestone in the circular economy due to the increased use of containers and bottles [15]. The PET in plastic package waste can be melted and re-extruded into filament at approximately 250^{o}C using existing equipment in the market [16]. Additionally, other commonly used thermoplastics, such as high-density polyethene (HDPE), are often objects of local research due to their presence in single-use plastic packing and melting capacity to be re-melted [17]. Similarly, polylactic acid (PLA) is also researched for its 100% recycling use in FDM additive manufacturing [18]. Those plastic materials could be locally recycled through open-source technology such as RecyclingBot [9], which allows for plastic recycling into FDM plastic filament with the benefits of local recycling [19]. Even though recycled plastic loses some of its mechanical properties, this loss is not significant [20,21]. Therefore, it is still possible to downcycle plastic waste in a less demanding function, such as insulation material for renovation solutions, allowing its inclusion in the construction value chain.

The experiment was divided into twelve infill geometries to quantify their influence on thermal performance. Figure 1 illustrates the proceedings of specimen preparation adopted in this study. The infill geometry patterns tested were selected due to their availability in various commercially slicing software. For the infill geometries, the following microarchitecture configurations were tested: 3D Honeycomb, Concentric, Cubic, Grid, Gyroid, Hilbert curve, Honeycomb, Octagram spiral, Rectilinear, Stars, and Triangles. Each design is illustrated in Figure 3 and was printed with a fixed infill percentage of 25% since good results were found in the literature using this percentage [12].

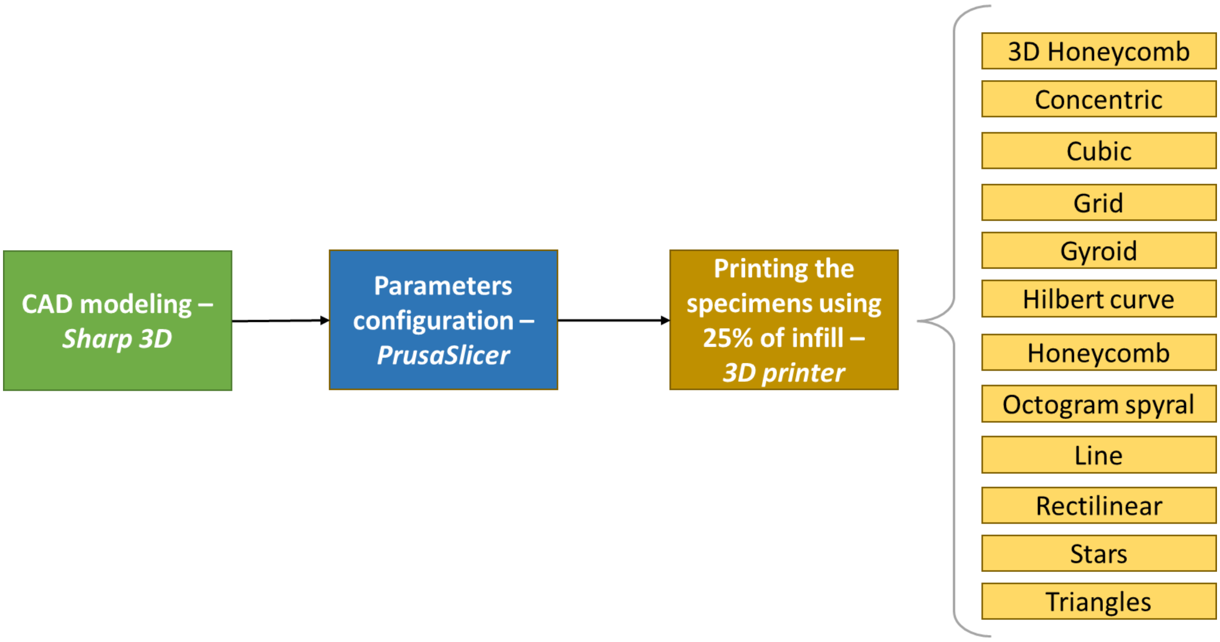

Figure 1. Sketch of the methodology adopted in this study. All 12 samples were tested on the hotbox to evaluate the thermal performance.

2.2 Thermal properties evaluation

The thermal transmittance of each specimen was evaluated using a calibrated hotbox [22], following the recommendations of ASTM C1363-11:2014 [23]. The hotbox consists of two five-sided chambers, the cold and the hot. The envelope is isolated with 20cm of extruded polystyrene. The thermal transmittance of the samples is obtained by measuring the heat flux rate needed to maintain the hot chamber at a steady temperature (in this study 35 ± 5ºC). In this experiment, the greenTEG gSKIN® U-Value Kit (KIT-2615C) was used to quantify the temperatures, the heat flux through the material, and the U-value.

