

Article

Resource Efficiency and Thermal Comfort of 3D Printable Concrete Building Envelopes Optimized by Performance Enhancing Insulation: A Numerical Study

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Abstract: 3D concrete printing has gained tremendous popularity as a promising technique with the potential to remarkably push the boundaries of conventional concrete technology. Enormous research efforts have been directed towards improving the material properties and structural safety of 3D printed concrete (3DPC) over the last decade. In contrast, little attention has been accorded to its sustainability performance in the built environment. This study compares the energy efficiency, operational carbon emission, and thermal comfort of air cavity 3DPC building envelopes against insulated models. Four insulations, namely expanded polystyrene (EPS), extruded polystyrene (XPS), polyurethane foam (PUF), and fiberglass (FG), are iteratively paired with three different 3DPC mix designs, and their resulting performances are reported. A numerical optimization analysis is performed to obtain combinations of 3DPC building models and insulation with the least energy expenditure, carbon production, and thermal efficiency. The results indicate that insulation considerably enhances the overall environmental performance of 3DPC structures. The optimization process also demonstrates the potential of using 3D printable fiber reinforced engineered cementitious concrete (3DPFRECC) with polyurethane infill for amplified sustainable performance in modern construction.

Keywords: 3D printed concrete; numerical optimization; sustainability; energy efficiency; building insulation



Citation: Ayegba, B.O.; Egbe, K.-J.I.; Matin Nazar, A.; Huang, M.; Hariri-Ardebili, M.A. Resource Efficiency and Thermal Comfort of 3D Printable Concrete Building Envelopes Optimized by Performance Enhancing Insulation: A Numerical Study. *Energies* **2022**, *15*, 1069. <https://doi.org/10.3390/en15031069>

Academic Editor:
Kuljeet Singh Grewal

Received: 5 January 2022

Accepted: 29 January 2022

Published: 31 January 2022

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1. Introduction

In recent years, the prominent emphasis on the rapidly changing global climate and energy crisis has necessitated increased research in sustainable construction technologies [1,2]. In this context, the advancement of extrusion-based additive manufacturing, also known as 3D concrete printing (3DCP), has gained momentum in the architecture, engineering, and construction (AEC) industry as a dominant option for a cleaner construction footprint [3–6]. The vote in favor of 3DCP is based on its potential to address the numerous environmental challenges attributed to the traditional construction methods: it drastically reduces labor and material costs, minimizes wastes, requires low mechanical energy, and cuts down construction time [7–9]. Additionally, this construction approach broadens the scope of geometrical freedom in building designs and allows for the modulation of materials and components to obtain optimal structural performance and functionalities [7,10]. However, the usual method of 3D concrete printing creates structures with heterogeneous and hollow features, which pose certain technological challenges to its practicality on large-scale

applications [11]. Accordingly, numerous studies are underway to improve the mechanical performance of 3DPC for extensive utilization in the construction industry. Some of the pertinent issues under investigation in this context include the properties of 3D printable cementitious materials [12–14], precision and quality control [15], modification of material rheology and thixotropy [5], and anisotropic behavior in the mechanical properties of printed concrete [16,17].

The 3D concrete printing process essentially builds a physical object layer by layer based on a predefined digital model [1,18]. The essential material properties that have been found to influence the 3D additive construction are flowability, buildability, extrudability, and open time [11,16,19]. These properties constitute the major parameters on which several experiments are conducted globally using varied concrete mix designs. The materials used in the 3DPC mix essentially comprise binders such as ordinary Portland cement (OPC), or a combination of cement, fine aggregates, and admixtures such as fly ash and silica fume [10]. However, modified mixes have been developed using rheology-enhancing admixtures, reinforcing additives, and high-performing binder variants [5,16,20]. Other studies have investigated the methods of material placement, hydration control, and reinforcement appropriate for improving the 3D printable concrete [15,21]. In terms of mix proportions, a study on the effect of mineral admixtures on 3D printable concrete reported a water-cement ratio of 0.4 and a sand-binder to admixture ratio of 1:3 for an optimal mix [22]. Another study on cement self-compacting mix considers a water-cement ratio of 0.42 and a sand-binder ratio of 1.542 to be optimal for 3D printing [23]. Additionally, the characteristics of the 3D printer, such as its nozzle velocity, shape, and printing method on concrete performance, are the focus of other empirical studies [24,25].

However, advances towards a sustainable built environment are focused on improved technologies and material characteristics, overall energy efficiency, and ecosystem preservation [26]. Thus, in addition to fulfilling the strength requirement, the 3DPC building must be habitable and resource-efficient [11]. Although comprehensive research on the ecological impacts of 3DPC is limited, some investigative studies have revealed insufficient energy and thermal efficiencies and high percentages of carbon emissions in 3DPC compared to conventional concrete envelopes [10,11]. Robati et al. [27] examined the correlation between the 3DPC mix design and its resultant thermal performance. The outcome showed that the thermal efficiency of 3D printable concrete is significantly influenced by the mix design, particularly its aggregate mass and material proportion. A recent analysis by He et al. [7] revealed that the energy efficiency and thermal comfort of 3D printed structures could be enhanced through hybridization and integration with existing technologies. In the research, a modular 3D printed vertical concrete green wall system (3D-VtGW) was developed and assembled with 3D printed multifunctional wall elements, which served a dual purpose as the building envelope and the bearer of an external green wall system. The prototype significantly reduced the exterior wall surface temperature and exhibited notable energy-saving potentials. Further, the literature has described the development and application of insulation to building envelopes to reduce energy consumption and greenhouse emissions (GHG) in modern construction [28–31]. The most widely used insulating materials reported are expanded polystyrene (EPS), fiberglass, and polyurethane foam (PUF) [32]. These infills have been integrated into the material repository of prominent building information and energy performance modeling software. However, there is a limited investigation on these insulating materials' effect on the energy efficiency and carbon emissions of 3DPC building envelopes.

