



Thermal Performance of Polymer-Modified Concrete for Sustainable Building Envelopes

TECHNICAL ARTICLE

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ABSTRACT

This study investigates the thermal performance of polymer-modified concrete composites, focusing on their potential to enhance energy efficiency in building envelopes. Four types of recycled polymers—low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (POLYP), and polyester—were integrated into concrete mixes at varying percentages (10%, 20%, and 30%). Key thermal metrics, including thermal transmittance (U-value), decrement factor (f), decrement delay (ϕ), admittance (Y), optimum thickness, and heat capacity per unit area, were measured using the admittance approach and a MATLAB program conforming to CIBSE standards. Results indicate that higher polymer content generally improves thermal damping and reduces cyclic transmittance. Notably, LDPE 30% exhibited the best performance, achieving a decrement factor of 0.179 and a time lag of 11.76 hours. HDPE 30% demonstrated a decrement factor of 0.206 and a time lag of 10.85 hours. Polyester 30% showed a decrement factor of 0.310 and a time lag of 8.50 hours. Sensitivity analysis revealed that optimal wall thicknesses for polymer-modified concretes are lower than those required for conventional concrete, with LDPE 30% requiring an optimal wall thickness of 0.128 meters compared to 0.269 meters for conventional concrete. This research underscores the dual benefits of waste management and energy performance improvement, advocating for the practical application of polymer-modified concrete in sustainable construction. The study ranks the polymers' efficiency as LDPE, HDPE, POLYP, and Polyester. These findings support the use of recycled polymers in concrete, promoting sustainability through effective waste management and improved thermal efficiency in building envelopes.

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1. INTRODUCTION

In the realm of sustainable construction, the demand for innovative materials that mitigate environmental impact and uphold energy efficiency standards has become paramount (Kehinde et al., 2020). The escalating global consumption and subsequent disposal of plastics have spurred investigations into eco-conscious disposal methods (Kumar et al., 2021). A notable approach involves repurposing recycled plastic as an alternative to conventional construction materials, particularly in concrete formulations (da Silva et al., 2021; Lamba et al., 2022; Alyousef et al., 2021). This study focuses on evaluating the thermal properties of concrete incorporating plastic sand substitutes, a topic garnering significant attention due to its potential for fostering sustainable construction practices (Steyn et al., 2021; Ullah et al., 2022; Tayeh et al., 2021).

Building insulation is crucial for reducing energy consumption and minimizing carbon emissions in the building sector. The construction industry continuously seeks innovative materials that provide excellent thermal performance while ensuring sustainability. Several studies have explored different insulation materials and techniques to enhance the thermal performance of building envelopes. One promising area of research is the use of thermal insulation plasters. Cuce et al. (2023) conducted a study highlighting the growing importance of thermal insulation plasters as a solution to reduce energy consumption in buildings. Their research involved testing a novel insulation plaster (NIP) on conventional briquettes with varying thicknesses. The results showed that using NIP as an insulation material led to significant improvements in the thermal resistance of the briquettes. Specifically, a briquette with a 2–2 NIP thickness achieved the lowest U-value (2.86 W/m²K) compared to a conventional briquette (5.5 W/m²K). The study demonstrated the potential of NIP as a cost-effective and efficient insulation solution for building envelopes.

Researchers are also investigating the performance of insulation materials at elevated temperatures to assess their fire resistance and suitability for building applications. Kontoleon et al. (2023) investigated the impact of insulation material properties on the thermal performance of a composite precast concrete wall system exposed to high temperatures. Their research focused on using expanded polystyrene (EPS) and rockwool (RW) as insulation layers within the precast concrete wall assembly. The study used a 3D finite element model to simulate the thermal behavior of the wall system when subjected to a standard temperature-time curve. The results revealed that the type, thickness, and positioning of the insulation material significantly influenced the wall's ability to resist heat transfer under fire conditions. For example, placing rockwool insulation on the fire-exposed side of the wall led to a considerable reduction

in temperature on the unexposed side, effectively enhancing the wall's fire resistance. Ustabas et al. (2024) conducted experimental research to analyze the fire retardation, compressive strength, and durability of concrete reinforced with novel plasters. The researchers examined how different types of plasters, including unplastered (UNP), roughly plastered (RP), and those with contemporary insulation plaster (CIP), performed at elevated temperatures. Concrete samples coated with varying thicknesses of these plasters were exposed to controlled temperatures (300°C, 450°C, and 600°C) for different durations (60, 90, and 120 minutes), and their compressive strength was subsequently measured. The findings indicated that the CIP-reinforced samples showed improved fire resistance and retained higher compressive strength compared to the other plaster types. The study highlighted the potential of using CIP as a protective measure to improve the fire resilience of concrete structures. Cuce et al. (2024) conducted an experimental study to evaluate the thermal performance of a traditional house retrofitted with aerogel insulation. Their research focused on determining the heat loss coefficient (HLC) and U-value of the house before and after applying an aerogel blanket. The results demonstrated a significant improvement in the thermal insulation of the house after retrofitting with aerogel insulation, leading to a reduction in heat loss. The study emphasized the effectiveness of aerogel as a superinsulation material for enhancing the energy efficiency of buildings.

The thermal performance of building envelopes plays a pivotal role in determining energy consumption, indoor comfort, and overall building sustainability. Parameters such as time lag and decrement factor are instrumental in assessing the dynamic thermal behavior of building envelopes. Existing literature has examined the thermal performance of walls in hot and humid tropical climates, analyzing parameters like time lag and decrement factor. Numerical models developed through finite difference methods have been employed to evaluate various wall configurations, revealing time lags ranging from 2 to 4 hours and decrement factors varying from 0.199 to 0.327, with differences noted between different months (Quagraine et al., 2020).

Building structures, one incorporating Phase Change Material (PCM) macrocapsules and another without PCM, were subjected to testing in a tropical environment for a year. Results indicated that the PCM-enhanced structure exhibited reduced indoor peak temperatures (0.2°C to 4.3°C), decreased thermal amplitude (–2.43% to 51.3%), an average time delay of 97.5 minutes, and a 24.69% reduction in decrement factor. Additionally, the PCM structure demonstrated an average 17.37% reduction in peak heat flux, leading to cost savings of 1.47 rupees/kWh/m²/day in peak cooling load (Rathore et al., 2020). The substitution of standard aggregate with waste or by-products has been shown to enhance the sustainability

of cement-based materials, promoting energy efficiency and reducing environmental impact. Investigations into innovative mortar and concrete formulations utilizing oil palm boiler clinker as aggregates have yielded promising results, with modified materials exhibiting improved thermal properties. Notably, concrete exhibited a notable 34% reduction in decrement factor and up to 58% increased time lag compared to conventional counterparts (Asadi et al., 2023). Studies have also explored the impact of envelope thickness and solar absorption on time lag and decrement factor in test cells constructed with compressed earth bricks stabilized with cement. Results indicated significant thermal inertia in the bricks, with time lag increasing and decrement factor decreasing with envelope thickness, while solar absorption exhibited a moderate impact (Toure et al., 2020). Furthermore, research has examined how individual thermophysical properties influence time lag and decrement factor in building elements. Testing of concrete wall samples revealed diverse effects on time lag and decrement factor, emphasizing the need for a comprehensive evaluation (Oktay et al., 2020).

Decrement factor and phase shift are critical in assessing wall thermal performance and influencing building energy usage, with factors such as physical properties and thickness playing key roles. Analysis has revealed the relationship between dimensionless thickness and dynamic Biot number on these indicators (Lu et al., 2024). Studies have also investigated the impact of waste plastic additives on the thermal performance of unfired clay bricks, with a new melt compounding method addressing adhesion challenges. Thermal simulations demonstrated significant improvements in thermal stability, offering substantial energy savings potential (Limami et al., 2020). Previous research focused on utilizing sawdust waste for a new bio-based insulation material, examining thermal characteristics, time lag, and decrement factor. Results indicated that higher density increases thermal conductivity, diffusivity, and volumetric heat capacity, while decreasing thermal diffusivity (Zine et al., 2023).

Additionally, investigations into the influence of cement, wood fly ash, and calcium bentonite on the mechanical and thermal properties of rammed earth in eco-friendly vernacular buildings have shown variations in thermal parameters, with notable improvements in compressive strength and thermal insulation recorded (Zarasvand et al., 2023). Efforts to enhance energy savings by integrating natural waste materials into traditional mud-bricks have yielded significant improvements in thermal efficiency and greenhouse gas reduction (Arumugam and Shaik, 2021). Similarly, evaluations of various PCM-stuffed terracotta brick configurations have identified OM32 PCM as particularly effective in hot-dry climates, offering potential improvements in energy efficiency and sustainability (Chelliah et al., 2021). Innovative approaches to enhance the energy efficiency

and thermal comfort of buildings have been explored, highlighting the promising thermal insulation properties of incorporating shredded PET into concrete panels (Elhamy and Mokhtar, 2024). Additionally, broader applications of PCMs in building envelopes have provided valuable insights into regulating indoor temperatures and reducing reliance on energy-intensive cooling systems (Mahrous et al., 2024).

Despite the existing body of literature, comprehensive data on time lag, decrement factor, and other unsteady thermal characteristics of various plastic-infused concrete formulations are limited. This research addresses this gap by investigating how polymer-modified concrete can enhance thermal performance in building envelopes. It compares conventional concrete with composites containing recycled polymers, such as LDPE, HDPE, POLY, and polyester, analyzing their dynamic heat transfer characteristics. The findings suggest that higher polymer percentages improve thermal damping and reduce cyclic transmittance, enabling comparable insulation to conventional concrete with thinner walls. This study underscores the potential for lighter, cost-effective, and thermally efficient building envelopes, emphasizing the dual benefits of waste management and improved energy performance.

