SSRG International Journal of Civil Engineering
ISSN: 2348-8352/ https://doi.org/10.14445/23488352/IJCE-V12I9P106
Volume 12 Issue 9, 61-73, September 2025

Original Article

The Role of Material Choice in Optimizing Energy-Positivity and Thermal Comfort: An Indian Housing Perspective

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Received: 07 July 2025 Revised: 08 August 2025 Accepted: 06 September 2025 Published: 29 September 2025

Abstract *-Amid rising carbon emissions in the building sector, this research paper explores the interrelated dynamics of thermal and energy efficiency within material selection and its cumulative effect on net carbon emissions in the Indian residential construction sector. The core argument presented is that ineffective material selection and application of construction methodologies, mainly due to the neglect of energy and thermal efficiency, lead to unsustainable consequences. To establish pragmatic relationships, a comparative analysis of Life Cycle Assessment (LCA) data on net carbon emissions and thermal performance metrics outlined by the Energy Conservation Building Code (ECBC) is detailed in the paper. This comparative analysis will enable the development of a material-centric decision framework. The findings indicate that optimization in construction often remains unaddressed due to the project-specific nature of materials. Referencing guidelines from the Bureau of Energy Efficiency (BEE), this study explores the limitations and potential of optimization through informed material selection. The findings emphasize the tremendous impact of materials on both local and global environmental scales, urging a life-cycle-based and climate-responsive approach to material selection in sustainable construction.*

Keywords *- Thermal comfort, Energy efficiency, Life Cycle Assessment, Material-choice, Optimization.*

1. Introduction

The building and construction sector is one of the largest contributors to global energy use and carbon emissions. As per the Global Status Report for Buildings and Construction (2022), buildings account for over 40% of total energy consumption and nearly 30% of energy-related CO_2 emissions worldwide [1]. The residential construction sector in India is rapidly expanding and is propelled by large-scale housing initiatives such as the Pradhan Mantri Awas Yojana (PMAY). This growth, while necessary, places considerable pressure on energy systems and intensifies the urgency to embed sustainability into the design and construction of housing [2, 3].

Current approaches to reducing environmental impact in buildings tend to treat operational energy (energy used during the building's lifetime) and embodied energy (energy used in material production and construction) as separate domains [5-7]. Similarly, while the Energy Conservation Building Code (ECBC) introduces broad thermal performance standards, it provides limited material-specific guidance, particularly across India's diverse climate zones [19]. As a result, the thermal behavior of materials, a critical factor influencing long-term energy demand, is often neglected during material selection. This paper addresses a specific gap in existing literature: an integrated framework that connects material choice with embodied carbon performance and thermal comfort in the Indian residential construction context.

By proposing a material-centric evaluation framework that integrates thermal conductivity, embodied energy, and Global Warming Potential (GWP) across different life cycle stages of construction materials, the said gap is addressed. Using a real-world case study of a multi-storey housing project in Pune, Maharashtra.

The study employs One Click LCA software and ECBC-validated thermal datasets to compare a base case model of conventional construction practices with alternative models using low-carbon materials such as GGBS, RCA, and AAC blocks [20, 22]. The aim is to identify trade-offs and synergies between energy efficiency and thermal comfort in material choices.

While numerous studies have examined either the operational or embodied energy of building materials, there is limited research that evaluates these dimensions in conjunction with material thermal performance. Moreover, most material-centric studies fail to contextualize thermal behavior within real-world Indian climatic conditions and construction practices. This study is unique in that it develops a comparative framework using actual project data, simultaneously assessing Global Warming Potential (GWP) and thermal conductivity across multiple material configurations. By bridging the gap between material-specific life cycle analysis and thermal efficiency benchmarks, the research proposes a dual-parameter evaluation method for architects and designers working within the constraints of Indian residential housing.

2. Research Premise

2.1. Objectives and Scope

The primary objective of this research is to assess the energy-positive attributes of building materials and construction techniques, evaluating them in relation to the thermal efficiency of material choices to achieve holistic optimization in building design and construction. This involves investigating factors crucial to integrating net-zero and thermally comfortable designs using 21st-century building materials. The paper will explore various elements impacting net carbon emissions, Global Warming Potential (GWP), and thermal transmittance coefficients, analyzing their interrelationships to optimize energy use and construction practices in general. The research is based on a case study of an ongoing construction project in Pune, India, employing variables to lay the groundwork for developing a comprehensive framework.

The analysis of energy-positive aspects in building materials and construction techniques is crucial for understanding the construction sector's impact on climate change. Sustainable building materials and techniques offer potential for substantial reductions in carbon footprint and energy consumption, while also enhancing energy generation, thus positively influencing overall sustainability in the housing sector. Additionally, considerations for building thermal comfort and the thermal efficiency of construction materials affect operational energy consumption, which subsequently impacts the project's Global Warming Potential (GWP) in later stages. To tackle this issue, the components of the framework are meticulously assessed for potential optimization in energy efficiency, especially within the context of multi-story housing projects.

A central question arises: Can a tool be developed to effectively illustrate and maximize construction efficiency by evaluating building materials based on their optimal balance of thermal efficiency and energy positivity? This tool would ultimately assist in evaluating and improving energy efficiency in construction [4, 6, 8].

2.2. Significance and Contributions

Researchers have investigated a range of sustainable construction methods over time, concentrating on the efficiency of materials and techniques in relation to energy performance and thermal dynamics. The central goal of these studies is to facilitate the adoption of sustainable building practices that can mitigate energy consumption within the construction industry. Previous investigations have rigorously assessed the energy efficiency of various building materials, using metrics such as embodied energy, operational energy, and comprehensive net carbon impacts.

A 2023 study examining the relative significance of operational versus embodied energy highlighted that both energy dimensions are crucial to achieving energy positivity. The research indicates that, in multi-story buildings, even in the absence of advanced technologies, adopting alternative, more energy-efficient heating and cooling systems could reduce up to 6 gigatonnes of embodied carbon (kgCO2e) by 2050. This depicts and highlights the importance of trade-offs during material and construction considerations in the first place [8].

The objective of this study is to propose and advance the creation of a comprehensive framework designed to assess and enhance the energy efficiency of building materials, including their thermal properties. A central feature of this framework is its ability to clearly present analyses and pinpoint Global Warming Potential (GWP) hot-spots across various stages of a project. Additionally, it incorporates insights from thermal efficiency standards based on accredited reports and findings.

In conclusion, this research has substantially refined the framework on two levels. At the macro level, it assesses the energy-efficient properties of building materials and advocates for environmentally sustainable construction practices. At the micro level, it examines the thermal efficiency of material selections within the housing sector.

The approach, supported by the tool developed in this study, holds promise for creating sustainable, energy-efficient, and thermally comfortable structures, particularly in multi-story housing configurations. It equips architects, engineers, and builders with the necessary insights to make informed decisions about building design and material choices.