To obtain a more extensive evaluation of the behavior of insulated 3DPC, it is imperative to quantify the effects of insulation on the sustainability performance of 3DPC structures. It is carried out by investigating optimal combinations of insulation and concrete walls, which result in the least damage to the built environment. Accordingly, this paper examines the energy efficiency, carbon emissions, and thermal comfort of three insulated 3DPC walls with distinct mix designs. An optimization analysis is conducted, and conclusions are drawn based on the wall and infill combination with the most period of thermal comfort and the least percentage of energy expenditure and carbon emissions.

2. Materials and Methods

This study aims to obtain an optimized combination of 3DPC wall and insulating material, demonstrating higher thermal and energy efficiencies and reduced carbon emissions. To achieve this goal, each uninsulated 3DPC model is initially analyzed for its sustainability performance. It is then paired with different insulating materials. Finally, each combination's resultant efficiency is evaluated based on an entire building performance analysis. Figure 1 presents the outline of the adopted methodology.

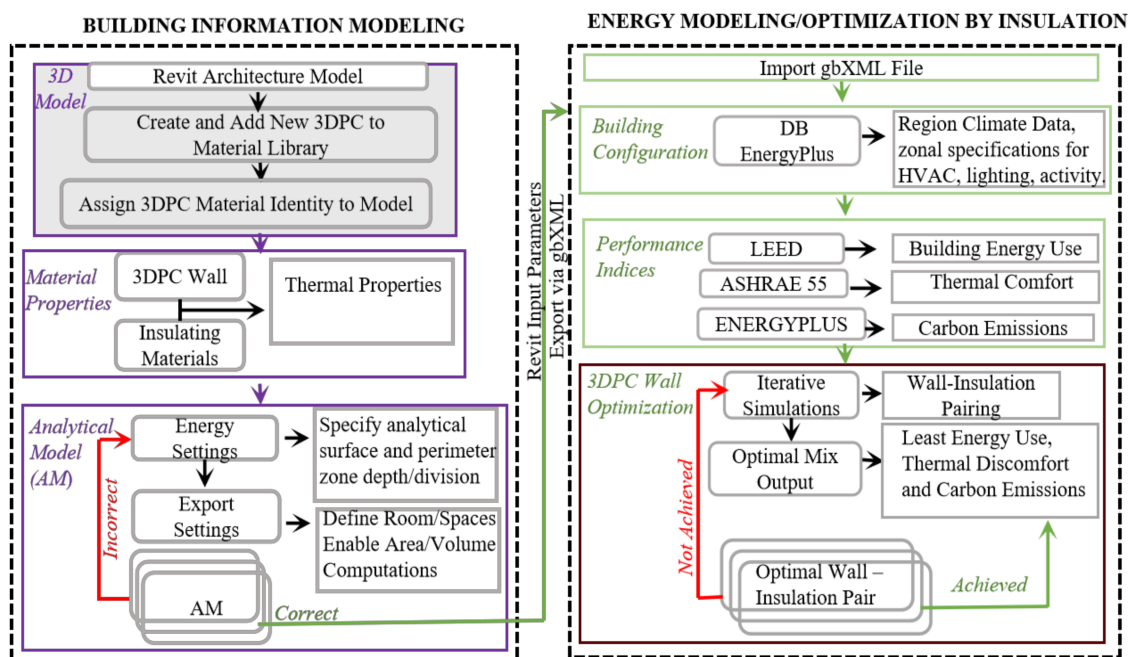


Figure 1. A flowchart showing the stepwise approach of the numerical study.

2.1. Model Development

A three-dimensional model of a residential building is developed on the Revit building information modeling (BIM) software. Revit is a widely used BIM tool with an interoperability function that enables building geometry and thermal data transfer to energy simulation tools via the Green Building XML (gbXML) schema [33]. Figure 2 illustrates the plan, zones, and walling layout of the building model. The literature indicates that numerous factors influence buildings' energy and thermal efficiencies. These factors range from the composition and design of the building envelope to the external climatic conditions surrounding the building system [10,34,35]. However, the material composition of the building envelope is the only factor considered in this study. The walls account for up to 25–30% of energy loss [36]. Hence the external walls of the building model are the specific focus of this investigation.

2.2. DPC Mix Designs

At this stage of the methodology, the material composition and properties of the external walls are defined. As inferred from the literature, extensive research has been conducted to optimize the printability and post-print parameters of 3DPC using different variations in materials and mix proportions. Therefore, three distinct 3DPC mix designs were adopted in this study based on previous optimization experiments. The mix proportions of each prototype are presented in Table 1. The first prototype (Mix 1) is a printable high-performance fiber-reinforced fine aggregates (HPFRFA) mix [37,38]. It was developed as an optimal mix by researchers at Loughborough University. It was printed into a slab with a thickness of 200 mm, compressive strength of 110 MPa, and flexural strength of 13 MPa and 16 MPa in both directions.