This study is structured to comprehensively evaluate the thermal performance of polymer-modified concrete in comparison to conventional concrete. The following sections systematically analyze key thermal metrics, including decrement factor, time lag, thermal transmittance, thermal admittance, optimum thickness, and heat capacity per unit area. By employing these parameters, the study aims to provide a detailed understanding of how incorporating recycled polymers such as LDPE, HDPE, polypropylene, and polyester can enhance energy efficiency and sustainability in building envelopes. Through sensitivity analyses and comparative assessments, this research not only underscores the environmental benefits of utilizing recycled polymers but also highlights their practical implications in sustainable construction practices.

2. METHODOLOGY

The admittance approach is utilized for ascertaining dynamic heat transfer coefficients (CIBSE, 2006; Shaik and Talanki, 2016a; Shaik and Talanki, 2016b). This approach involves both transient and cyclic responses, which are essential aspects of dynamic thermal modeling. In this study, we applied the cyclic-response admittance method to evaluate the thermal properties of the building materials. This method considers the effects of dynamic conditions on heat transfer, thermal absorption, and thermal storage properties by calculating unsteady-state multiplier factors applicable to the steady-state properties of building materials.

Under steady-state conditions, the temperature difference between indoor and outdoor environments creates a thermal gradient across the building fabric. This gradient is influenced by the thermophysical properties of the wall materials and their surface resistances. The cyclic admittance method simplifies this process by using a hypothetical sol-air temperature instead of the actual outside air temperature to define the thermal gradient. The hypothetical sol-air temperature in the admittance method accounts for the rate of heat flow into the external building surface due to convection from the surrounding air, solar shortwave radiation, and radiative exchange with the environment. Similarly, the internal wall surface's heat flow, affected by radiation from internal sources like occupants, lights, and heaters, and convection from room air, is represented by the environmental temperature, another hypothetical measure.

To solve the one-dimensional heat flow diffusion equation with periodic convective boundary conditions at the sol-air node, we employed matrix algebra. It is assumed that heat transfer occurs only in one direction through the building walls, with no heat generation and no temperature gradient in the other two directions. Consequently, the temperature distribution in a homogeneous wall is governed by one-dimensional unsteady heat flow, described by the diffusion equation:

The methodology adopted follows the procedure outlined by Davies (2004).

$$\frac{\partial^2 T}{\partial Z^2} = \frac{\mu C_p}{k} \frac{\partial T}{\partial t} \quad (1)$$

Where T is the temperature, Z is the spatial dimension across the wall thickness, μ is the material density, C_p is the specific heat capacity, and k is the thermal conductivity.

The boundary condition at the wall's inner surface:

$$\left(\frac{\partial T}{\partial Z} \right)_{T=0} = S_i [T_{T=0}(t) - T_i] \quad (2)$$

The boundary condition at the wall's outside surface:

$$\left(\frac{\partial T}{\partial Z} \right)_{T=L} = S_o [T_{T=L}(t) - T_{T=L}(t)] \quad (3)$$

$T_{T=0}$ represents the inner surface temperature of the wall and $T_{T=L}$ represents the outer surface temperature of the wall.

T_i is the indoor temperature and T_{∞} is the outdoor air temperature.

$$T = [M \sinh(Zl + jZl) + N \cosh(Zl + jZl)] \exp(j2\pi t / P)$$

Where $Z = \sqrt{\pi \rho C_p / ks}$, P = period, l = finite thickness, M = heat flux, N = thermal resistance

$$\begin{bmatrix} T_i \\ Q_i \end{bmatrix} = \begin{bmatrix} \cosh(y + jy) & (\sinh(y + jy)) / d \\ (\sinh(y + jy)) \times d & \cosh(y + jy) \end{bmatrix} \begin{bmatrix} T_e \\ Q_e \end{bmatrix} \quad (4)$$

Here, T_i, T_e denotes the internal and external periodic temperatures respectively, Q_i, Q_e denotes internal and external periodic heat flux respectively. The cyclic depth (y) and the characteristic admittance of the slab (d) are defined as:

$$y = \sqrt{\pi} \mu C_p Y^2 / \lambda T = \sqrt{\pi} C m / T \quad (5)$$

$$d = \sqrt{j} 2 \pi k \mu C_p / T = \sqrt{j} 2 \pi C / m T \quad (6)$$

The transmission matrix for a single layer is depicted as:

$$\begin{bmatrix} L_1 + jL_2 & (L_3 + jL_4) / d \\ (-L_4 + jL_3) \cdot d & L_1 + jL_2 \end{bmatrix} \quad (7)$$

The constants L_1, L_2, L_3 , and L_4 are calculated using the formulas:

$$\begin{aligned} L_1 &= \cosh(y) \cos(y), \\ L_2 &= \sinh(y) \sin(y) \\ L_3 &= \frac{\cosh(y) \sin(y) + \sinh(y) \cos(y)}{\sqrt{2}}, \\ L_4 &= \frac{\cosh(y) \sin(y) - \sinh(y) \cos(y)}{\sqrt{2}} \end{aligned}$$

For composite walls, the transmission matrix is expressed as:

$$\begin{bmatrix} T_i \\ Q_i \end{bmatrix} = \begin{bmatrix} 1 & -S_i \\ 0 & 1 \end{bmatrix} \begin{bmatrix} c_1 & c_2 \\ c_3 & c_1 \end{bmatrix} \begin{bmatrix} d_1 & d_2 \\ d_3 & d_1 \end{bmatrix} \cdots \begin{bmatrix} 1 & -S_o \\ 0 & 1 \end{bmatrix} \begin{bmatrix} T_e \\ Q_e \end{bmatrix} \quad (8)$$

In these equations, S_i and S_o represent the transmission matrices for internal and external surface resistance of the wall, respectively, while c and d denote the layers of the wall.

The aggregate relation between the interior and exterior of composite walls is represented by:

$$\begin{bmatrix} T_i \\ Q_i \end{bmatrix} = \begin{bmatrix} W_1 & W_2 \\ W_3 & W_4 \end{bmatrix} \begin{bmatrix} T_e \\ Q_e \end{bmatrix} \quad (9)$$

Thermal Transmittance (U): This measures the heat flow through a wall, with a lower U value indicating better insulation properties.

$$U = \frac{1}{\frac{1}{h_{so}} + \left(\frac{Y_1}{k_1} \right) + \left(\frac{Y_2}{k_2} \right) + \cdots + \frac{1}{h_{si}}} \quad (10)$$

Thermal Admittance (Y): This quantifies the heat flow into the thermal storage of a wall, considering heat capacity, thermal conductivity, thickness, and density. A higher Y value suggests a greater thermal mass.

$$y_i = \left(\frac{Q_i}{T_i} \right)_{T_{e=0}} = -\frac{W_1}{W_2}, Y = |y_i| \quad (11)$$

Decrement Factor (f): This measures the attenuation rate of heat transfer through a wall due to its thermal storage capacity, with a lower f value indicating higher thermal mass.

$$f_c = -\frac{1}{UW_2}, f = |f_c| \quad (12)$$

Decrement Delay (ϕ): This is the time required for a heat wave to travel from the outer to the inner surface of a wall, important for understanding thermal lag characteristics.

$$\phi = \frac{12}{\pi} \arctan \left(\frac{\text{Im}(f_c)}{\text{Re}(f_c)} \right) \quad (13)$$

Optimal Wall Thickness (OT): This is determined for maximal thermal capacity.

$$OT = 1.2 \sqrt{\frac{\beta T}{v}} \quad (14)$$

Surface Factor (F): This indicates the responsiveness of a building material's surface to short-wave radiation, helping in selecting materials for specific climatic conditions.

$$F_c = 1 - R_{si} Y_c \quad F = |F_c| \quad (15)$$

Factor Time Lag (ψ): This is the time lag between peak heat flow entering and leaving the wall surface, influencing design choices for optimizing thermal comfort.

$$\psi = \frac{12}{\pi} \arctan \left(\frac{\text{Im}(F_c)}{\text{Re}(F_c)} \right) \quad (16)$$

Heat Capacity per Unit Area (χ): This is given by:

$$\chi = \frac{t}{2\pi} \left| \frac{W_4 - 1}{W_2} \right| \quad (17)$$

In this equation, χ is the heat capacity per unit area ($\text{J} \cdot \text{K}^{-1} \cdot \text{m}^{-2}$), and t represents the period of the temperature cycle (seconds). W_4 and W_2 are specific matrix elements from the transmission matrix, indicative of the wall's thermal attributes.

3. MATERIALS AND METHODS

3.1 MATERIALS

The composite concrete specimens in this study were created using a standard mix of fine aggregate, coarse aggregate, Portland cement, and water. This mix was modified by incorporating plastic polymers repurposed from waste to enhance the thermal performance characteristics of conventional concrete. This approach

addresses both economic and environmental concerns by reducing reliance on virgin materials and leveraging the cost-efficiency of recycling.

Four types of polymer materials were examined as sand substitutes within the concrete mixture: low-density polyethylene (LDPE), polypropylene (PP), polyester, and high-density polyethylene (HDPE) (Figure 1). These materials were selected due to their availability as recycled waste and their potential to improve concrete performance. Grade 53 Ordinary Portland Cement (OPC), as per IS 12269-2013 standards (BIS, 2013), was used for its consistent quality and performance. Coarse aggregates, compliant with IS 383 requirements (BIS, 1970), consisted of crushed rock with a maximum size of 20 mm, a specific gravity of 2.78 gm/cm^3 , and a water absorption rate of 0.83%. Fine aggregate was sourced from natural river sand, with a maximum particle size of 2.36 mm.