2.3. Case Building Parameters

To ensure contextual relevance and practical applicability, this study uses an ongoing residential project in Pune, Maharashtra, as a reference model for evaluating material performance. The selected development, titled Suyog Sweet Home Heights, exemplifies a typical mid-rise apartment block in an Indian urban setting, making it well-suited for examining both traditional and sustainable construction practices.

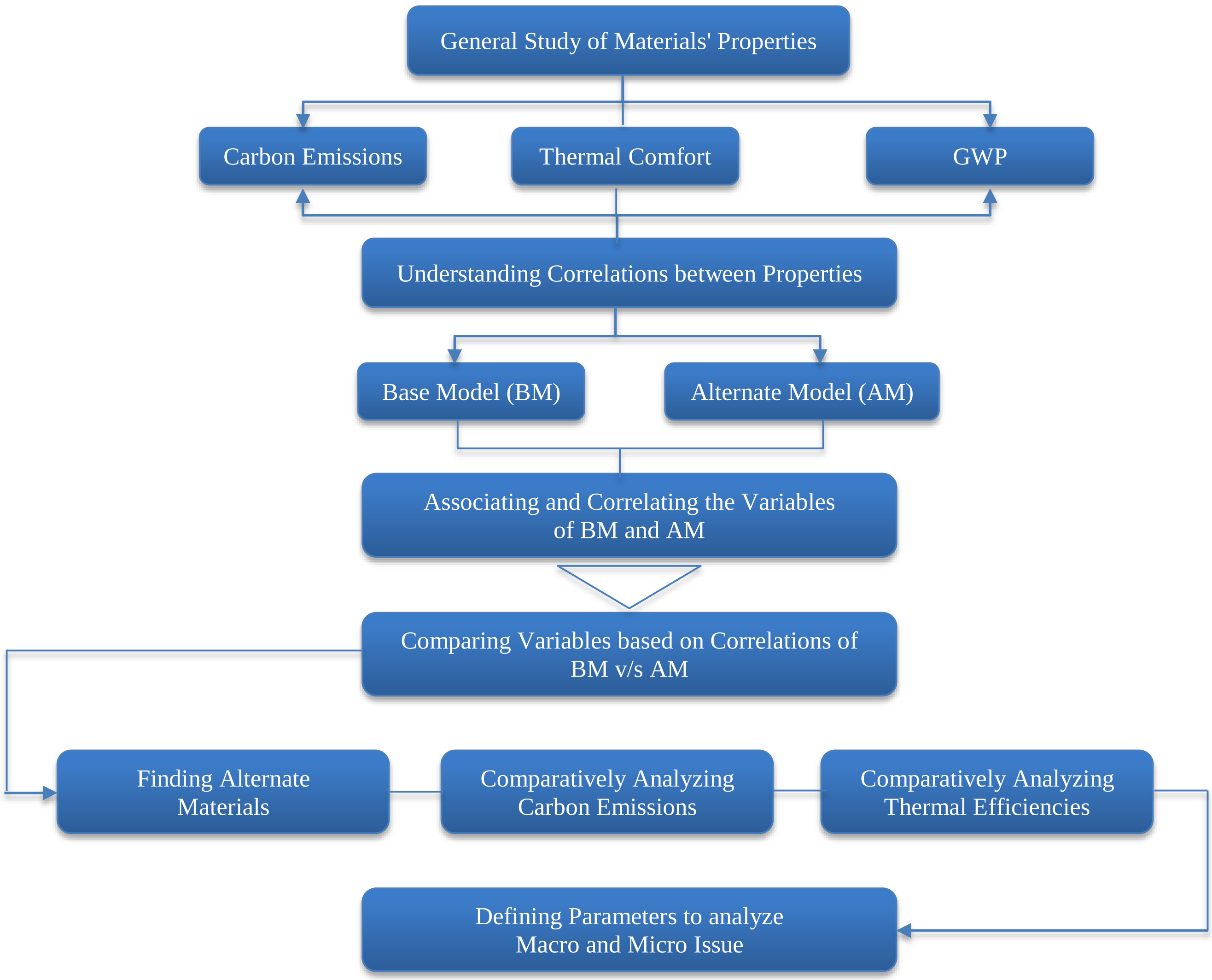

Fig. 1 Structure of the study as formulated by the authors

The building characteristics used for the analysis are outlined below:

1. Project Name: Suyog Sweet Home Heights
2. Location: Pune, Maharashtra, India
   Climate Zone: Composite (as per ECBC classification)
3. Typology: Multi-storey apartment complex
4. Number of Floors: G+7
5. Total Built-Up Area: 10,880 m²
6. Occupancy Type: Residential
7. Envelope System: RCC frame with masonry infill (BM: Fired Clay Brick, AM: AAC block)
   Wall-to-Window Ratio (WWR): Approximately 30%
8. Window Glazing: Single-glazed clear float glass
9. Roof Construction: RCC slab with waterproofing and screed finish
   Shading Devices: Minimal fixed shading; relies on orientation
10. HVAC Strategy: Naturally ventilated; no centralized air conditioning in the baseline model
11. Lighting Load: Conventional LED lighting in common and individual units
12. Data Source: Developer-provided Bill of Quantities (BoQ), architectural drawings, and field verification

All simulation inputs for embodied carbon and thermal efficiency were based on actual building specifications, and operational assumptions followed standard BEE residential occupancy benchmarks.

The case model allowed for direct comparison between conventional and alternative materials, isolating the effect of material change without altering form or usage patterns. This approach made it possible to assess performance differences arising solely from material substitution, providing a focused lens for evaluating energy and thermal optimization strategies.

3. Literature Review

According to Nejat et al. and the Global Alliance for Buildings and Construction, nearly 40% of global energy-related CO_2emissions originate from the building sector. Therefore, a transition towards low-carbon and sustainable construction technologies is crucial to achieving net-zero ambitions and reducing greenhouse gas emissions [9].

Thisinvolves measures such as adopting energy-efficient construction practices, incorporating environmentally responsible materials, advancing construction technologies, and integrating renewable energy sources. The International Energy Agency estimates that through technological innovation and improved efficiency, the construction industry could reduce its energy-related emissions by as much as 45% by 2050 [10]. Achieving this requires addressing both embodied emissions and operational energy use, which together can substantially increase the overall reduction potential.

While thermally efficient materials and new construction technologies may introduce trade-offs in energy use, emissions, and performance metrics, their long-term value lies in reducing operational energy demand. This not only leads to cost savings but also improves user comfort and productivity [1]. For their successful adoption, supportive policies and a detailed understanding of materials, their alternatives, and their broader impacts are necessary. Analytical tools and frameworks must therefore accompany such policies [11], beginning with industry-wide education on how material selection influences outcomes across the entire construction life cycle.

Material and technology choices play a decisive role in achieving energy-positive buildings since the thermal characteristics of materials directly affect their associated emissions [12]. The thermal transmittance of envelope materials, for instance, has a major effect on operational-stage emissions, which typically represent 50–70% of a building's total carbon output [13]. At the same time, reviews show that embodied energy is highly dependent on the selected construction methods and material palette [14]. Although there is no straightforward one-to-one relationship between thermal performance and carbon intensity, both are interlinked through composition, processes, technologies, and socioeconomic contexts. These factors shape the broader goal of energy-positive design, making material selection a central aspect of reducing emissions and enhancing efficiency.