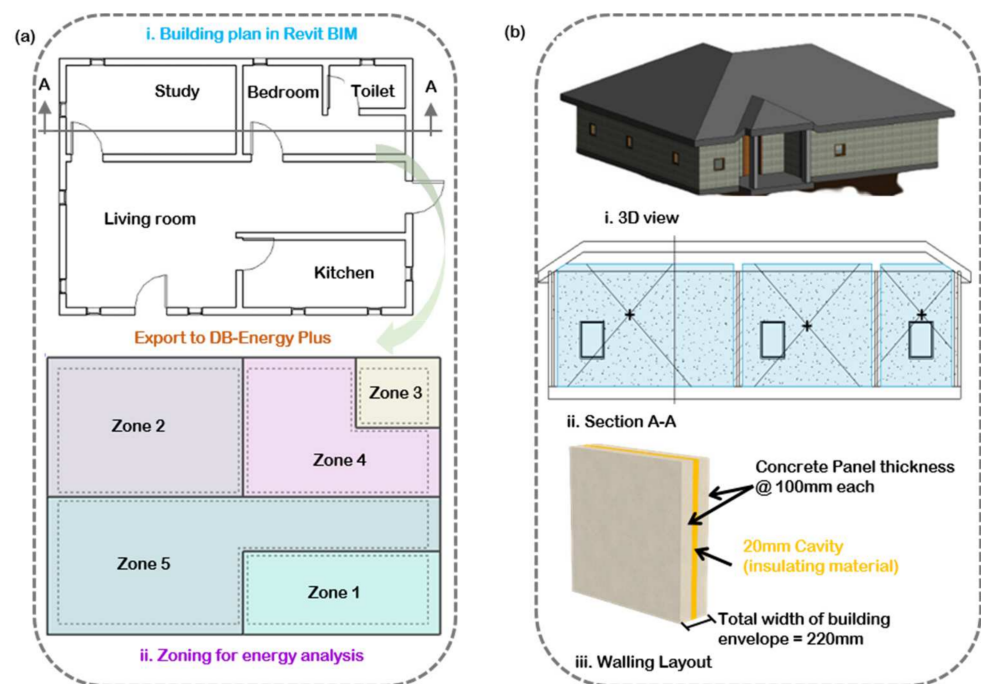


Figure 2. Building information: (a) (i) Building plan; (a) (ii) Zoning layout; (b) (i) Building Elevation; (b) (ii) Sectional view; (b) (iii) Walling layout.

Table 1. Mix Designs of the Adopted 3DPC Prototypes.

Materials	Mix Proportions [kg/m ³]		
	Mix 1	Mix 2	Mix 3
Portland cement	579	613.7	729
Calcium aluminate cement	-	-	55
Fine Aggregate (Sand)	1241	767.2	495
Silica fume	83	57.5	110
Water	232	402.8	400
Fly ash	165	287.7	253
Water-cement ratio	0.28	0.28	0.25
Flour Silica	-	-	55
ANC, HRWA, VMA	-	-	6,6,6
PVA fiber	-	21.29	26
Source	[37]	[19]	[39]

The second mix design considered is the 3D printable fiber-reinforced cementitious concrete (3DPFRCC) with polyvinyl alcohol (PVA) fibers [19]. The prototype developed was a hollow L-shaped structure with $78 \times 60 \times 90$ cm dimensions and was printed in 150 min. This result was found to demonstrate the excellent buildability and printability of the mix design. The third prototype (Mix 3) adopted in this study is a 3D printable fiber-reinforced engineered cementitious concrete (3DPFRECC) mix combined with three admixtures for improved thixotropic and rheological properties [39]. The additives comprised attapulgite nano clay (ANC), a hydroxypropyl methylcellulose viscosity modifying agent (VMA), and a polycarboxylate-based high-range water reducer (HRWR). The mix was printed into solid slabs, which exhibited 9.6% more ultimate strain than the cast concrete samples. Each mix design was used separately to model the base case residential building at a uniform wall thickness of 200 mm to observe the definitive influence of the different concrete mixes in the analysis.

2.3. Insulation Materials

Building envelope insulation is vital for the thermal and energy efficiency of a building because the envelope accounts for 50–60% of total heat gained and lost in the structure [40]. The selection process of the insulation materials considered in this study is based on their life-cycle costs, reusability, and thermal, mechanical, and moisture resistant behavior. The four insulating materials selected in this study include expanded polystyrene (EPS), extruded polystyrene (XPS), polyurethane foam (PUF), and Fiberglass (FG) (Figure 3).

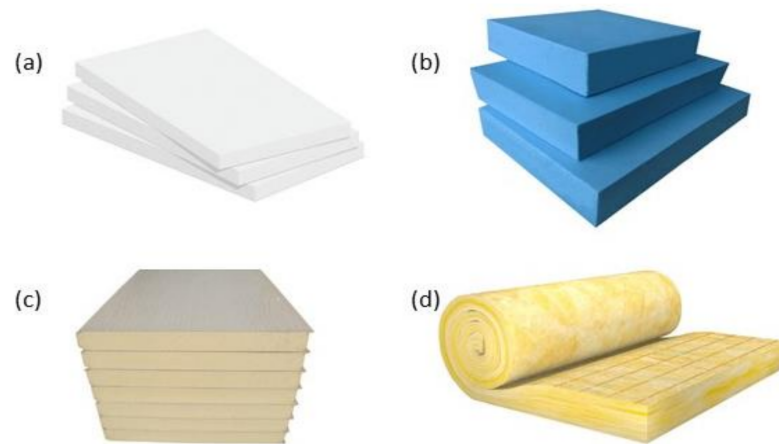


Figure 3. Insulating materials: (a) Expanded polystyrene boards (b) Extruded polystyrene boards; (c) Polyurethane foam insulation panels; (d) Fiberglass roll sheet.