Polymers LDPE, PP, polyester, and HDPE were incorporated into the concrete samples at 10%, 20%, and 30% by weight. These polymers were processed into a fine powder with an average diameter of 0.7 to 1 mm through pulverization. 100 mm cubes were cast for each material sample, the concrete mix proportioning was done as per the IS:10262-2009 standards (BIS, 2009). After casting the concrete samples and allowing for a standard setting period, the specimens underwent a meticulous water-curing process over 28 days to ensure optimal hydration. Following the curing process, a series of tests were conducted to measure thermal conductivity and specific heat using a KD2 Pro thermal properties analyzer. This testing protocol, involving specialized thermal probes, allowed for precise determination of these critical thermophysical properties.

The thermophysical properties measured included thermal conductivity (K), specific heat capacity (Cp), and density (ρ), which influence heat transfer rates, thermal energy storage, and structural aspects, respectively. These measurements were conducted according to relevant standards (ASTM, 2016). Table 1 presents the data, detailing these properties for each modified concrete sample containing varying percentages of polymers, as well as the control sample of conventional concrete.

This research focuses on assessing the key thermal metrics thermal transmittance, decrement factor, decrement delay, admittance, optimum thickness, and heat capacity per unit area to evaluate the efficacy of composite concrete samples in real-world applications. These metrics provide a comprehensive view of the material's potential to enhance thermal comfort and energy efficiency in buildings. The parameters were chosen for their relevance to building physics and their potential to inform sustainable design practices. The small-scale concrete specimens with varying polymer percentages were used to predict their performance in external wall construction. A hypothetical wall (0.2 m thickness, 0.015 m plaster) was evaluated using thermophysical



Figure 1 a. Low density polyethylene b. High density polyethylene c. Polypropylene d. Polyester.

S. NO	MATERIAL	K (W/mK)	Cp (J/kgK)	ρ (kg/m ³)
1	Low density polyethylene 10%	0.568	1096.79	2126.2
2	Low density polyethylene 20%	0.523	1227.47	2031
3	Low density polyethylene 30%	0.48	1474.37	1943.2
4	Polypropylene 10%	0.956	881.97	2330
5	Polypropylene 20%	0.823	1034.12	2110
6	Polypropylene 30%	0.712	1070.5	2085
7	High density polyethylene 10%	0.612	1106.16	2336
8	High density polyethylene 20%	0.584	1281.18	2201.1
9	High density polyethylene 30%	0.592	1331.81	2185
10	Polyester 10%	0.991	942.02	2349.2
11	Polyester 20%	0.949	985.96	2422
12	Polyester 30%	0.931	1045.63	2458.8
13	Conventional Concrete	1.42	1126	2482

Table 1 Thermal Properties of Wall Materials.

properties from 100 mm cubic specimens. This analysis informs potential thermal performance improvements with polymer-modified concrete, focusing on thermal transmittance and thermal mass. This approach bridges laboratory experimentation and real-world application, enhancing understanding of material performance in situ.

3.3 WALL UNSTEADY THERMAL CHARACTERISTICS

Unsteady-state thermal behavior was investigated using a one-dimensional heat transfer model with periodic convective boundary conditions. A MATLAB program utilizing the cyclic admittance method was developed to solve the heat transfer equation.

Program Validation

The computer program's accuracy and reliability were validated against established standards, specifically those of the Chartered Institution of Building Services Engineers (CIBSE) and the results from Davies, in accordance with Indian standards IS 3792-1978 (BIS, 1978).

The validation used a lightweight concrete composite wall with the following specifications: wall thickness of 0.2 meters, thermal conductivity of 0.19 W/mK, specific heat capacity of 1000 J/kgK, and density of 600 kg/m³. The wall was plastered on the interior surface with cement plaster (thickness: 0.013 meters, thermal conductivity: 0.5 W/mK, specific heat capacity: 1000 J/kgK, density: 1300 kg/m³).

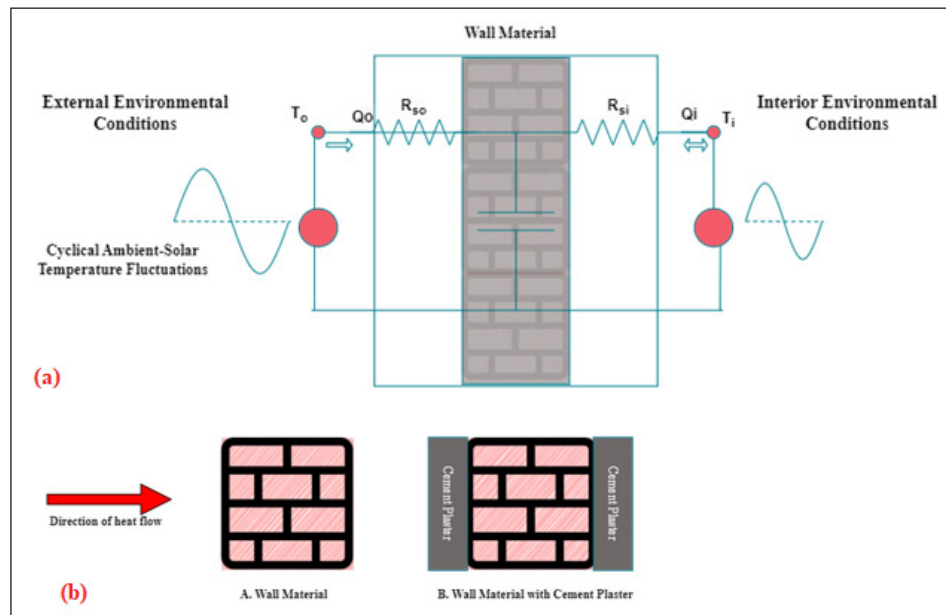


Figure 2 (a) Schematic illustration of a wall depicting periodic heat transfer from the exterior to the interior environment. **(b)** Configuration of the walls.

The program's results for this wall configuration were compared to those of Davies, as shown in Table 2. The comparison confirmed the program's accuracy in computing unsteady-state heat transfer characteristics, aligning with established standards. Surface resistances for the walls were considered according to CIBSE standards: $0.13 \text{ W/m}^2\text{K}$ for the inside surface and $0.04 \text{ W/m}^2\text{K}$ for the outside surface. The analysis assumed horizontal heat transfer through the vertical walls.

UNSTEADY PROPERTY OF WALL	PROGRAM	DAVIES	DEVIATION
Transmittance	0.7942	0.794	-0.03
Admittance	2.817	2.82	0.11
Decrement Factor	0.548	0.55	0.36
TimeLag	6.895	6.9	0.07

Table 2 Comparison of Results.

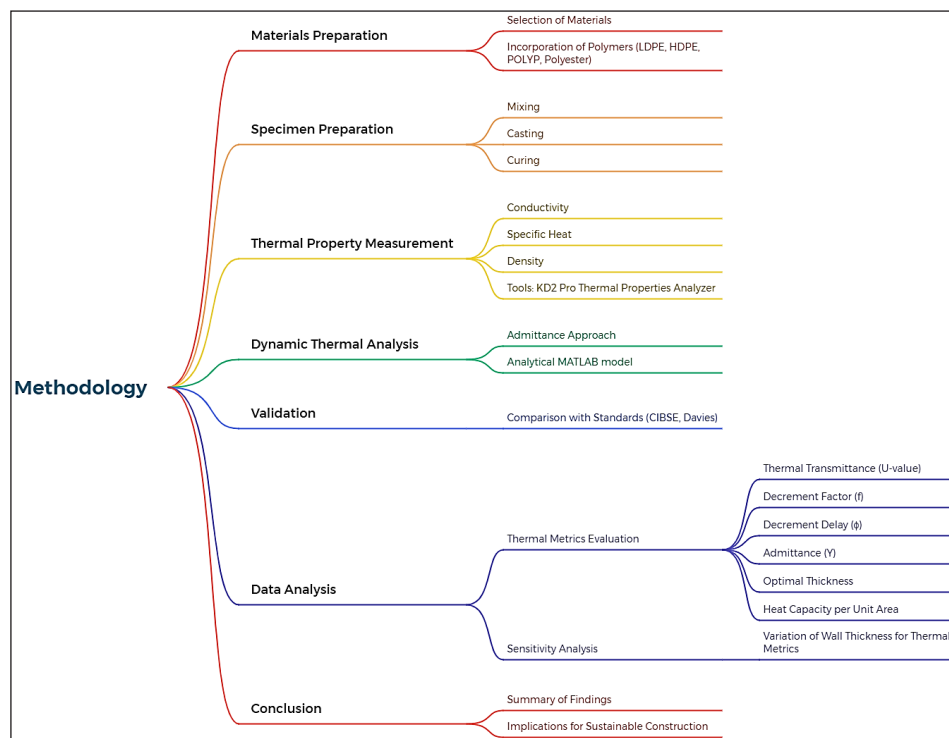


Figure 3 Methodology diagram illustrating the key steps of the study.

4. RESULTS AND DISCUSSIONS

The thermal performance characteristics of polymer-modified concrete composites for external wall construction were analyzed. The study examined a standard wall assembly with a 0.2 m thickness of modified concrete and a 0.015 m plaster layer. Figure 2 illustrates (a) the heat transfer schematic and (b) the wall configurations, while Figure 3 outlines the study's methodology. The relationship between wall composition—categorized by wall code—and its thermal performance parameters, including Decrement Factor, Time Lag, Surface Factor and its Time Lag, Optimum Thickness, and Heat Capacity, was explored, as presented in Tables 3 and 4.