Concrete, especially Ready-Mix Concrete (RMC), exemplifies this challenge. Cement production alone contributes about 8% of worldwide CO_2emissions and accounts for nearly 19–20% of India's emissions [15, 16]. Alternative formulations have been investigated; mixes with 45% GGBS exhibit a thermal admittance of 4.20 $W/m^2 \cdot K$, compared to 4.03 $W/m^2 \cdot K$ for Portland Cement (PC) concrete [17]. Other substitutes for PC concrete also report higher thermal admittance values. Thermal conductivity figures reflect similar variations. RMC typically ranges from 2.02 to 2.67 W/mK [18], yet modifications using supplementary binders or recycled aggregates show marked improvements.

Mixtures incorporating 10% recycled binders, 30% RCA, or 45% GGBS reduce conductivity values significantly, with results spanning from 1.88 W/mK to as low as 0.73 W/mK [17]. These findings are summarized in Table 1, adapted from the Energy Conservation Building Code for Residential Buildings [19].

Despite the breadth of data in the ECBC on material specifications, it does not prescribe standards for thermal efficiency coefficients, technologies appropriate to specific materials, or material choices suited to climatic zones. Instead, it emphasizes compliance requirements for building form, fenestration, ventilation, and mechanical systems. While it recommends that designers consider passive design strategies in line with local climates and materials, it leaves the question of detailed material performance open-ended. In this sense, the responsibility of interpretation falls heavily on architects and engineers, who must navigate between regulatory prescriptions and practical constraints. This gap creates an urgent opportunity for further research and field-based validation, especially to ensure that construction practices can transition from generalized guidelines to performance-driven, context-sensitive standards. When correlating the objectives of our study goals with the report, it does not align and has certain gaps regarding material-design association, technological advancement, promoting exploration and inclusion of new-age building materials, which the paper attempts to address. Beyond concrete, there are materials like EPS, EU and XPS which, despite their poor embodied energy, provide superlative cell thermal insulation that can reduce heat gain in buildings by over 24% [20]. Despite advancements, a notable gap persists between evolving technologies and their full integration into modern architecture, highlighting the urgency to explore alternatives.

Innovative construction methods, such as 3D-printed concrete and modernized vernacular technologies, offer opportunities for reducing Global Warming Potential (GWP) through new architectural possibilities and the use of recycled materials, GWP can potentially be lowered by approximately 15%. Active strategies like green roofs and Building-Integrated Photovoltaic (BIPVs) also contribute to GWP reduction. BIPVs, which integrate solar cells into building structures, generate clean energy, while green roofs provide benefits such as reduced energy costs and improved air quality. The integration of both active and passive methods highlights the potential to achieve energy-efficient architecture, underscoring the importance of optimizing new construction technologies and materials.

Table 1. Thermal properties of building materials as compiled within BEE 2017

Type of Material	Density	Thermal Conductivity
	kg/m^3	W/m.k
Solid Burnt Clay Brick	1920	0.81 - 0.98
Solid Burnt Clay Brick	1760	0.71 - 0.85
Solid Burnt Clay Brick	1600	0.61 - 0.74
Solid Burnt Clay Brick	1440	0.52 - 0.62
Perforated Burnt Clay Brick	1520	0.631
Fly Ash Brick	1650	0.856
Fly Ash Brick	1240	0.639
Solid Concrete Block 25/50	2427	1.396
Solid Concrete Block 30/60	2349	1.411
Aerated Autoclaved Concrete (AAC) Block	642	0.184
Cement Stabilized Soil Block (CSEB)	1700-1900	0.84 - 1.30
Dense Concrete	2410	1.74
RCC	2288	1.58
Brick Tile	1892	0.798
Lime Concrete	1646	0.730
Mud*Phuska*1622 0.51	9	
Cement Mortar	1648	0.719
Cement Plaster	1762	0.721
Gypsum Plaster	1120	0.512
Cellular Concrete	704	0.188
AC Sheet	1520	0.245
GI Sheet	7520	61.06
Timber	480	0.072
Timber	720	0.144
Plywood	640	0.174
Glass	2350	0.814

While previous research has explored low-carbon materials [14, 16], and others have studied thermal properties of construction systems [6, 7], few have attempted to integrate both through a single evaluative model.

For instance, studies such as [8] highlight the relative importance of operational vs. embodied energy, but overlook how thermal conductivity affects long-term carbon outcomes. Similarly, [12] proposes a multi-objective optimization framework but is limited to hypothetical or climate-agnostic scenarios. In contrast, this study offers a contextualized, material-level comparison grounded in Indian climatic realities. It extends the discourse by combining Life Cycle Inventory data, ECBC thermal values, and a real construction case, resulting in a practical framework that enhances both thermal comfort and carbon mitigation through material optimization, a dimension that is underexplored in existing literature.

4. Research Methodology

There are two main approaches used in the research process to understand the correlations between thermal comfort and carbon emissions. First, the software One Click LCA provides standards and data for carbon emissions and the Global Warming Potential (GWP) of construction materials used in the Base Model (BM) and potential materials for an Alternative Model (AM). Second, for thermal comfort, several external studies and books are consulted to acquire thermal admittance values and the thermal efficiencies of materials. These values are cross-checked with the latest experimental data in the ECBC 2017 and ECBC 2021 documents by the Bureau of Energy Efficiency.

Life Cycle Assessment (LCA) was carried out using the One Click LCA platform, which enables project-level evaluations of environmental impacts across a building's lifespan. In line with ISO 14040 guidelines, the tool quantifies a wide spectrum of categories, with Global Warming Potential (GWP) being central to this study.

The software's database incorporates information on material production, transport, energy use, financial inputs, and associated carbon flows, allowing an integrated view of project sustainability [21]. The decision to employ One Click LCA was based on its comprehensive global dataset and comparative analysis features, which make it particularly effective for examining construction materials under multiple performance criteria.

It supports scenario testing and visualization, thereby improving the reliability of LCA outcomes in design research [22]. For this research, the "Net Zero Carbon Tool" module was applied to a residential case study, *Suyog Sweet Home Heights* in Pune, with data obtained directly from the developer.

The tool estimates net carbon emissions by considering embodied, operational, and end-of-life stages, while also factoring in offsets and reuse benefits. The assessment covered a 60-year reference period, with parameters including built-up area, material inventories from the bill of quantities, transport distances, and operational energy inputs.

Two scenarios were developed: A Reference Model (BM) reflecting standard construction practices and an Alternative Model (AM) incorporating material substitutions with lower embodied emissions.

A preliminary sensitivity check explored trade-offs between thermal efficiency and embodied carbon, enabling a more balanced approach to construction efficiency. These models form the basis for evaluating how material choices influence affordability, performance, and long-term carbon outcomes.