The tests were performed in two panels as illustrated in Figure 2. Each panel was printed with six internal geometry variations, totalling 12 samples, as shown in figure 3. The panel's dimensions were 500x1000mm to fit inside the hotbox, as illustrated in 4-B. Therefore, the dimension of each specimen inside the panel used to measure the thermal transmittance was 175 x 250 x 100 mm, as shown in figure 2, with a support structure with the minimum support structure necessary.

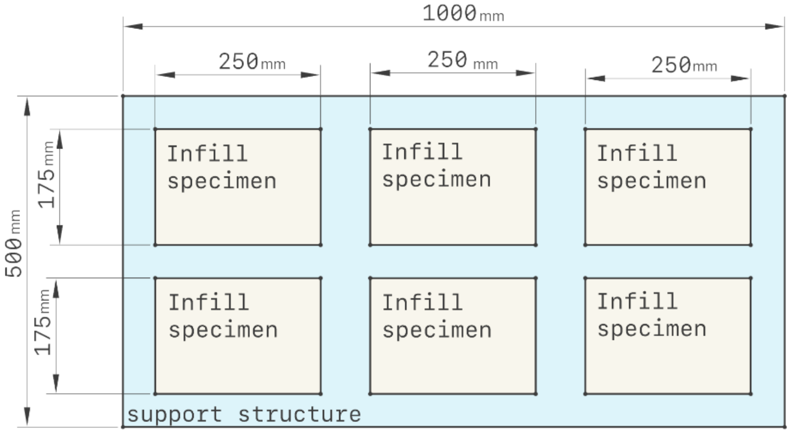

Figure 2. Panel size and configuration used for the thermal tests. With an overall size of 1000x500x100mm.

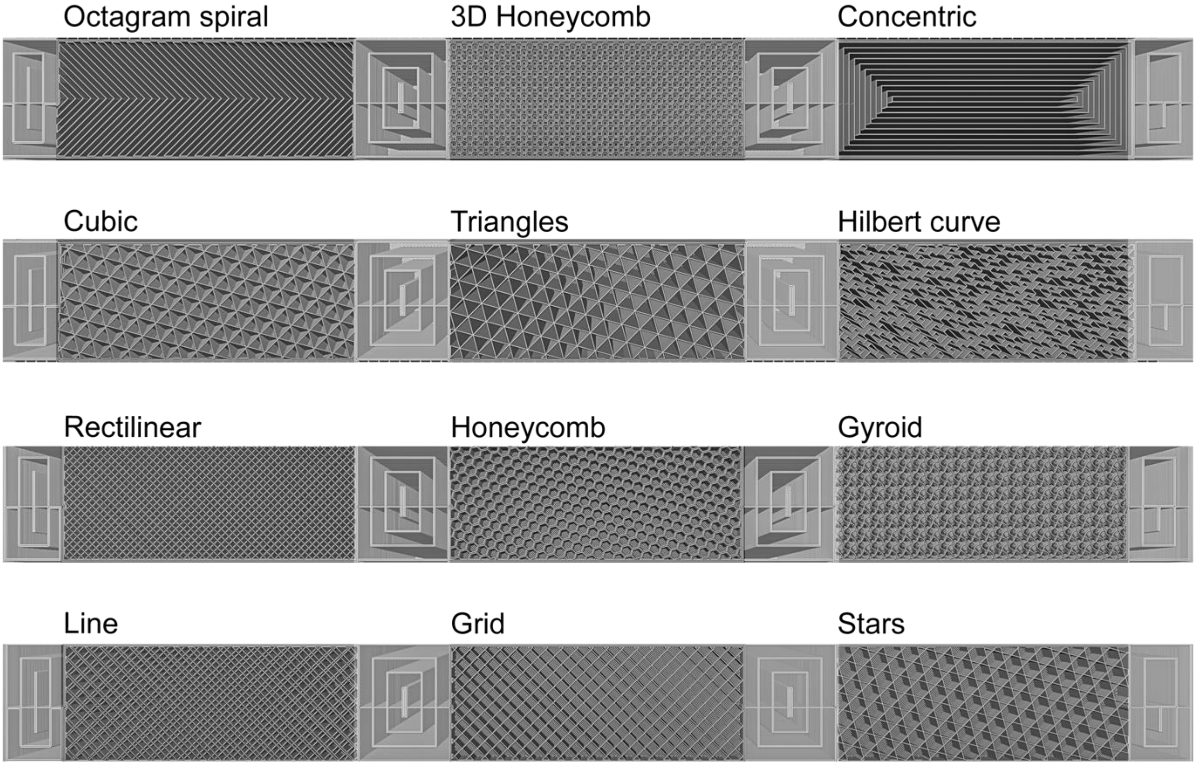

Figure 3. Test panels section view displaying the 12 infill geometries tested.