A sensitivity analysis assessed the impact of varying wall thicknesses up to 1 meter on these thermal properties, aiming to identify the most efficient configurations. The results highlight practical implications and design considerations for the use of these modified concrete composites in sustainable and energy-efficient building design.

The following subsections interpret each set of results, discussing the data and exploring the implications within the broader context of sustainable construction and energy efficiency.

4.1 DECREMENT FACTOR

The decrement factor (f) is a critical parameter for evaluating a material's capacity to attenuate external temperature oscillations, contributing to thermal comfort within buildings (Shaik and Setty, 2016). A lower decrement factor indicates a material's ability to reduce the amplitude of temperature fluctuations, which is beneficial in climates with significant diurnal temperature variations. Figure 4 illustrates the decrement factors

of various polymer-modified concrete composites compared to conventional concrete.

The data reveal that the decrement factor varies with the type and proportion of polymer additive. For the LDPE series, increasing the LDPE content from 10% to 30% results in a lower decrement factor, indicating enhanced thermal damping. Polypropylene and Polyester modified samples exhibit similar trends, with distinct decrement values reflecting the importance of polymer type in thermal performance. Within each polymer category, the 30% substitution variants consistently demonstrate superior thermal moderation compared to the 10% and 20% variants. Compared to conventional concrete (indicated by the green bar), all 30% polymer-modified composites show lower decrement factors. This suggests these materials are more effective at mitigating external temperature fluctuations, potentially improving thermal comfort and reducing the need for active heating and cooling systems. Notably, LDPE 30% exhibited the most significant reduction in decrement factor (0.17913).

4.2 TIME LAG

Time lag (ϕ) is a crucial factor in building physics, representing the delay between the peak outdoor temperature and the peak indoor temperature (Saboor et al., 2021). A higher time lag can enhance thermal comfort, particularly in regions with significant diurnal temperature variations, by reducing the need for heating or cooling during peak hours. Figure 5 illustrates the time lag across various polymer-modified concrete samples compared to conventional concrete.

The data indicate that LDPE samples show an increasing time lag with higher polymer content, with LDPE 30% achieving the longest delay. This suggests higher LDPE percentages enhance the material's ability to delay heat transfer. Polypropylene and Polyester modified samples

WALL CODE	U (W/m ² K)	f	Φ (h)	Y (W/m ² K)	F	Ψ (h)
LDPE10%	1.7739	0.2656	9.8179	4.5982	0.47914	1.6309
LDPE20%	1.6835	0.23144	10.53	4.5833	0.48111	1.625
LDPE30%	1.5917	0.17913	11.757	4.613	0.47577	1.6249
POLYP10%	2.3763	0.39047	7.4854	4.8618	0.43841	1.6866
POLYP20%	2.1996	0.34699	8.1755	4.805	0.44664	1.6695
POLYP30%	2.0304	0.31672	8.7541	4.724	0.45932	1.6542
HDPE10%	1.8573	0.24548	10.056	4.7115	0.45985	1.6392
HDPE20%	1.8048	0.21264	10.736	4.7333	0.45577	1.6371
HDPE30%	1.82	0.20583	10.854	4.7613	0.45099	1.6385
POLYEST10%	2.4188	0.369	7.6837	4.9308	0.4262	1.6854
POLYEST20%	2.3677	0.33645	8.126	4.9497	0.42201	1.6763
POLYEST30%	2.345	0.30898	8.5055	4.9804	0.41601	1.6689
CONCR	2.8373	0.33422	7.6277	5.2762	0.36684	1.677

Table 3 Unsteady Wall Thermal parameters.

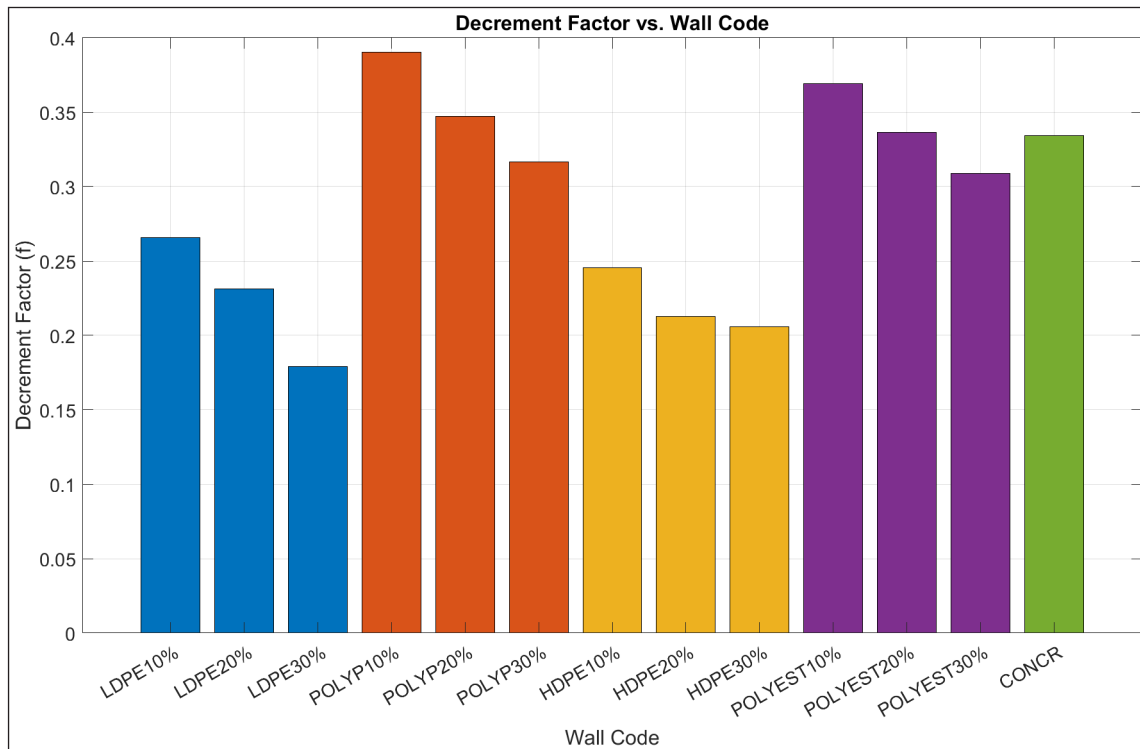


Figure 4 Decrement Factor vs Wall Codes.

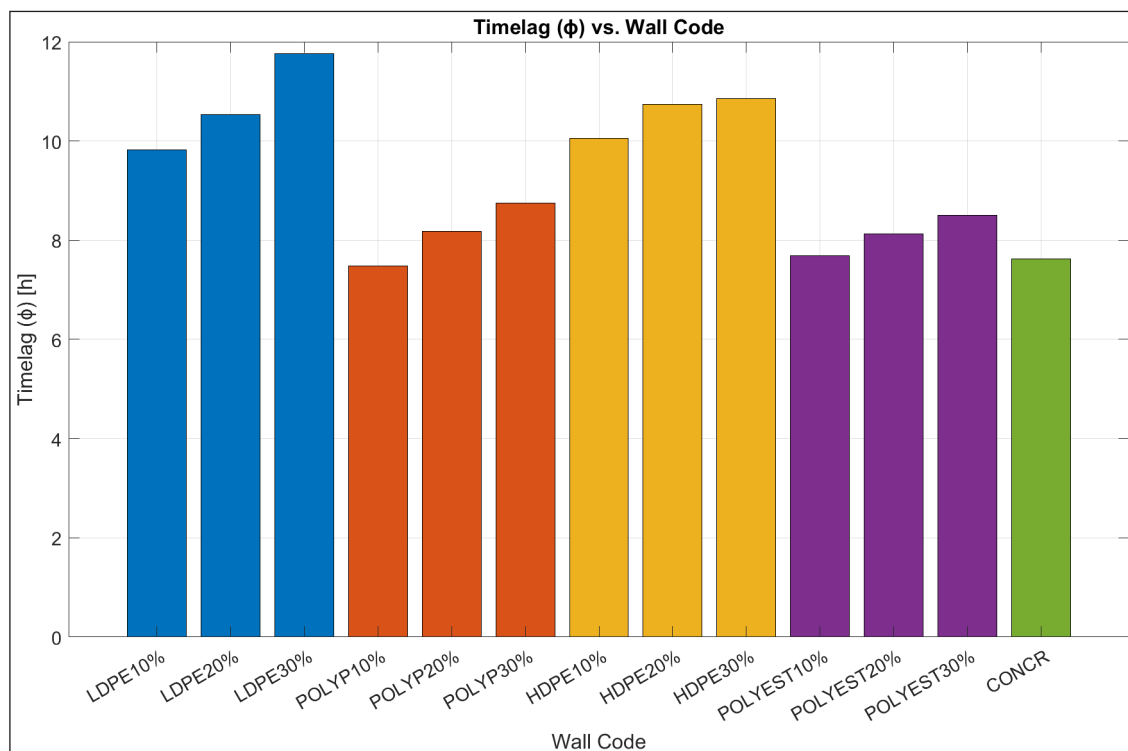


Figure 5 Time Lag vs Wall Codes.

exhibit similar trends, with distinct time lag values reflecting the different thermal characteristics of the polymers.