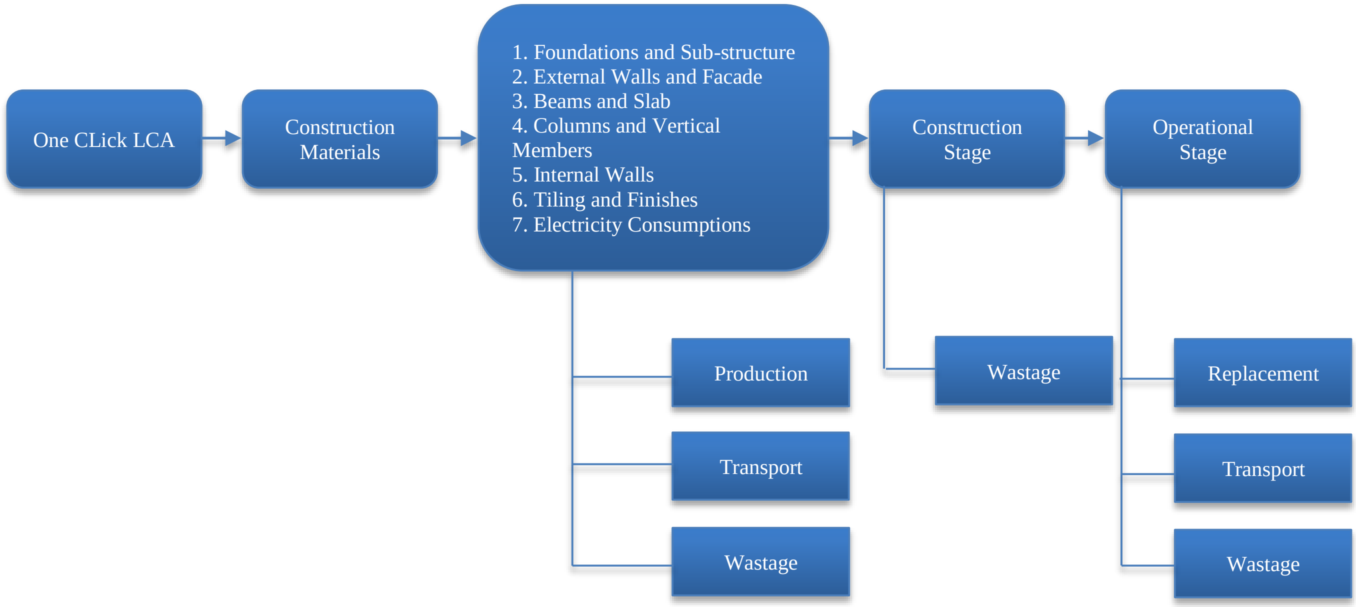

Fig. 2 Process followed for using one click LCA

4.1. Life Cycle Inventory (LCI)

The Life Cycle Inventory (LCI) forms the backbone of the environmental analysis in this research. It systematically records the inputs and outputs tied to construction materials, tracing them from initial resource extraction through processing, transportation, use, and eventual end-of-life treatment. By capturing energy requirements, emissions, and logistics data, the LCI enables a comprehensive picture of material-related impacts. Within this study, it serves as the reference point for comparing embodied carbon values and thermal behavior across both the baseline configuration and the proposed alternative material palette.

4.1.1. LCA: Boundaries and Assumptions

The LCI in this research follows a cradle-to-grave approach, covering the complete life cycle of each material. This includes:

1. 1A1-A3: Raw material extraction, processing, and manufacturing
2. A4-A5: Transportation to the site and construction/ installation phase
3. B4-B6: Use, maintenance, and replacement cycles
4. C2-C4: Demolition, waste transport, and end-of-life disposal
5. D: Benefits beyond system boundary (e.g., recyclability credits)

Activities outside the construction material system, such as on-site labor energy or user-dependent variations in building operation, were intentionally excluded to maintain a clear focus on material performance. A service life of 60 years was assumed for all simulations, in accordance with widely accepted norms and the One Click LCA Net Zero Carbon Tool's default benchmarking.

4.1.2. Material Data and Sources

Material data was sourced from multiple channels:

1. Bill of Quantities (BoQ) provided by the developer for the case project
2. ECBC 2017 and 2021 for thermal performance values Integrated datasets within One Click LCA, including Indian LCI and global averages.
3. Peer-reviewed literature for missing or alternate values

The primary environmental indicators tracked in this inventory include:

1. Embodied carbon (kgCO_2e/kg of material)
2. Embodied energy (MJ/kg)
3. Thermal conductivity (W/mK)

Correspondingly, Table 1 presents an excerpt of the LCI data compiled for selected materials used in both the Base Model (BM) and Alternative Model (AM) against the aforementioned parameters.

Key Observations:

1. EPS-based finishes demonstrated extremely low thermal conductivity but came with high embodied emissions.
2. GGBS as a cement substitute significantly reduced emissions, over 50%, with negligible structural or thermal performance loss.
3. AAC blocks provided the lowest thermal conductivity and dramatically reduced embodied emissions compared to conventional bricks.
4. Locally available adobe blocks outperformed fired clay bricks in both carbon impact and thermal control, with added benefits from shorter transport distances.

5. Results and Discussion

The environmental assessment of the case project was carried out using One Click LCA, with a particular focus on Global Warming Potential (GWP) as the primary indicator of embodied emissions. A Base Model (BM) was established to reflect standard construction practices in Pune, drawing on material inventories provided by the developer and supplemented with secondary data for thermal properties from published sources. The BM serves as a reference point for evaluating current industry norms, especially in relation to national sustainability targets.

To complement the BM, an Alternate Model (AM) was developed, introducing selected material substitutions aimed at reducing embodied emissions while improving thermal comfort. Both models were analyzed not only for their carbon performance but also for their contribution to indoor environmental quality through thermal conductivity values.

Comparative plots were generated to highlight differences between conventional and alternative material sets, providing a dual perspective on climate impact and occupant comfort. The scope of the LCA extended across all major life cycle stages, including production, construction, operational use, and end-of-life treatment. The analysis also considered benefits occurring beyond the building boundary, such as reuse or recycling potential. While multiple environmental indicators can be examined in LCA, this study centers on GWP, reported in kilograms of carbon dioxide equivalent (kgCO_2e), because of its relevance to climate change and its recognition as a common benchmark in the construction sector.

Thermal comfort and the ability of building materials to regulate heat transfer are critical for both occupant well-being and the energy performance of buildings. In practice, thermal comfort influences how effectively indoor spaces support daily living, while thermal conductivity determines how easily heat passes through a material. Conductivity is measured in watts per meter-kelvin (W/mK), with lower values generally associated with better insulation and reduced dependence on mechanical cooling or heating.

Although detailed experimental data on thermal properties for Indian construction materials remain limited, available values from the literature were compiled for this study. To streamline analysis, the selected materials were organized into three broad categories: Ready-Mix Concrete (RMC), Bricks, and Tiling/Finishes. Within each category, materials were further classified as either Base Model (BM) or Alternate Model (AM) variants, as outlined in Table 2. This structure enables direct comparison between conventional practices and alternative options that may improve both carbon outcomes and thermal performance.