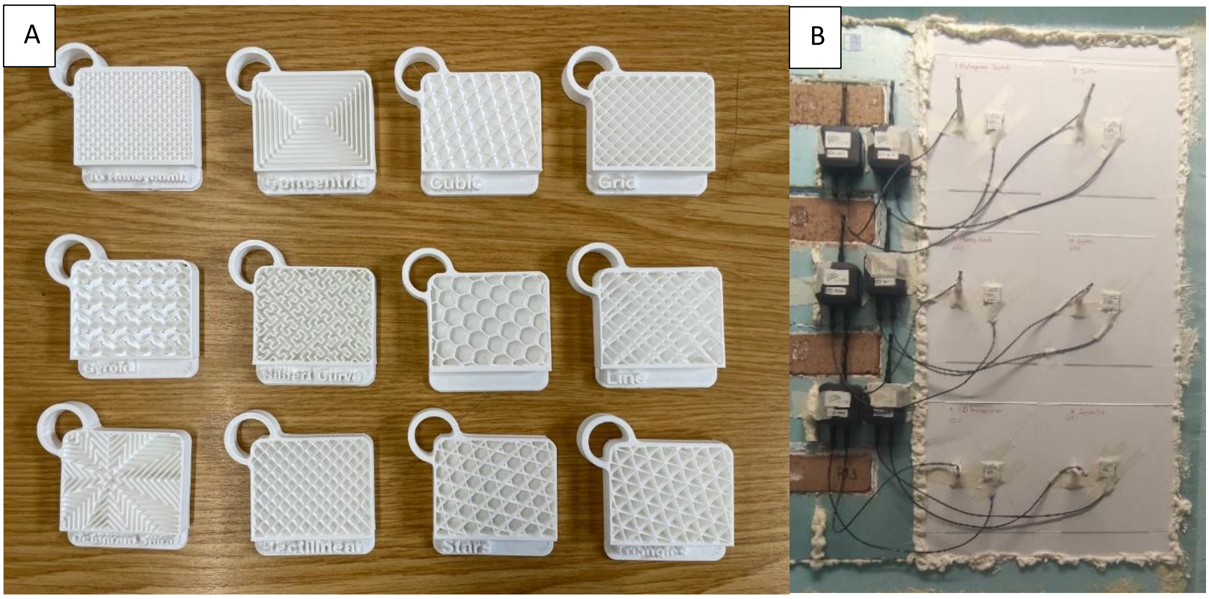

Figure 4. Left-A illustrates the twelve infill patterns chosen to estimate their influence on thermal performance. The right-B represents the hotbox proceeding to calculate the thermal conductivity of the panel, each one with six samples. Six heat flux sensors were installed in the centre of each sample. The authors took both photos during the laboratory test.

3. Results and discussion

Reducing the U-value improves the insulation properties, leading to lower energy consumption during the building operation. The influence of the internal microarchitecture in the U-value is presented in Figure 5. The density was constant for each sample at 25% (i.e., 307kg/m^3). The Concentric infill obtained the best results with a U-value of 0.52 w.m^{-2}.k^{-1}, Gyroid and Hilbert curve with 0.65 w.m^{-2}.k^{-1}. The difference between the best and worst geometries' performance is 72%, showing the importance of optimising the structure to improve thermal performance.

The Concentric geometry obtained the best result in thermal resistance. As expected, the Concentric geometry material which makes no direct contact with the external perimeters of the tested specimen resulted in the best thermal performance of the tested geometries. Although the Concentric presented a good thermal performance, the geometry offers no structural support to the external perimeters. This may result in a specimen unsuitable for applications where the 3D-printed insulation could be exposed to impacts. The second-best solution in terms of thermal insulation was the Hilbert curve. However, the difference between the thermal performance of the Hilbert curve and Gyroid was minimal, leaving the decision optimal according to the requirements for its application.