Overall, modified concrete samples with higher polymer concentrations tend to have greater time lags, indicating improved thermal inertia. Compared to conventional concrete, the LDPE 30%, Polypropylene 30%, and Polyester 30% samples demonstrate enhanced time lags, highlighting their potential to provide better

thermal comfort by delaying indoor heat peaks. Notably, LDPE 30% shows the highest time lag, surpassing conventional concrete, underscoring its effectiveness in thermal energy management. This significant delay in thermal response suggests that LDPE-modified concrete could be particularly beneficial for walls where managing heat intake and release is critical for minimizing energy consumption in heating and cooling systems.

4.3 SURFACE FACTOR AND TIME LAG

Figure 6 compares the “Surface Factor and Time Lag (ψ) vs. Wall Code” for various polymer-modified concrete composites relative to conventional concrete. The Surface Factor, shown by the bars, indicates the rate at which a material absorbs heat, while its associated Time Lag, depicted by diamond markers, shows the delay in peak temperature reaching the interior surface. Conventional concrete (CONCR), represented by the green bar and diamond, has the lowest Surface Factor and a relatively high Time Lag, indicating slow heat absorption and significant thermal inertia. This is advantageous for thermal management, as it delays heat transfer to the interior.

LDPE-modified samples have slightly higher Surface Factors than conventional concrete but exhibit lower Time Lags, indicating a faster thermal response. LDPE30% has the shortest Time Lag within its category, suggesting rapid heat transfer. Polypropylene (POLYP) modified samples show increasing Surface Factors with decreasing Time Lags from POLYP10% to POLYP30%, though still longer than LDPE variants, indicating a more delayed thermal response. HDPE-modified samples show a slight decrease in both Surface Factor and Time Lag with increasing polymer content. HDPE30% has a Time Lag comparable to LDPE30%, indicating similar thermal response characteristics. Polyester-modified samples display decreasing Surface

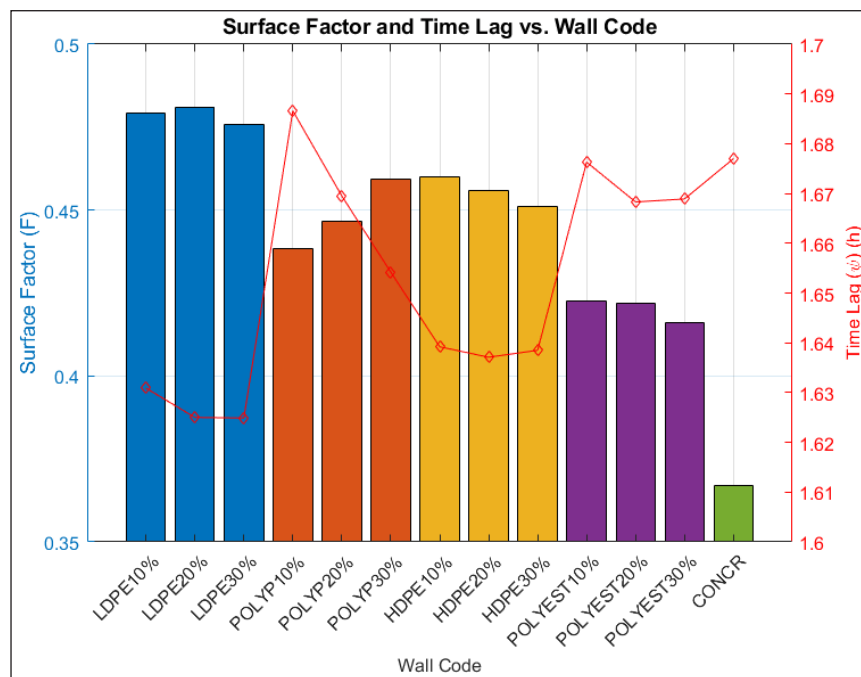


Figure 6 Surface Factor and its associated Time Lag vs Wall Codes.

WALL CODE	OPTIMUM THICKNESS (m)	$\chi \times 10^4$ (J/K. m ²)	u (W/m ² K)
LDPE10%	0.15312	69550	0.4712
LDPE20%	0.14182	68377	0.3896
LDPE30%	0.12791	67220	0.2851
POLYP10%	0.22439	75618	0.9279
POLYP20%	0.19989	74445	0.7632
POLYP30%	0.1804	72725	0.6431
HDPE10%	0.15583	70953	0.4559
HDPE20%	0.14683	70364	0.3838
HDPE30%	0.1467	70624	0.3746
POLYEST10%	0.22508	76526	0.8926
POLYEST20%	0.2141	76564	0.7966
POLYEST30%	0.20697	76711	0.7246
CONCR	0.26863	81162	0.9482

Table 4 Wall Thermal Parameters.

Factors and Time Lags with higher polymer content. Their Time Lags are comparable to conventional concrete but slightly higher than LDPE and HDPE variants.

Each polymer-modified concrete sample exhibits distinct thermal behavior. Despite higher initial heat absorption rates, their Time Lags vary, influenced by the type of polymer. These findings highlight the potential for tailored concrete composites to optimize thermal comfort in building construction (Talanki and Shaik, 2016).

4.4 OPTIMUM THICKNESS

Figure 7 compares the “Optimum Thickness vs. Wall Code” for various polymer-modified concretes and conventional concrete, assessing the ideal thickness required for maximum thermal capacity. Optimum thickness is vital for designing building envelopes as it influences thermal energy storage and overall energy efficiency. For LDPE-modified samples, the required optimum thickness decreases with increasing polymer content. LDPE10% requires 0.153 meters, while LDPE30% reduces to 0.128 meters, indicating that higher LDPE content results in a more thermally responsive material requiring thinner walls. Polypropylene (POLYP) modified samples show a similar trend, with optimum thickness decreasing from 0.224 meters at POLYP10% to 0.180 meters at POLYP30%.

HDPE-modified samples exhibit a slight decrease in optimum thickness with increasing HDPE content. HDPE10% requires 0.156 meters, while HDPE30% requires 0.147 meters, indicating stable thermal capacity requirements across the HDPE series. Polyester-modified samples also show a consistent decline in optimum thickness, with POLYEST10% requiring 0.225 meters

and POLYEST30% needing 0.207 meters. Conventional concrete (CONCR) has the highest optimum thickness at 0.269 meters, suggesting that traditional concrete needs thicker walls for maximum thermal storage. Overall, modified concretes with higher polymer content generally allow for thinner walls to achieve maximum thermal capacity compared to traditional concrete. This can result in lighter, more cost-effective building designs with adequate thermal performance.

4.5 HEAT CAPACITY

Figure 8 compares the “Heat Capacity vs. Wall Code,” illustrating the heat capacity per unit area (χ) for various polymer-modified concrete composites and conventional concrete (CONCR). Heat capacity is a critical parameter for thermal regulation, influencing how the internal environment responds to external temperature changes. Conventional concrete, with the highest heat capacity at 81162 J/K·m², serves as the benchmark, highlighting its strong buffering ability against temperature fluctuations, beneficial for energy conservation in buildings.

The LDPE series shows a gradual decrease in heat capacity with increased polymer content, from 69550 J/K·m² for LDPE10% to 67220 J/K·m² for LDPE30%. The HDPE series demonstrates consistent thermal storage characteristics, with HDPE10%, HDPE20%, and HDPE30% showing heat capacities of 70953 J/K·m², 70364 J/K·m², and 70264 J/K·m², respectively. The Polyester series presents a slight increase in heat capacity with higher polymer content, with POLYEST10% at 76526 J/K·m² and POLYEST30% at 76534 J/K·m², closely matching conventional concrete.

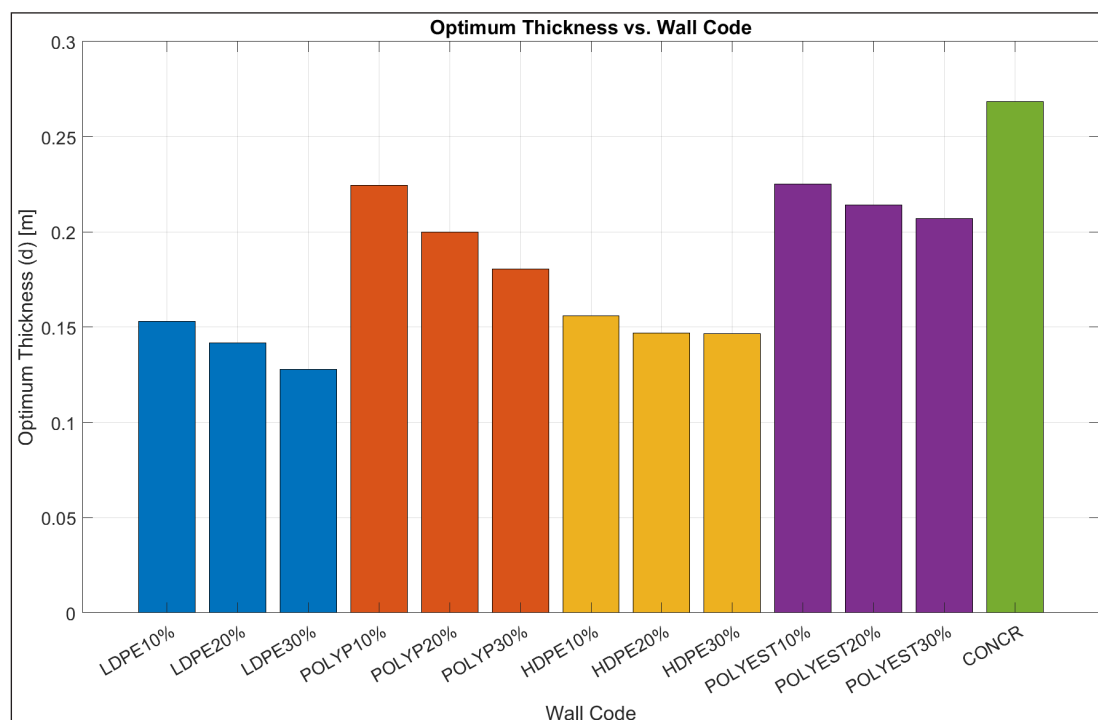


Figure 7 Optimum Thickness vs Wall Codes.