EPS is a well-established insulation material that has been extensively incorporated in various building applications as a lightweight concrete aggregate, decorative molding, backfilling, and as a core in panel application for buildings [41–43]. EPS is considered a durable and economical material characterized by its light yet rigid foam with good thermal insulation, impact resistance, load-bearing capacity at low weight, absolute water, and vapor barrier, and airtightness in controlled environments [41]. The extruded polystyrene foam (XPS) is a moisture-resistant material with a stable thermal resistivity value and high compressive strength and is peculiar for its recyclability [44]. Further, PUF has been widely used in thermal insulation in industrial fields due to its relatively low thermal conductivity, low density, and remarkable mechanical properties [45,46]. Fiberglass insulation, also known as glass wool, is an easily available, low-cost insulating material made by a typical combination of glass (35% or more of which is recycled glass), sand, soda ash, limestone, and other minerals. Fiberglass insulation has many applications in green building projects due to its good thermal, acoustic, and fire-safe qualities [47].

2.4. Thermal Transmittance of 3DPC Mix Designs

Thermal transmittance or U-value is an important parameter that influences the thermal environment of the building envelope. The U-value defines the ability of an element of structure to transmit heat under steady-state conditions [48]. This ability is dependent on the thickness and thermal conductivity (K-value) of the structure under consideration. To estimate the thermal transmittance of Mixes 1, 2, and 3, their thermal conductivities were first calculated using the prediction formula adopted from the experimental study by Kim et al. [49]. The thermal conductivity of a given mix design can be expressed as a function of the volume fraction of mix proportions, W/C ratio, temperature, and moisture conditions of concrete. The volumetric computation of aggregates in the mix designs was obtained to calculate their respective thermal transmittance (U-values). The absolute volume of fine aggregates was obtained from its mass and specific density as follows [50]:

$$\text{Absolute volume} = \frac{\text{Mass of loose material [kg]}}{\text{Specific density of material} \times \text{Density of Water} \left[\frac{\text{kg}}{\text{m}^3} \right]} \quad (1)$$

where the density of water is 1000 [kg/m³] (62.4 [lb/ft³]) at 4 °C (39°F). The specific gravity for cement, fine aggregate, silica fume, and fly ash is taken as 3.15, 2.59, 2.35, and 2.35, respectively [50].

Thus, the thermal conductivity of λ each mix design was predicted using the Equations (1) and (2) as follows:

$$\lambda = k_{ref} [0.293 + 1.01AG] \times [0.8 \times [(1.62 - (1.54W/C)) + 0.2Rh] \times [1.05 - 0.0025T] \times [0.86 + 0.0036S/A] \quad (2)$$

where λ = Thermal conductivity of concrete, AG = Volume fraction of aggregate in concrete, W/C = Water-cement ratio, Rh = Relative humidity, T = Temperature, S/A = Volume fraction of fine aggregate in concrete, and k_{ref} is a referenced thermal conductivity measured from specimens at a condition of AG = 0.70, W/C = 0.4, S/A = 0.4, T = 20 °C, and Rh = 1.0.

The value of k_{ref} is experimentally equal to 1. In the study by Kim et al. [49], the authors established a close relationship between the thermal conductivity of concrete predicted from Equation (2) and the measured values by achieving a sample correlation coefficient of 0.95, thus making the prediction model reasonable for heat conduction analysis of concrete elements. Moreso, Equation (2) was used to calculate the thermal conductivities of 3D printable concrete, M25 concrete, and first-class bricks based on average climatic conditions in Mumbai [10]. The base case building considered in this study is a single-story residential building with a built-up area of 1200 m² and a panel thickness of 100 mm (combined thickness of 200 mm) based on conventional building models in China. The location-based climatic conditions used include an average external temperature of 21.5 °C and relative humidity of 78% over a typical meteorological year.

Thermal transmittance is expressed as the reciprocal of thermal resistance (R-value). The R-value is derived from the thermal conductivity and thickness as:

$$R = \frac{\text{Wall thickness}}{\text{Thermal conductivity}} \quad (3)$$

$$\lambda = \frac{1}{R} \quad (4)$$

The wall thickness of 200 mm was kept constant in the estimation of the R-value for each mix. Thus, using Equations (3) and (4), the U-values of mixes 1, 2, and 3 were obtained as 3.9 W/m²K, 3.8 W/m²K, and 2.6 W/m²K, respectively.

2.5. Energy Simulation and Optimization Analysis

The energy modeling software used to analyze the building performance of the model is the DesignBuilder EnergyPlus (DB-EnergyPlus) simulation package [51]. DB-EnergyPlus is a powerful energy modeling program that provides engineers and designers access to various environmental performance simulation capabilities, including whole-building energy consumption, daylighting, HVAC, and financial analysis [51]. The software is fully integrated with an enormous repository of location and weather files, geometry, construction and materials, thermal zones, occupancy operating schedules, and HVAC systems. Bernado et al. [52] utilized the DB-EnergyPlus tool in developing a calibrated energy simulation model of a school building to investigate the impact of improving its ventilation system on energy performance. Other researchers employed DB-EnergyPlus to analyze and optimize perforated double-skin facades and thermal bridges of vacuum insulation panels [53,54].