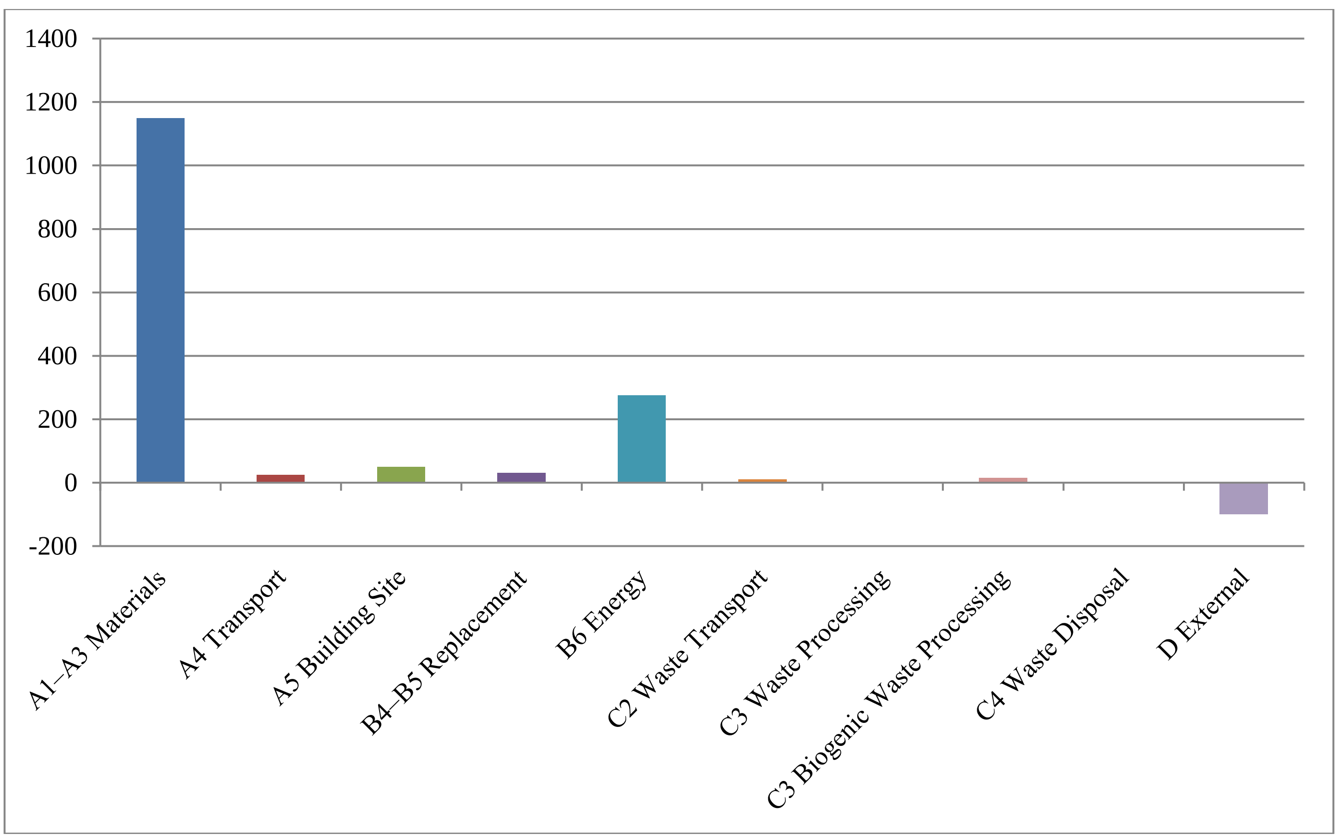

Fig. 3 Net carbon kg CO2e across the life-cycle stages

Table 2. Material classification and descriptions

Material	Description
RMC - Bm1	Ready-mix concrete with 100% Portland Cement and 0% recycled binders
RMC - Bm2	Ready-mix concrete with 10% recycled binders
RMC - Am1	Ready-mix concrete with 45% GGBS content
RMC - Am2	Ready-mix concrete with 45% GGBS content and 30% Recycled Coarse Aggregate (RCA)
RMC - Am3	Ready-mix concrete with 45% GGBS content and 30% Recycled Coarse Aggregate (RCA) and reduced (water : cement) ratio
Bricks - Bm1	Fired Common Clay Bricks
Bricks - Am1	Aerated Autoclaved Concrete Blocks
Bricks - Am2	Unfired Common Clay Bricks
Bricks - Am3	Dense Blocks to Medium-dense Concrete
Tiling - Bm1	Vitrified Ceramic Tiles
Tiling - Am1	EPS Flooring
Tiling - Am2	Terrazzo Flooring
Tiling - Am3	Marble Flooring

5.1. BM Analysis

The Base Model (BM) simulation using One Click LCA shows that construction materials are the dominant source of greenhouse gas emissions within the project. Across all life cycle phases, the embodied carbon of materials accounts for approximately 78.6% of the total Global Warming Potential (GWP). This finding underlines how strongly material selection influences the environmental profile of a building.

To better understand the role of individual materials, a radar chart, reference Figure 4, was generated to display their relative contributions to carbon emissions. The results indicate that Brickwork (Bm1) and Ready-Mix Concrete (RMC-Bm1 and Bm2) are the largest emitters, contributing 39.7% and 18.7% of the total, respectively. Finishes such as tiling also add to the footprint, though at a lower level of about 4.4%.

These outcomes suggest that any meaningful reduction in project-level emissions must focus on rethinking commonly used high-impact materials like bricks and RMC. Alternative compositions or substitution with lower-carbon options could play a decisive role in achieving more sustainable building outcomes.

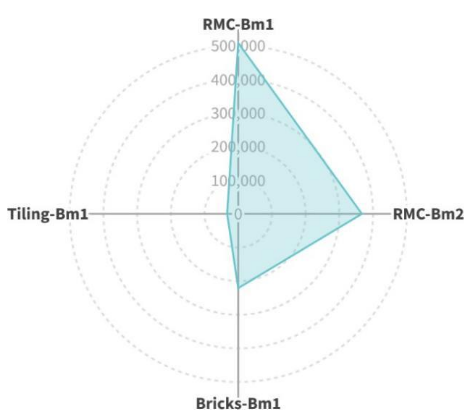

Fig. 4 Carbon emissions in kg CO_2e across the material classifications

5.1.1. Thermal Efficiency of Material Classifications

Thermal performance was examined through the conductivity values presented in Figure 5. These values indicate the extent to which individual materials contribute to insulation and occupant comfort.

Among the base model options, RMC-Bm2, containing 10% recycled binders, recorded the highest thermal conductivity at 2.66 W/mK, while Fired Common Clay Bricks (Bricks-Bm1) showed the lowest at 0.71 W/mK.

Although this dataset does not incorporate the influence of specific building elements or life-cycle phases, it provides a clear initial comparison of material behaviour.