Polyester-modified concretes, particularly at 30% polymer content, emerge as the most effective alternative to conventional concrete, offering minimal deviation in heat storage capacity while potentially providing benefits such as reduced weight and improved sustainability profiles. These insights are crucial for construction practices aiming to enhance thermal performance without compromising the energy storage potential of materials. The heat capacity data can guide the selection of wall materials for energy-efficient building designs, ensuring an optimal balance between thermal comfort and storage capability.

4.6 CYCLIC TRANSMITTANCE

Figure 9 illustrates the “Cyclic Transmittance (u) vs. Wall Code,” evaluating each material’s ability to conduct cyclic thermal loads, essential for maintaining indoor comfort in environments with significant temperature fluctuations. Lower cyclic transmittance indicates better performance in resisting these daily temperature cycles. Conventional concrete (CONCR) has the highest cyclic transmittance at 0.9482, indicating lower effectiveness in resisting cyclic thermal loads. LDPE-modified samples show a decreasing trend in cyclic transmittance with increased LDPE content, with LDPE30% having the lowest

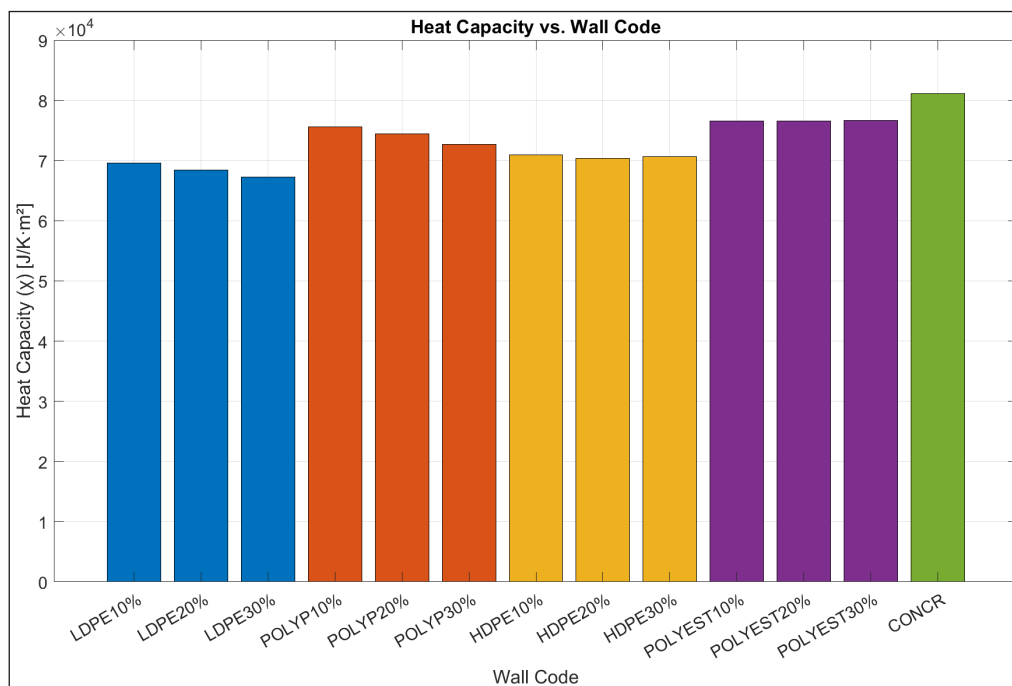


Figure 8 Heat Capacity vs Wall Codes.

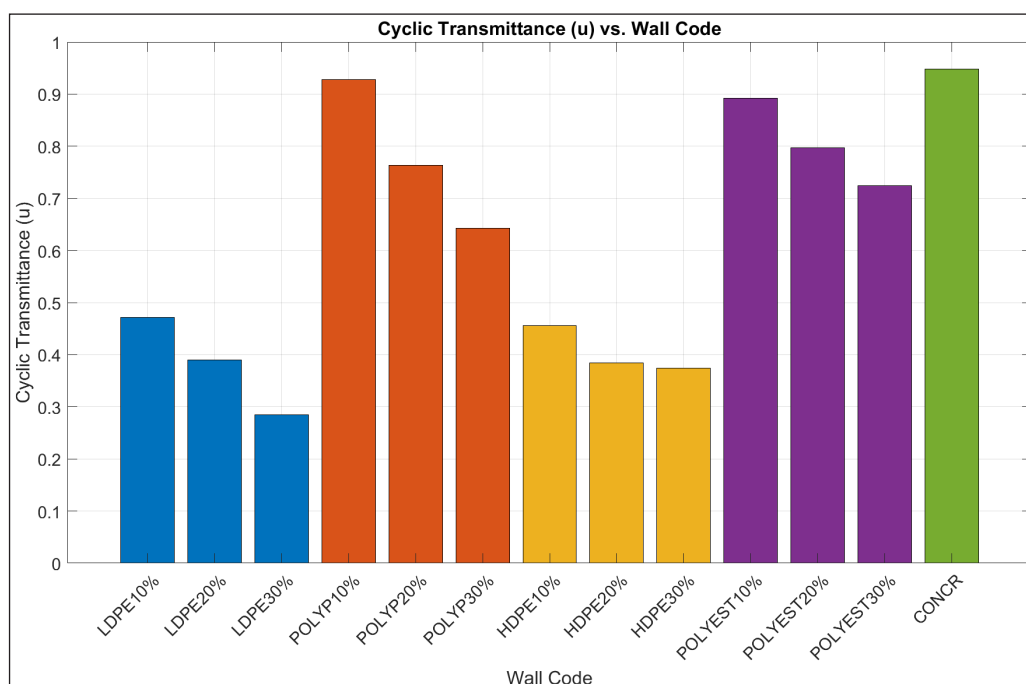


Figure 9 Cyclic Transmittance vs Wall Codes.

value at 0.2851, indicating superior performance among the LDPE variants. Polypropylene (POLYP) samples also exhibit improved resistance with higher polymer content, with POLYP30% at 0.6431.

HDPE-modified samples show relatively stable performance, with cyclic transmittance values slightly decreasing as polymer content increases, but not as significantly as LDPE or POLYP. HDPE30% has a cyclic transmittance of 0.4274. Polyester (POLYEST) samples demonstrate a consistent performance, with lower transmittance than conventional concrete but higher than LDPE and POLYP. POLYEST30% shows the best performance within its group at 0.6829. Overall, the data suggest that higher contents of LDPE and POLYP in modified concretes offer significantly improved cyclic thermal resistance compared to conventional concrete. These findings can guide the selection of materials for walls in areas with pronounced daily temperature cycles, promoting energy-efficient building designs.

5. SENSITIVITY ANALYSIS OF WALL THICKNESS

This section examines the impact of wall thickness on the thermophysical properties of modified concrete composites. By expanding the thickness range from zero to one meter, the analysis aims to uncover the full potential of each material's performance under varying conditions. Wall thickness plays a crucial role in sustainable building design, affecting resource use, thermal mass, and energy consumption. The results of this analysis will inform optimal design choices, contributing to sustainable construction practices. The

following sections discuss the relationship between wall thickness and key thermal properties, guiding the identification of ideal wall thicknesses for energy-efficient buildings.

5.1 DECREMENT FACTOR

Figure 10 illustrates the relationship between wall thickness and decrement factor for various polymer-modified concretes and conventional concrete (CONCR). As wall thickness increases, the decrement factor decreases, indicating enhanced thermal damping. However, beyond a certain point, additional thickness results in diminishing returns. For LDPE-modified samples, the decrement factor plateaus around 0.4 meters, suggesting minimal additional benefit in thermal damping beyond this thickness. Polypropylene (POLYP) and High-Density Polyethylene (HDPE) samples exhibit similar trends, with stabilization near the 0.4-meter mark. Polyester-modified samples (POLYEST10%, POLYEST20%, POLYEST30%) show consistent performance, leveling off around 0.35 meters, indicating optimal thermal damping at this thickness. Conventional concrete (CONCR) demonstrates the lowest decrement factors across all thicknesses, with optimal performance around 0.5 meters, beyond which further thickness provides negligible improvement. This analysis underscores the importance of selecting appropriate wall thicknesses to optimize thermal performance in building design, balancing energy efficiency and material savings.