The properties of the materials and the building site information served as input data for the energy analysis tool. After creating a standard Revit Architecture model of the building, an analytical model (AM) was set up to generate a gbXML file. Preparation of the Revit analytical model is crucial to the success of the transition process. The analytical model is based on the definition of rooms and spaces, which are superimposed on the underlying Revit architectural model [51]. Next, the design was manually exported to DB-EnergyPlus using the Export gbXML dialog built into Revit. Next, the building model was partitioned into zones. Energy simulation outputs such as heat gains, emissions, daylighting, and energy use of each zone are visualized separately. To observe the specific influence of the input data on the behavior of the external walls, the default configurations and values of the other building features such as glazing, roof, and door specifications were maintained for each material combination analyzed. The input parameters used in the energy analysis are outlined in Table 2.

Table 2. Building Input Parameters *.

Parameters	Values
Thermal conductivity of EPS	0.035 (W/m.K)
Thermal conductivity of FG	0.0465 (W/m.K)
Thermal conductivity of XPS	0.03 (W/m.K)
Thermal conductivity of PUF	0.028 (W/m.K)
Roof Insulation	0.39 (W/m ² K)
Floor insulation	0.46 (W/m ² K)
Infiltration rate	0.7 (ac/h)
HVAC equipment	Fan coil unit (4-pipe)
Lighting power density	5 W/m ²
Occupancy density	55 m ² /person

* As obtained from the location-based building information repository on DB-EnergyPlus.

The energy efficiency indicator utilized in the analysis is the LEED energy expenditure evaluation. The specifications used to quantify thermal comfort are provided by the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE Standard 55-2010) [55]. This standard predicts the thermal comfort of building spaces based on six environmental and personal factors: relative humidity, airspeed velocity, air temperature, radiant temperature, occupants' clothing insulation, and metabolic rates. The DB-EnergyPlus simulation software was configured to compute thermal comfort based on the ASHRAE Standard 55 using the specified values for the given factors. The standard uses quantitative indices known as the Predictive Mean Vote (PMV) and Percentage of People Dissatisfied (PPD) to measure the degree of thermal neutrality experienced by a group of occupants based on a seven-point thermal sensation ranging from −3(Cold) to +3(Hot). ASHRAE 55 specifies that a space is considered thermally comfortable if at least 80% of its occupants can be expected not to object to the ambient condition, i.e., the majority experience thermal sensations between the range of −0.5 and +0.5 (Neutral) on the PMV scale.

The ASHRAE 55 Adaptive Comfort Model [55] was adopted to assess thermal comfort at both 80% and 90% acceptability limits and measure the number of occupied hours beyond the occupants' thermal comfort zone. Table 3 presents the matrix of material combinations selected for optimization analysis.

Table 3. Building Component Optimization Matrix (A_{ij}).

Mix Designs	Control Models	EPS	FG	XPS	PU
Mix 1	P_0	InsP-1	InsP-2	InsP-3	InsP-4
Mix 2	R_0	InsR-1	InsR-2	InsR-3	InsR-4
Mix 3	S_0	InsS-1	InsS-2	InsS-3	InsS-4

3. Results and Discussion

3.1. Energy Efficiency and Thermal Comfort Performance

Figure 4a illustrates the energy efficiency of insulated 3DPC building envelopes. The energy sources specified for this analysis are mainly electricity and natural gas. An evident difference can be observed in the energy expenditure between the insulated walls and the control models (P_0 , R_0 , and S_0). This is indicative of higher operational energy demand by the air cavity walls. The insulation notably reduced the building energy use by an average of 8300 KW over a typical meteorological year. Moreover, FG-insulated walls expended more energy across the board in comparison to the other insulated models. The fiberglass infill used is the 20 mm thick R-22 with thermal conductivity of 0.0465 W/m.K. The EPS and XPS insulated envelopes show similar energy efficiency behaviors and are 1079 KW lower in annual energy consumption than the FG- insulated walls. The EPS and XPS insulating materials have thermal conductivity values of 0.035 W/m.K and 0.03 W/m.K, respectively, with the same thickness, which implies a 30% lower heat transfer rate than the fiberglass insulation. Interestingly, the thermal conductivity of the PU foam used is 0.028 Wm.K, and the PU-insulated envelopes expended 1900 KW of energy less than the FG-infilled walls. Obviously, the energy efficiency of the insulating materials is indicative of their thermal transmittance. Ultimately, InsS-4 was found to be the optimal combination with the least energy requirement, saving approximately 9500 KW more energy than the control models and 1400 KW more than insulated walls.

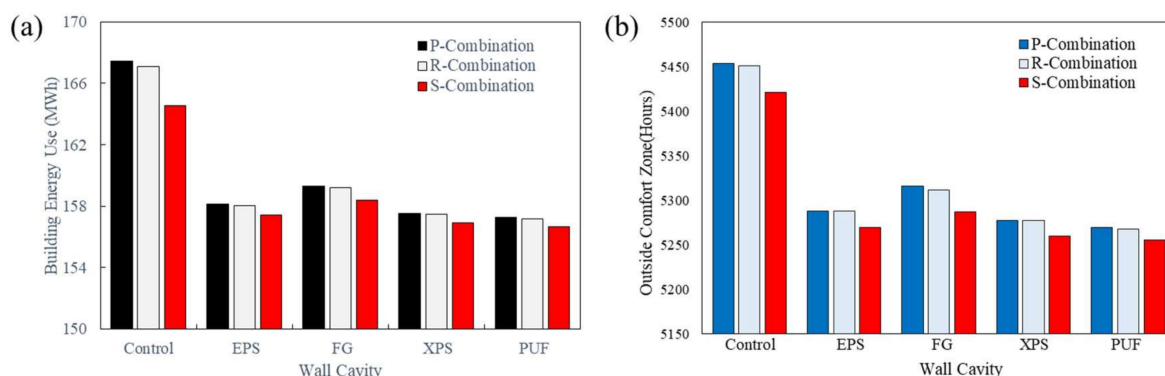


Figure 4. (a) Insulation effect on 3DPC building energy use; (b) Effect of insulation on 3DPC thermal comfort efficiency.