The results serve as a baseline against which alternative models can be developed, enabling more detailed assessments of thermal comfort and long-term energy efficiency in later stages of analysis.

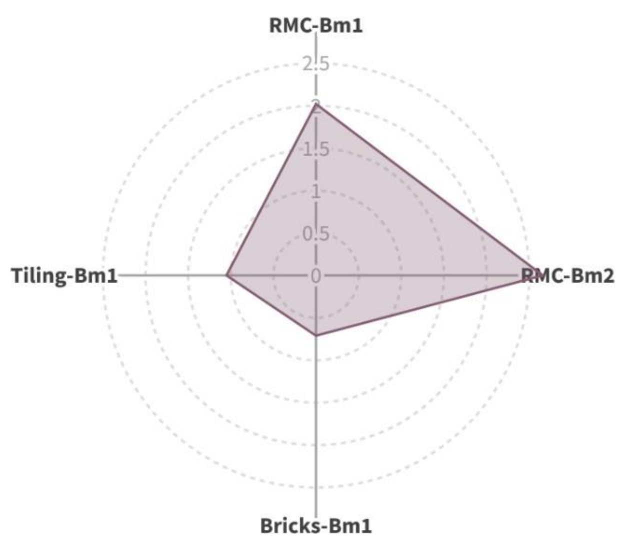

Fig. 5 Thermal conductivity in W/mK across the material classifications

5.2. Alternate Models against BM

The authors have established criteria to prioritize alternatives based on findings that materials, particularly concrete derivatives and finishes along with bricks, contribute significantly to Global Warming Potential (GWP) across life cycle stages.

Analysis of thermal efficiency highlights bricks as potentially offering substantial thermal comfort benefits, while suggesting a need for reassessment of Ready Mix Concrete (RMC). Using this insight, the authors have developed the Alternative Model (AM) to reduce GWP and enhance thermal efficiency as opposed to the Base Model (BM).

5.2.1. RMC and its Constituent Alternatives

In Figure 6, the carbon emissions contribution of RMC-Bm1, that is, 100% PC and 0% recycled binders, is the greatest. Conversely, all three alternate options with certain GGBS and RCA contents with play of mixing ratios show approximately 52.34% to 63.41% reduction in carbon emissions. By incorporating Ground Granulated Blast Furnace Slag (GGBS) and Recycled Coarse Aggregate (RCA), the GWP contributions for RMC in all Alternative Models (AMs) are reduced by 259594.33 $kgCO_2e$ or more. Analysis also suggests that reducing the water: cement ratio of RMC-Am2 to get RMC-Am3 has a non-substantial impact on the AM's final output.

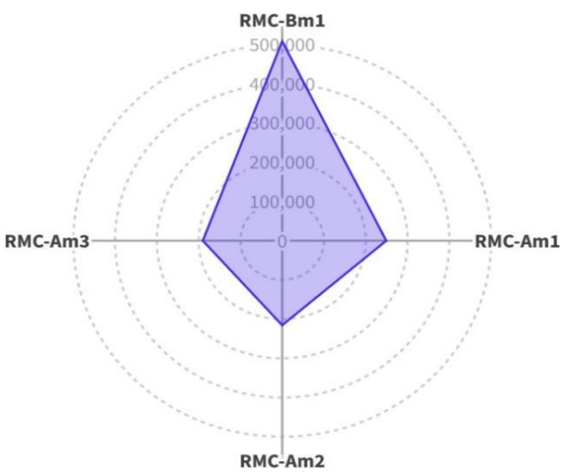

Fig. 6 Carbon emissions in $kgCO_2e$ of RMC in BM and alternatives for AM

In Figure 7, the thermal conductivity comparison outlines that both RMC-Bm1 and RMC-Am1 have similar values. This suggests that incorporating GGBS does not have as great an impact on the thermal efficiency of the material. In fact, aggregates are experimentally proven to reduce thermal conductivities of materials, and hence, RMC-Am2 with its 40% RCA and RMC-Am3 with reduced mixing ratios and 40% RCA provide superior thermal efficiencies in comparison.

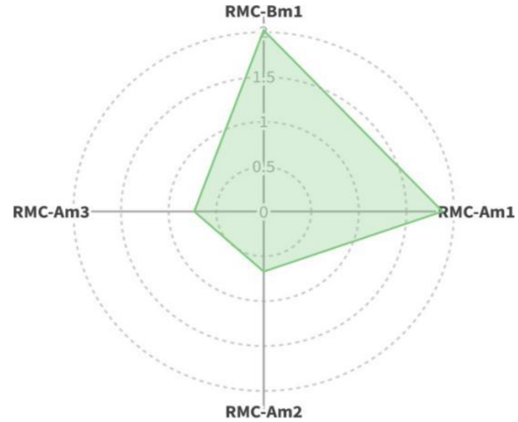

Fig. 7 Thermal conductivity in W/mK of RMC in BM and alternatives for AM

5.2.2. Brick and Its Constituent Alternatives

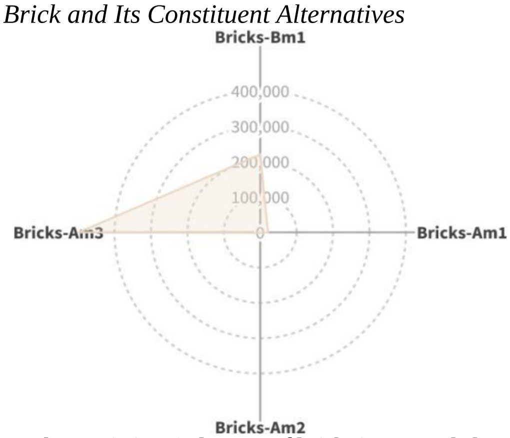

Fig. 8 Carbon emissions in $kgCO_2e$ of bricks in BM and alternatives for AM

Figure 8 suggests that the contribution of carbon emissions to Bricks-Am3 is the highest. Bricks-Bm1 is a fired common clay brick, whereas Bricks-Am2 are an unfired AM counterpart, wherein the former has a 130 times higher carbon emission contribution, making the adobe blocks a very sustainable alternative. Additionally, the aerated blocks (Bricks-Am1) contribute 92.83% less to the carbon emissions because of the porosity of the material itself, as opposed to the dense solid concrete blocks (Bricks-Am3).

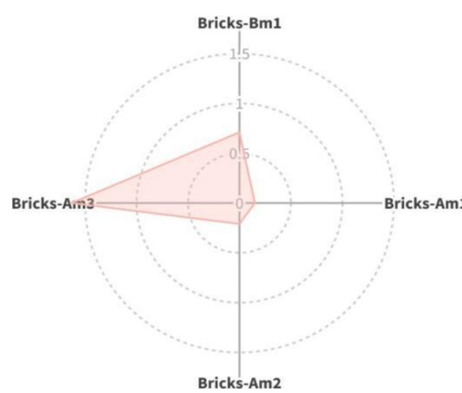

Fig. 9 Thermal conductivity in W/mK of bricks in BM and alternatives for AM

The thermal conductivity comparison can be interpreted in a very similar way to the previous graph. In Figure 9, the thermal conductivity of Bricks-Am3, dense concrete blocks, is the highest owing to its material composition. Conversely, because of the material's porosity, the aerated concrete blocks (Bricks-Am1) have a thermal conductivity value of 0.15, far lower than the latter. Additionally, the adobe blocks (Bricks-Am2) provide better thermal efficiency in comparison to their fired clay counterpart (Brick-Bm1), again making it a better choice for both energy-positivity and thermal efficiency.