5.2 TIME LAG

Figure 11, "Time Lag vs. Wall Thickness," shows the delay in peak temperature transmission through various wall materials as thickness increases, capped at a practical

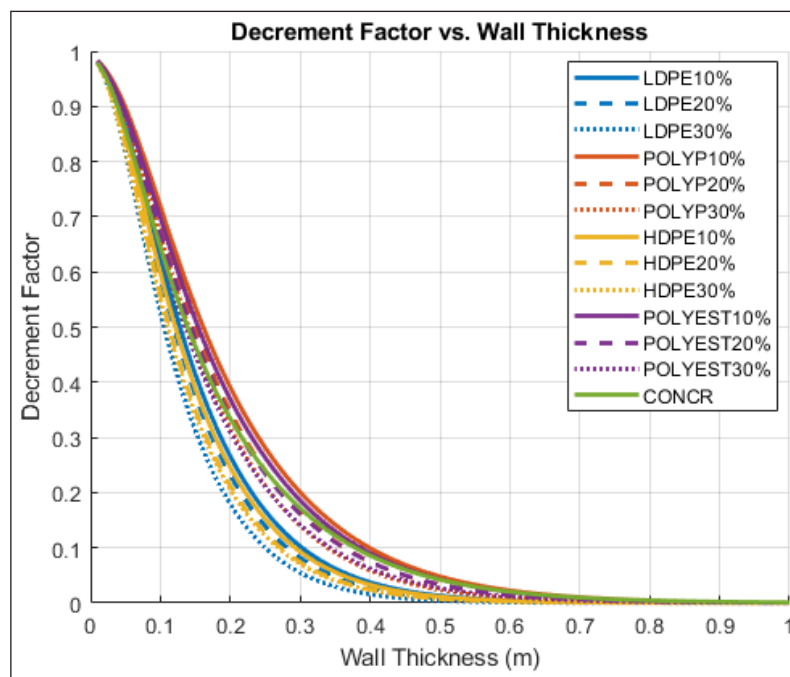


Figure 10 Decrement Factor vs Wall Thickness.

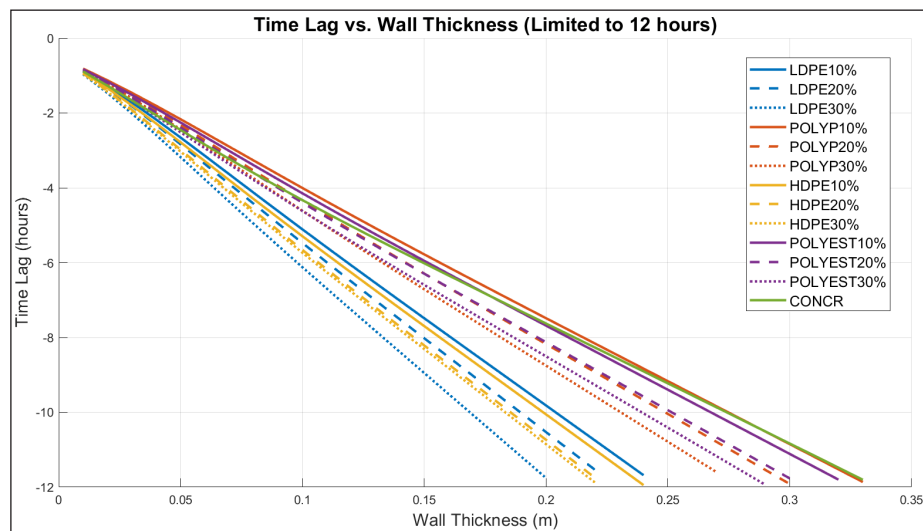


Figure 11 Time Lag vs Wall Thickness.

time lag limit of 12 hours. The graph indicates that as wall thickness increases, the time lag also increases for all materials until a point of diminishing returns. For the LDPE-modified samples (LDPE10%, LDPE20%, and LDPE30%), there is a steady increase in time lag with wall thickness, with LDPE30% reaching the 12-hour mark at the thinnest wall dimension, suggesting higher efficiency in thermal delay per unit thickness. The Polypropylene (POLY) series demonstrates a similar trend, with POLY30% achieving the 12-hour mark at a slightly greater thickness than the LDPE series, indicating minor differences in efficiency. HDPE-modified concretes show a continuous increase in time lag, with HDPE30% requiring slightly more thickness to reach the 12-hour mark compared to LDPE30% and POLY30%, indicating moderate variance in thermal inertia properties among these materials. Polyester-modified samples (POLYEST10%, POLYEST20%, POLYEST30%) exhibit a consistent rise in time lag as thickness increases, with POLYEST30% reaching the 12-hour threshold at a thickness comparable to the HDPE series.

Conventional concrete (CONCR) shows a gradual increase towards the 12-hour limit, indicating significant thermal inertia but requiring the thickest wall to achieve this compared to the polymer-modified samples. This graph illustrates the optimal wall thickness for each material type where a maximum practical time lag of 12 hours is reached, highlighting the potential of polymer-modified concretes to offer substantial thermal inertia with thinner walls than conventional concrete, supporting their use in designs focused on thermal efficiency and material economy.

5.3 SURFACE FACTOR AND TIME LAG

Figure 12, “Surface Factor and Its Time Lag vs. Wall Thickness,” provides an analysis of the interplay between surface factor and time lag for various wall materials, with the time lag capped at a practical limit of 12 hours. The surface factor, indicative of a material’s reactivity

to external thermal flux, initially increases with wall thickness, reaches a peak, and then declines and stabilizes. This peak represents the point where materials achieve maximum reactivity before additional thickness ceases to substantially affect the thermal response.

The top curves in the graph represent the surface factor, while the bottom curves represent the associated time lag. The associated time lag, reflecting the delay in heat penetration, steadily increases with wall thickness up to 0.25 meters, beyond which no significant change is observed. This stabilization suggests that beyond a certain thickness, the benefit of added mass in delaying thermal transmission is maximized. Examining the polymer-modified samples, LDPE variants show an early plateau in time lag, indicating an efficient delay in thermal transmission at relatively lower wall thicknesses. Polypropylene (POLY) and High-Density Polyethylene (HDPE) samples follow a similar trend, with their time lag curves leveling off just under the 0.25-meter wall thickness, suggesting a good balance between material thickness and thermal delay.

The Polyester (POLYEST) modified samples exhibit a more gradual increase in time lag, indicating that these materials may require slightly thicker walls to achieve the same level of thermal delay as other polymers. Conventional concrete (CONCR), indicated by the green line, has a lower surface factor across the thickness range, signifying a more stable but less reactive thermal performance. It reaches a time lag plateau comparable to that of polymer-modified concretes, reinforcing that these novel materials can perform on par with conventional options within practical limits.

5.4 AREAL THERMAL HEAT CAPACITY

Figure 13, “Heat Capacity vs. Wall Thickness,” demonstrates the relationship between the thermal storage capability of various construction materials and wall thickness. Heat capacity per unit area is a

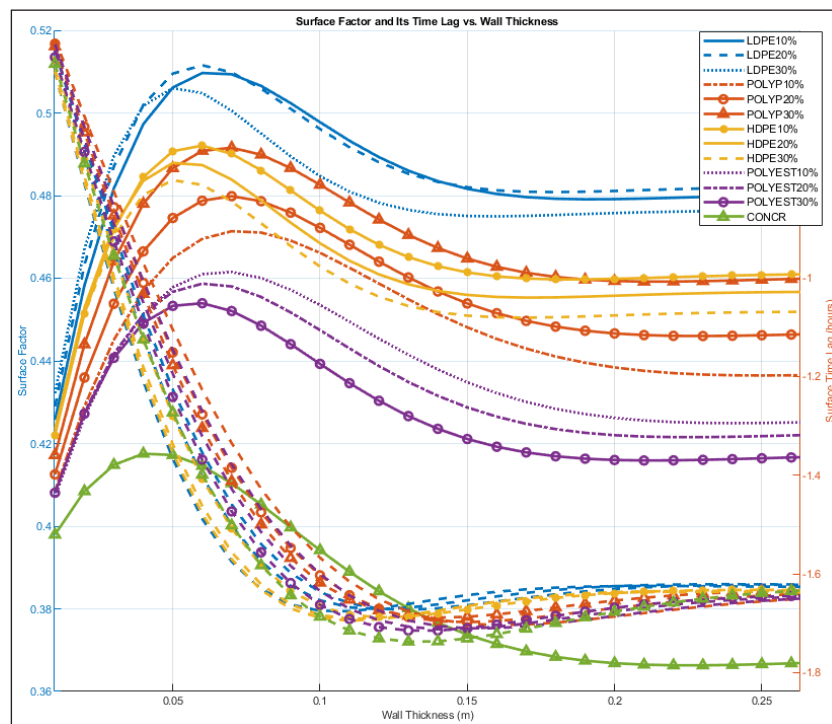


Figure 12 Surface Factor and Time Lag vs Wall Thickness.

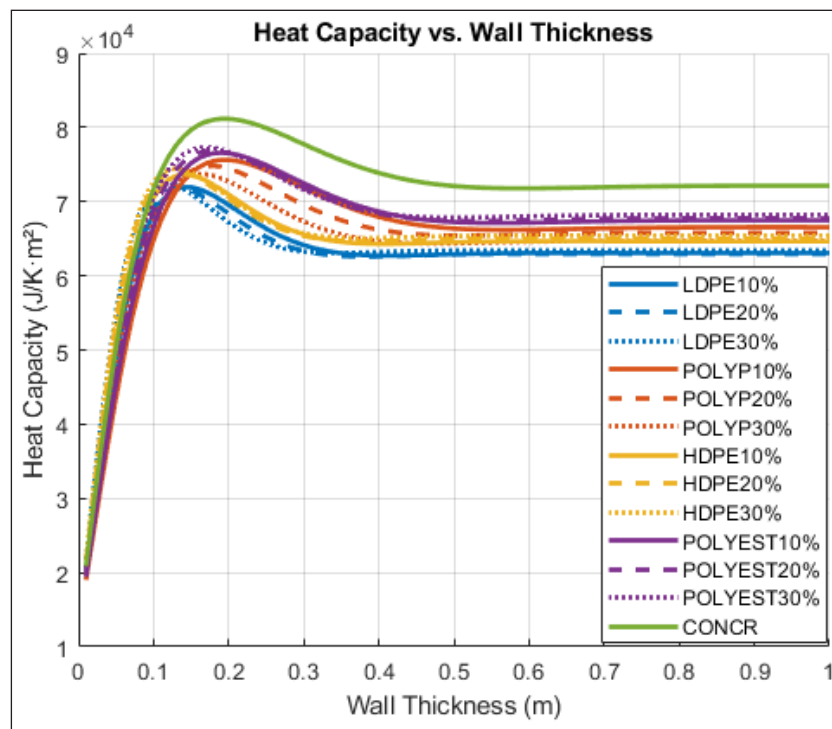


Figure 13 Heat Capacity vs Wall Thickness.

crucial metric influencing a building's thermal inertia. All materials show an initial increase in heat capacity with wall thickness, which then plateaus, indicating a limit to the benefits of additional material.