Figure 4b portrays the impact of insulation on the thermal performance of 3DPC walls. The observed trend among the insulated models is similar to their energy-saving performance. Typically, long periods of thermal discomfort require proportionate measures of energy expenditure for temperature regulation. The air cavity wall models averaged 160 h more discomfort hours than insulated walls, meaning that more hours of mechanical heating and cooling were required by the occupants within the uninsulated enclosure. All the walls insulated with polyurethane cut down occupants' thermal discomfort hours by about 178 h compared to control models. Overall, the InsS-4 building required 187 h less mechanical cooling through the year than all three control models and showed only a slight decrease in discomfort hours among infilled models.

The adaptive thermal comfort and energy transfer results at the zone level are portrayed in Figure 5. The ASHRAE 55 Adaptive Comfort Model [55] was adopted to assess thermal comfort at both 80% and 90% acceptability limits. It uses the Predicted Mean Vote (PMV) to set the requirements for indoor thermal conditions, and it stipulates at least 80% of the occupants be satisfied with the prevailing thermal environment. Figure 5a–c shows the number of hours during which 80% and 90% of the occupants objected to the thermal condition at each zone for combinations P, R, and S. Zones 2 and 1 represent the spaces with the highest and least periods of thermal unacceptability. This is possibly due to the specified zone activities, lighting requirements, and equipment installments at the zoning

stage of energy modeling. The effect of the wall insulation is relatively prominent at zone 2. The Zone 2 P₀ wall in Figure 5a produced 38 more hours of thermal unacceptability than the Zone 2 InsS-4 wall.

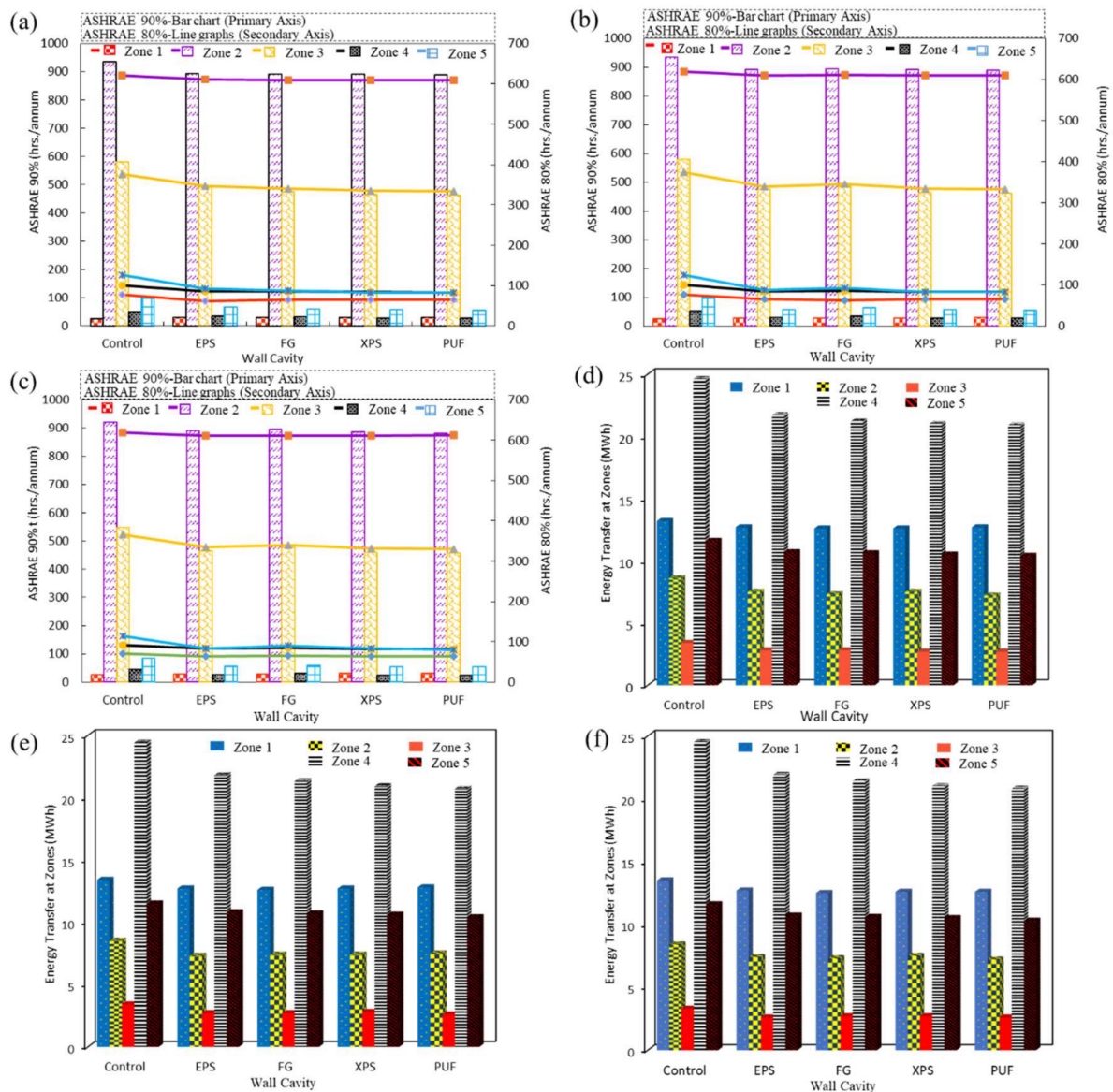


Figure 5. Performance of insulated 3DPC at ASHRAE thermal comfort acceptability limits for (a) Mix 1; (b) Mix 2; (c) Mix 3. Insulation effects on thermal energy transfer of 3DPC Walls for (d) Mix 1; (e) Mix 2; (f) Mix 3.