5.2.3. Tiling and Finishes, and its Constituent Alternatives

Figure 10 outlines that the carbon emissions contribution of Tiling-Am1 is the highest, at 185567.06 kgCO_2e, owing to its plastic derivative composition and life-cycle background. While the previous one has an inorganic composition with high carbon emissions, its natural counterpart of marble flooring and finishes (Tiling-Am3) comparatively has a 95.6% reduction. Similarly, both Tiling-Bm1 and Tiling-Am2 are partly natural materials and hence, have reduced carbon emissions altogether.

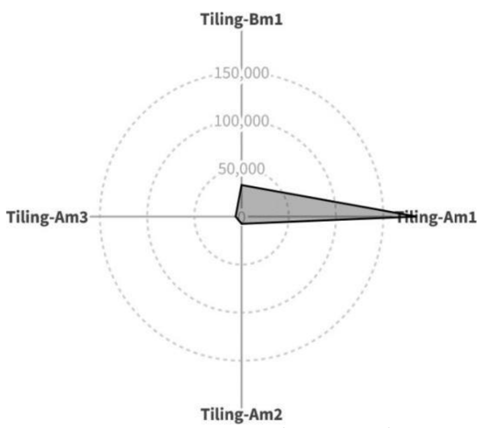

Fig. 10 Carbon emissions in kgCO_2e of tiling and finishes in BM and alternatives for AM

The thermal conductivity of the materials for Tiling and Finishes, though, has a contrasting implication as opposed to the previous plot. As shown in Figure 11, even though the EPS flooring has high carbon emissions, it has extremely low thermal conductivity (given it has a denser packing and lower porosity, similar to that of XPS flooring) of 0.04 W/mK, whereas its marble counterpart has a conductivity of 2.77 W/mK.

This highlights the dilemma that architects face when choosing materials, wherein the materials providing thermal efficiency lack on the sustainability front or vice versa. Tiling-Am2, that is, terrazzo flooring, is evidently the only option that provides both lower GWP and higher thermal efficiency.

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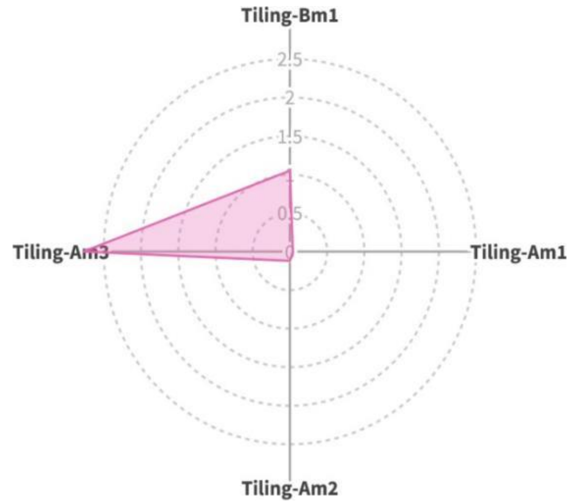

Fig. 11 Thermal conductivity in W/mK of tiling and finishes in BM and alternatives for AM

5.3. Overlayed Analysis of AM for Thermal Efficiency and GWP

A review of Figures 12 and 13 highlights distinct performance patterns among the material categories. In the case of structural components, Ready-Mix Concrete (RMC) emerges as the dominant source of embodied carbon, with emission values significantly higher, by roughly 160–190%, than lighter alternatives such as brick masonry.

Conversely, finishes and tiling stand out not so much for their mass contribution but for their strong influence on the building's thermal comfort, making them critical to energy performance despite smaller quantities.

When tested against substitution scenarios, RMC modified with Recycled Aggregates (RCA) or Ground Granulated Blast Furnace Slag (GGBS) demonstrates potential to curb both heat transfer and carbon intensity. Brick alternatives show a comparable trend, suggesting scope for incremental improvement in masonry units as well.

For surface treatments, however, the trade-off is sharper: coatings and finishes can either favor reduced emissions or enhance thermal regulation, but rarely both simultaneously, making them a more complex category for optimization.

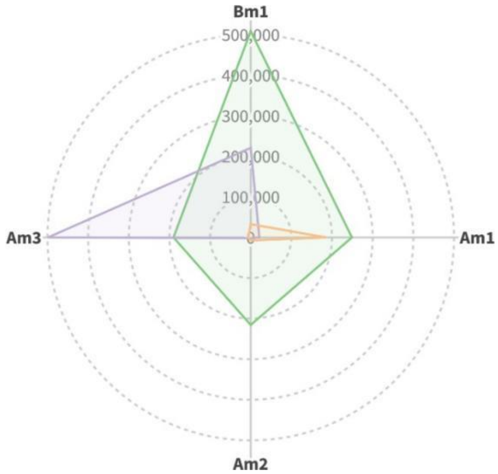

Fig. 12 Carbon emissions in W/mK of all alternatives for AM

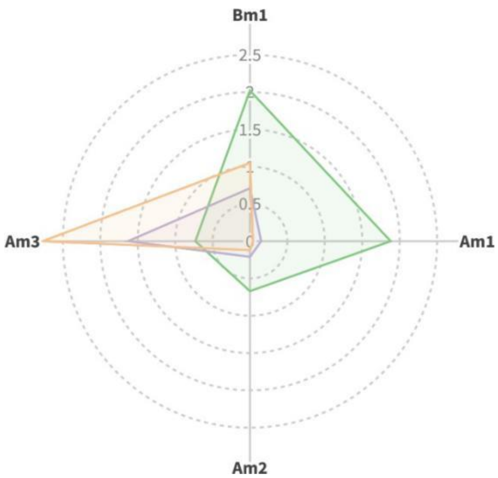

Fig. 13 Thermal conductivity in W/mK of all alternatives for AM

5.4. ECBC Trade-Off Compliance's Coordinating Material Choices

Bringing together the results of the One Click LCA and the comparative thermal performance study highlights how early-stage material decisions shape outcomes on two distinct levels. At the broader scale, the environmental impact of a project is determined by the cumulative emissions linked to each material, measured through indicators such as embodied carbon, global warming potential, transport intensity, and end-of-life scenarios. Availability of substitutes adds another layer, where cost and accessibility can alter the environmental benefits of switching to alternatives. At the building scale, choices in materials directly influence thermal regulation and user comfort, which in turn affect operational energy demand and long-term maintenance costs.