LDPE-modified concretes reach their heat capacity peak before a wall thickness of approximately 0.2 meters, suggesting an efficient thermal storage limit. Polypropylene (POLYP) and HDPE samples also exhibit peaking and plateauing of heat capacity, with no significant gains beyond a 0.25-meter thickness. This

suggests optimized wall thickness for maximal thermal regulation without excess material. Polyester (POLYEST) samples indicate a marginally higher thickness threshold for peak heat capacity, suggesting a slight advantage in thicker walls. Conventional concrete (CONCR) shows the highest heat capacity, with a peak suggesting an optimal thickness just over 0.25 meters for maximum thermal storage. These findings highlight the importance of selecting appropriate wall thicknesses to optimize thermal performance and material efficiency in building design.

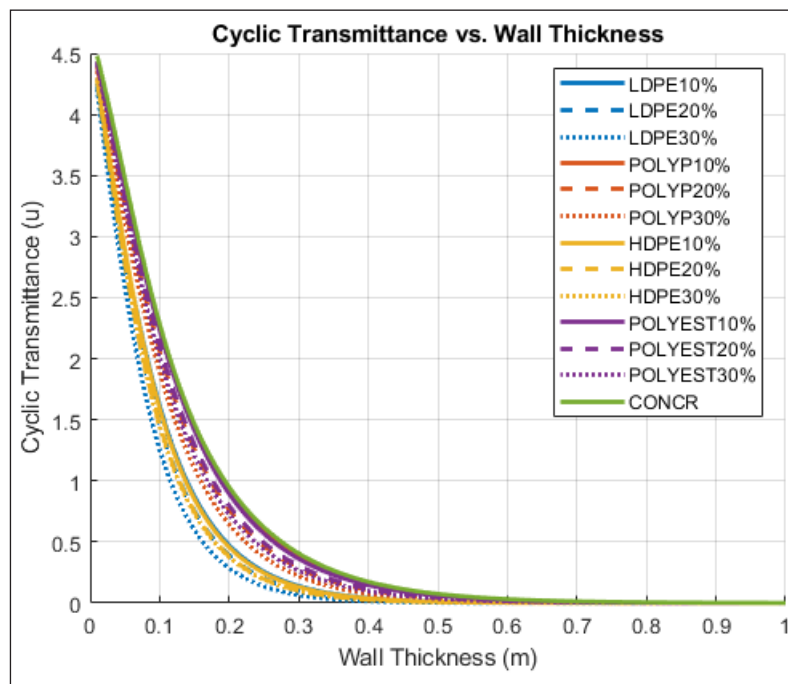


Figure 14 Cyclic Transmittance vs Wall Thickness.

5.5 CYCLIC TRANSMITTANCE

Figure 14, “Cyclic Transmittance vs. Wall Thickness,” provides insights into the dynamic thermal performance of various building materials as wall thickness varies. Cyclic transmittance (u) measures the material’s ability to conduct heat in response to cyclical temperature changes, with lower values indicating better insulation against such fluctuations.

The figure shows that cyclic transmittance decreases sharply with an increase in wall thickness across all materials, indicating improved insulation with thicker walls. This trend is pronounced up to a certain thickness, after which the rate of improvement in insulation slows and the curves begin to level off. The LDPE, Polypropylene (POLYP), and High-Density Polyethylene (HDPE) series all demonstrate significant reductions in cyclic transmittance with increasing wall thickness, approaching a stable value beyond 0.3 meters. This suggests an optimal thickness for thermal insulation before additional material yields minimal improvement.

For Polyester (POLYEST) modified samples, the decrease in cyclic transmittance with thickness follows a similar trend but with a slightly higher stable value, suggesting marginally less effective insulation performance at increased thicknesses compared to other polymers. Conventional concrete (CONCR) presents the highest cyclic transmittance across all thicknesses, maintaining superior insulative properties throughout. It reaches a near-constant value at around 0.25 meters, indicating that conventional concrete efficiently achieves its insulation potential within this range.

Overall, a wall thickness of approximately 0.25 to 0.3 meters is generally adequate for the materials to reach their effective limit of cyclic thermal insulation. This information

is crucial for optimizing material use in sustainable construction, allowing for the design of walls that provide maximum insulation without excess material use.

6. CONCLUSIONS

This study provides an extensive evaluation of the thermal performance of polymer-modified concrete composites, highlighting their potential benefits in sustainable construction. The key findings from the analysis are summarized below:

1. DECREMENT FACTOR

Polymer-modified concretes significantly outperform conventional concrete. LDPE30% exhibited the lowest decrement factor at 0.17913, while conventional concrete had a decrement factor of 0.33422. Higher polymer content consistently led to improved performance across all polymer types.

2. TIME LAG

LDPE30% showed the highest time lag of 11.757 hours, compared to 7.6277 hours for conventional concrete. This suggests an enhanced heat transfer delay, crucial for reducing energy consumption in heating and cooling systems.

3. SURFACE FACTOR AND TIME LAG

LDPE30% had a surface factor of 0.47577 and a time lag of 1.6249 hours. Polyester-modified samples, particularly POLYEST30%, maintained higher time lags at 1.6689 hours with a surface factor of 0.41601, comparable to conventional concrete.

4. OPTIMUM THICKNESS

Polymer-modified concretes require thinner walls for maximum thermal capacity compared to conventional concrete. LDPE30% requires an optimum thickness of 0.12791 meters, significantly lower than the 0.26863 meters required for conventional concrete, indicating lighter, more cost-effective building designs.

5. HEAT CAPACITY

While conventional concrete had the highest heat capacity at 81162 J/K·m², polymer-modified concretes, especially POLYEST30% at 76534 J/K·m², offered comparable thermal storage capabilities with potential benefits like reduced weight and improved sustainability.

6. CYCLIC TRANSMITTANCE

Polymer-modified concretes exhibited significantly lower cyclic transmittance values compared to conventional concrete. LDPE30% had the lowest cyclic transmittance at 0.2851, while conventional concrete exhibited a value of 0.9482, indicating superior performance in resisting cyclic thermal loads.

7. SENSITIVITY ANALYSIS OF WALL THICKNESS

Optimal wall thickness for polymer-modified concretes ranges from 0.25 to 0.3 meters, beyond which additional thickness yields minimal benefits. For instance, LDPE30% reaches an optimal decrement factor at around 0.4 meters.

SUMMARY OF BEST PERFORMING MATERIALS

LDPE30%: Best overall performance with a decrement factor of 0.17913, a time lag of 11.757 hours, an optimum thickness of 0.12791 meters, and a cyclic transmittance of 0.2851.

HDPE30%: Strong performance with a decrement factor of 0.20583, a time lag of 10.854 hours, and an optimum thickness of 0.1467 meters.

Polypropylene (POLYP) 30%: Good thermal properties with a decrement factor of 0.31672, a time lag of 8.7541 hours, and an optimum thickness of 0.1804 meters.

Polyester (POLYEST) 30%: Effective in heat capacity at 76534 J/K·m², with a decrement factor of 0.30988 and a time lag of 8.5055 hours.

The integration of recycled polymers such as LDPE, HDPE, Polypropylene, and Polyester into concrete significantly enhances its thermal performance, making it a viable option for energy-efficient building designs. These materials improve thermal damping, delay, and insulation properties while allowing for thinner, lighter, and more sustainable building structures. This research

supports the practical application of polymer-modified concrete in sustainable construction and advocates for future exploration into their long-term durability, cost implications, and broader environmental benefits.

NOMENCLATURE

SYMBOLS

C_p	Specific heat capacity (J/kg·K)
d	Characteristic admittance of the slab
f	Decrement Factor (Dimensionless)
F	Surface Factor (Dimensionless)
k	Thermal conductivity (W/m·K)
l	Finite thickness (m)
M	Heat flux (W/m ²)
N	Thermal resistance (m ² ·K/W)
P	Period (s)
T	Temperature (K)
U	Thermal transmittance (W/m ² ·K)
Y	Thermal admittance (W/m ² ·K)
Z	Spatial dimension across the wall thickness (m)
S_i	Transmission matrix for internal surface resistance of the wall
S_o	Transmission matrix for external surface resistance of the wall
W_1, W_2, W_3, W_4	Matrix elements from the transmission matrix
$T_{(T=0)}$	Inner surface temperature of the wall (K)
$T_{(T=L)}$	Outer surface temperature of the wall (K)

GREEK SYMBOLS

μ	Material density (kg/m ³)
ϕ	Decrement delay (h)
χ	Heat capacity per unit area (J/K·m ²)
ψ	Factor time lag (h)

SUBSCRIPTS

e	Exterior surface
i	Interior surface
si	Internal air surface
so	External air surface

DATA ACCESSIBILITY STATEMENT

Data supporting the findings of this study are available from the corresponding author upon reasonable request.

COMPETING INTERESTS

The authors have no competing interests to declare.

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