As seen in Figure 5d–f, the general trend for zonal energy transfer shows that each insulated zone lost lower amounts of energy through the building envelope in comparison to the uninsulated models. It is evident that zone 4 transferred the highest energy in apparent contrast to the other zones. This observation can be attributed to the initial zone specifications imputed at the start of the analysis process. The influence of the insulation is clearly visible at this zone, where the insulated envelopes transferred approximately 700 KW less energy through its surface when compared with the control models. Although all insulated models demonstrate roughly equal amounts of energy loss across the board, there is actually an estimated difference of 800 KW of energy transfer between all PU-walls than the other insulated models. Ultimately, mix 3 and PU insulation (InsS-4) revealed the least thermal energy loss, 3800 KW less energy transferred than the control wall at zone 2.

3.2. Operational Carbon Emissions

Figure 6a shows the overall effect of insulation on the operational carbon production of 3DPC walls. Operational carbon is a function of the fuel type and the efficiency of the energy systems used in the building. High carbon production can be attributed to correspondingly high operational energy use. Carbon emissions are visibly higher in control 3DPC walls than the models with cavity insulation. The result indicates that the carbon footprint of the control models is 2400 kg higher than the insulated combinations under the same building designs and climatic conditions. Further, the fiberglass-insulated cavity walls gave off slightly more emissions in the insulated wall category. From comparative computations, the FG-infilled walls emitted roughly 285 kg, 337 kg, and 504 kg more carbon than EPS, XPS, and PU-insulated walls, respectively. Moreover, the InsS-4 wall model produced approximately 2700 kg less carbon than P_0 , R_0 , and S_0 walls.