Few studies evaluating the influence of 3D-printed internal geometry on thermal performance were found in literature. Nonetheless, Grabowska and colleagues [24] evaluated the thermal conductivity of 3D-printed plastic insulation materials using Stereolithography (SLA) method in different sizes, densities, and infill patterns – rectilinear, Honeycomb, and triangular. The best thermal insulation properties (i.e., lower thermal conductivity) were obtained for Honeycomb and rectilinear with a single layer and larger size of the closures (air voids). This is consistent with our study, where the triangles have lower performance than rectilinear and Honeycomb. The authors [24] achieved a thermal conductivity of 0.0591 W/(m.k), resulting in a U-value of 0.591 w.m^{-2}.k^{-1} considering 0.10m of thickness. The U-value was lower than that obtained in this study – 0.780 w.m^{-2}.k^{-1} for Honeycomb – since the density is 40% lower. This can be explained due to the lower thermal conductivity of air (0.025 W.m^{-1}.ºC^{-1}) compared with the thermoplastics (around 0.20 W.m^{-1}.ºC^{-1}) [25]. Therefore, increasing the air voids can achieve better thermal performance. However, since the density is lower, the mechanical performance is also reduced as a trade-off [26]. Another study [12] pointed out that the relation between the thermal conductivity and the infill percentage assumes a continuous variable pattern, decreasing with increased air voids.

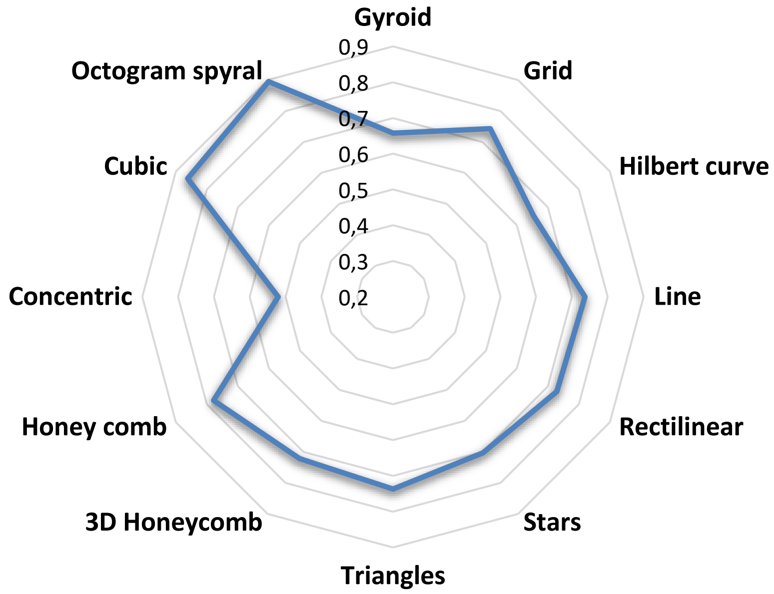

Figure 5. Thermal transmittance (w.m^{-2}.k^{-1}) of 12 microstructures using a fixed infill percentage of 25%.

To achieve higher thermal performance, future tests should include varying not only the geometry but also the density of the samples to values below 25% (adopted in this study). In this case, better thermal performance is expected, but on the other hand, the mechanical performance may be lower due to a lower density. Furthermore, the resistance to fire is an important parameter to consider in a building renovation façade panel. Although this study did not evaluate the fire resistance performance, flame retardant additives can be incorporated into the PET-G polymer composite to improve its fire resistance performance [27]. Moreover, considering the complex designs achievable by additive manufacturing, there are various ways that these renovation solutions can be arranged for building energy renovation. There are renovation solutions that take advantage of the polymer material properties, such as its light refraction or capability of storing liquids [13]. These renovation solutions rely on leaving the plastic exposed as the façade material. However, its integration with materials commonly used façade materials, such as mortar and paint, needs further research due to possible compatibility issues between materials.

4. Conclusion

This study evaluated the influence of internal 3D-printed microstructure on thermal performance. Twelve specimens printed with PET-G thermoplastic were evaluated using 25% of infill density. It was observed a difference of 71% between the highest and lowest thermal transmittance value in the same infill density – 0.520 w.m^{-2}.k^{-1} for concentric microstructure and 0.894 w.m^{-2}.k^{-1} for Octagram spiral. These results show the importance and capability of the internal geometry of a 3D-Printed object. Although the thermal tests investigate the thermal performance of 3D printed specimens with specific configurations, other materials and nozzle dimensions are expected to achieve similar results. Hence, displaying the potential of using additive manufacturing in the construction sector.

Similarly, complex internal structures allowed by the additive manufacturing process have shown great potential to be used in the building renovations sector. The same can be expected when comparing the development of an insulation panel manufactured with recycled plastics, enabling the integration of recycled plastic filament into the economic chain of the building renovation sector.

On the other hand, using additive-manufactured renovation solutions in the built environment requires further research and development. Some variables, such as durability, fire resistance, long-term performance, etc., require additional testing and information before confirming their usability as materials for building renovation solutions.

Since lower infill percentage results in better thermal performance, future activities may include an evaluation of the influence of infill percentage on thermal performance. Additionally, the geometries could be compared regarding the infill's mechanical performance in future tests. Therefore, the best overall geometry could be selected for specific usage.

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