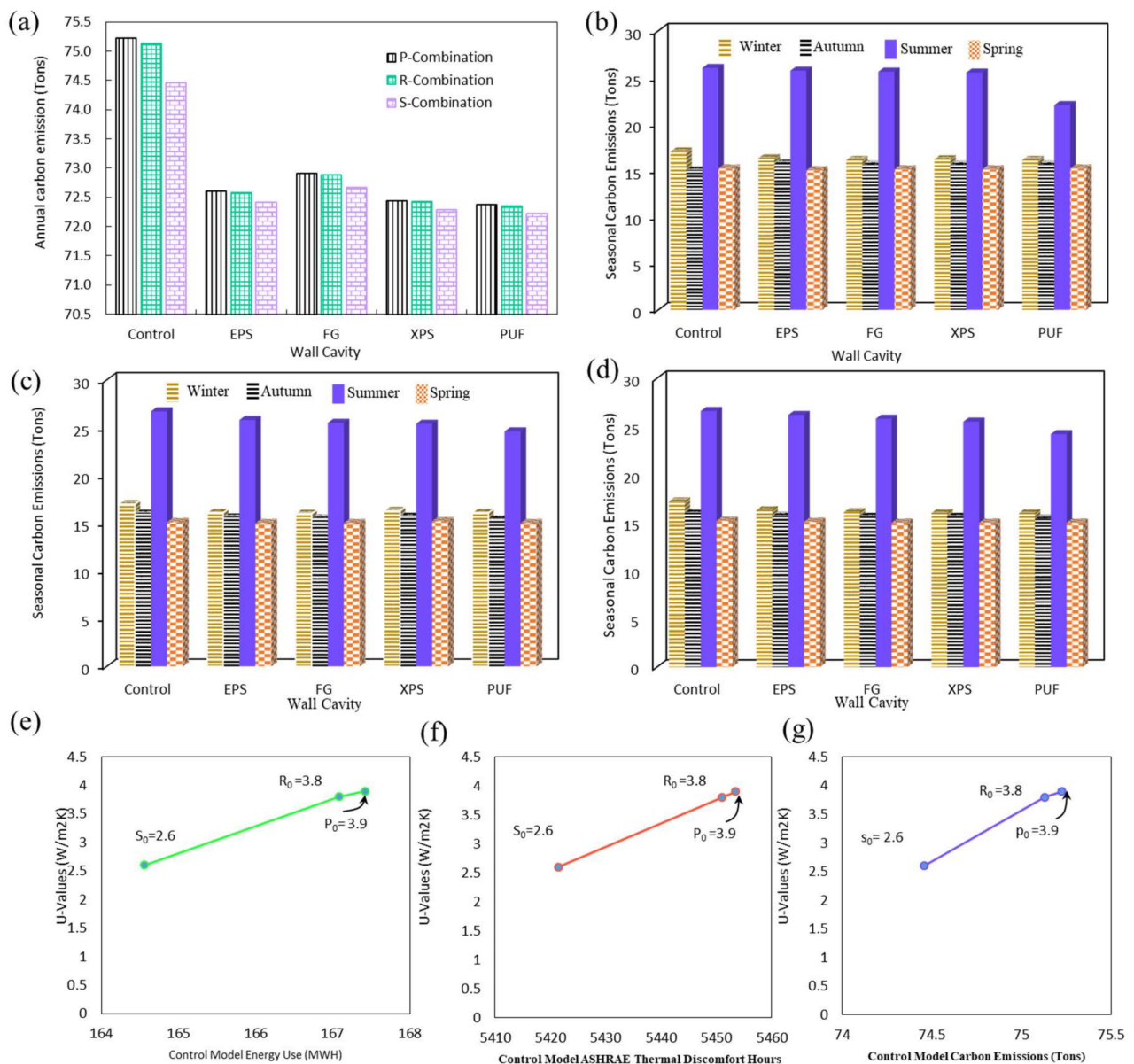


Figure 6. (a) Insulation effects on operational carbon emissions of infilled wall cavities. Variations in seasonal carbon production of insulated 3DPC walls for (b) Mix 1, (c) Mix 2, (d) Mix 3. (e) Correlation between U-value and energy use. (f) Correlation between U-value and thermal comfort performance. (g) Correlation between U-value and carbon emissions.

The seasonal breakdown of carbon emissions shown in Figure 6b–d illustrates that carbon production is 1.5 times higher in summer than in other seasons in insulated and uninsulated walls. This is partly due to the increased space cooling energy consumption required in the notoriously humid subtropical climate of the building's location, with dew points often reaching 26 °C or more. The analysis indicated that the InsS-4 combination lowered summer carbon emissions by an average of 2096 kg and 2800 kg compared to the insulated and uninsulated models, respectively. The infilled wall emissions in the other seasons show similar trends. However, closer observation shows that the PU-insulated combinations generally emit slightly lesser amounts of carbon when compared to insulated walls. Overall, the InsS-4 proved to be the optimal pair with the least annual and seasonal carbon production.

3.3. The U-Value Effect

Figure 6e–g illustrates the impact of thermal transmittance on the performance variations in energy and thermal efficiencies of mixes 1, 2, and 3. Only the uninsulated mixes (P_0 , R_0 , and S_0) are considered to observe this correlation distinctly. Previous computations show that S_0 has the lowest U-value at 2.6 Wm²/K. As a result, the output of annual energy use for wall S_0 is 2863 KW and 2519 KW lower than those of P_0 and R_0 , respectively. The same trend can be observed in the carbon emissions and thermal discomfort results, with S_0 showing amplified sustainability performance than the other air cavity walls. On average, S_0 produced 767 kg of carbon less than P_0 and 674 kg less than R_0 without insulation. By inference, 3DPC building envelopes with low U-values expend less energy to maintain comfortable conditions within the building, minimizing operational carbon emissions.

4. Conclusions

This study has described the sustainability behavior of insulated 3DPC wall cavities and the proposed combination of components for improved energy and thermal performance of printed building envelopes. The energy efficiency, operational carbon emissions, and thermal comfort performance of the digital 3D structure were analyzed with the DB-EnergyPlus modeling software and were observed to improve considerably when paired with insulating materials. Furthermore, optimization analysis was conducted to determine what combination of 3DPC mix design and insulation demonstrated amplified resource efficiency. The following conclusions have been drawn from this numerical study:

- The polyurethane-insulated wall element saved approximately 9500 KW more energy than the uninsulated models and 1400 KW more than the walls with expanded polystyrene, extruded polystyrene, and fiberglass insulations.
- The analysis also indicated that the PUF-insulated walls lowered summer carbon emissions by an average of 2096 kg and 2800 kg compared to the insulated and uninsulated models, respectively.
- The PUF-insulated building required 187 h less mechanical cooling through the year than the uninsulated envelopes and showed a slight decrease in discomfort hours compared to other insulated models.
- Additionally, the research showed that 3DPC building fabrics with low thermal transmittance make for more habitable and resource-efficient buildings.
- Ultimately, the results characterize the energy-saving potential of PUF-insulated 3D Printed Fiber Reinforced Engineered Cementitious Concrete (3DPFRECC) walls as an optimal combination for sustainable construction. Although the variation in the ecological performance between the insulated and control 3DPC models seems marginal over a one-year span, the cumulative difference would add up to a significant amount of GHG emissions and energy use over the structure's lifespan.
- Based on the results in this study, it is safe to say that similar improvements in thermal and energy efficiency can be achieved by extending the applicability of polyurethane insulation to other concrete technologies such as cast-in-place concrete walls.

This study is not without its limitations. First, the exact experimental conditions and parameters used in the 3DPC mix designs adopted are not reproduced but only simulated and designed based on actual standards. Secondly, the analysis carried out in this work was totally dependent on the typical meteorological conditions of the building location under consideration. Additionally, this study focused only on the external walls of the building while adopting the default configurations of all other building components. Future research and developments are encouraged to improve the material composition of 3DPC with an increased focus on their thermal performance and ecological behavior with emerging insulation technologies.

Author Contributions: Conceptualization, B.O.A. and K.-J.I.E.; methodology, B.O.A.; software, B.O.A.; investigation, B.O.A., K.-J.I.E., M.H., A.M.N. and M.A.H.-A.; writing—original draft, B.O.A.; resources, M.A.H.-A.; data curation, B.O.A., K.-J.I.E., A.M.N. and M.A.H.-A.; writing—review and editing, K.-J.I.E., M.H., A.M.N. and M.A.H.-A.; supervision, M.A.H.-A. and M.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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