Yet, these findings gain relevance only when embedded in real-world design and construction practice. The building envelope, for instance, must comply with standards set by the Bureau of Energy Efficiency. Parameters such as the Envelope Performance Factor (EPF) or U-value thresholds define minimum energy conservation and thermal adequacy requirements. Integrating such compliance checks with material-level life cycle data produces a more complete picture that bridges regulatory expectations with sustainability ambitions.

The study illustrates how balancing energy and thermal efficiency requires a structured optimization approach. Two variables stand out as central:

- Energy efficiency is captured through embodied impacts like GWP and net emissions.
- Thermal efficiency is reflected in conductivity values and responsiveness to local climate.

Together, these act as guiding metrics for a multi-layered evaluation framework. The framework connects emissions, material mass, and life-cycle performance and incorporates considerations such as construction duration, which is particularly relevant to emerging techniques like 3D-printed concrete or adapted vernacular systems. Such technologies often shorten building timelines while reshaping carbon outcomes. Ultimately, the intersection of design choices, construction methods, and material selection defines the environmental footprint of a project. Recognizing financial constraints, the objective remains to work toward solutions that are both climate-positive and socially viable, aligning with broader sustainability targets while addressing the immediate needs of communities.

5.5. Sensitivity Analysis

To further investigate which material substitutions shape both carbon performance and thermal behavior, the study applied a sensitivity framework. This involved adjusting selected input variables in a controlled manner to track how modifications in composition or physical characteristics altered results such as Global Warming Potential (GWP) and thermal efficiency. The exercise was intended to pinpoint the parameters with the greatest leverage over building performance, thereby guiding design strategies that remain robust under varying conditions.

5.5.1. Parameters Varied

Four major construction categories were explored, each tested through incremental changes relevant to Indian building practice and supported by reliable LCA datasets:

1. GGBS Content in RMC - Varied from 0% to 45% in increments (RMC-Bm1 to RMC-Am1 - Am3)
2. Recycled Coarse Aggregate (RCA) in Concrete - Introduced at 30 - 40% to assess its impact on embodied carbon and thermal conductivity
3. Thermal Conductivity in Bricks - Compared fired clay bricks, AAC blocks, and adobe bricks.
4. Finish Materials - Compared EPS (synthetic), terrazzo (semi-natural), and marble (natural)

The selection of these variations reflects both their widespread use in India's construction sector and their relevance to climate-responsive performance. The resulting dataset provided insight into how subtle material changes can amplify or mitigate the overall environmental footprint of a project.

5.5.2. Analysis and Findings

Concrete Variations

1. Increasing GGBS content in concrete from 0% to 45% resulted in a GWP reduction of up to 63.41%, while thermal conductivity saw only marginal improvement.
2. Incorporation of 30–40% RCA further enhanced carbon reduction but slightly increased thermal resistance, suggesting a beneficial synergy for both energy efficiency and thermal comfort.

Brickwork Variations

1. Switching from fired clay bricks to AAC blocks led to a 92.83% drop in carbon emissions and a drop in thermal conductivity from 0.74 W/mK to 0.15 W/mK.
2. Adobe blocks (Bricks-Am2) offered the best balance: lowest embodied carbon with moderately low thermal conductivity (0.61 W/mK), outperforming both clay and dense concrete bricks.

Finishes Variations

1. EPS finishes showed excellent thermal insulation (0.04 W/mK) but came at the highest carbon cost (3.20 $kgCO_2e/kg$) due to synthetic origins.
2. Marble and terrazzo alternatives, while thermally less efficient, provided significant reductions in embodied carbon, with terrazzo striking a viable mid-point in the trade-off.

5.5.3. Implications

This analysis confirms that material efficiency cannot be evaluated through a single lens. While some materials perform exceptionally in terms of thermal insulation, they may significantly worsen a project's carbon profile, and vice versa.

Walling and concrete compositions had the most substantial influence on overall performance among all tested variables.

The findings emphasize the necessity of a dual-pronged material evaluation strategy that gives equal importance to embodied emissions and thermal behavior. Such a layered understanding can serve as a vital reference for architects and policy-makers aiming to prioritize climate-responsive design within cost and construction constraints.

6. Conclusion

This study adds to the understanding of the material selection in Indian construction by linking thermal performance with environmental impact. Earlier research often examined either embodied carbon or operational energy in isolation. Here, both aspects were considered together, showing how thermal properties of materials influence Global Warming Potential (GWP) and long-term efficiency.

The case study demonstrated that alternatives such as GGBS, RCA, and EPS can reduce emissions while also improving thermal comfort when compared to conventional materials. However, the results also showed that embodied carbon and thermal efficiency do not always align.

This makes it necessary to evaluate materials through multiple criteria instead of focusing on a single factor.

The key findings of the study are as follows:

1. Carbon emissions and thermal efficiency are not directly related and must be studied separately.
2. Thermal efficiency based on material classifications significantly influences material selection, thereby impacting Global Warming Potential (GWP) control.
3. GWP, energy efficiency, and thermal efficiency are interconnected factors that require collective optimization when evaluating materials and their alternatives.

By proposing a tool to optimize material selection based on energy efficiency, thermal performance, and GWP, this research fills a critical gap in sustainable construction methodologies. The study encourages architects and builders to adopt this multi-dimensional approach, ensuring the long-term balance between sustainability and functionality.

It positions itself as a stepping stone toward achieving India's climate goals outlined in Sustainable Development Goal (SDG) 7, advancing the region's discourse on sustainable building practices.

Acknowledgments

The authors gratefully acknowledge the support and contributions of various individuals and institutions that have facilitated the completion of this research paper. Their support has been instrumental in shaping the outcome of this study. They extend their appreciation to Ar. Ketaki Pednekar, for her constructive suggestions as subject expert, Ar. Pratik Mour for assisting in enhancing the rigor of the research, and Mr. Kevin Shah, Developer - Suyog Sweet Home Heights, for providing the relevant technical data of the case study. The authors also thank SRM Institute of Science and Technology, Chennai, India, and SMEF's Brick School of Architecture, Pune, India, for the logistics support needed to complete the research. They also sincerely appreciate the contributions of all individuals and entities who have assisted us in any capacity. Their support has been crucial to the successful completion of this study.

References

[1] 2022 Global Status Report for Buildings and Construction, United Nations Environment Programme (UNEP), 2022. [Online]. Available: https://www.unep.org/resources/publication/2022-global-status-report-buildings-and-construction

[2] "*National Policy Roadmap for Home Automation Technologies for Residential Energy Efficiency*," Bureau of Energy Efficiency, Report, 1-99, 2021. [Publisher Link]

[3] "*Energy Statistics 2020*," National Statistical Office, Report, pp. 1-117, 2020. [Publisher Link]

[4] Enrica De Cian, and Ian Sue Wing, "Global Energy Consumption in a Warming Climate," *Environmental and Resource Economics*, vol. 72, pp. 365-410, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[5] Liu Yang, Haiyan Yan, and Joseph C. Lam, "Thermal Comfort and Building Energy Consumption Implications - A Review," *Applied Energy*, vol. 115, pp. 164-173, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[6] A.D. La Rosa et al., "Environmental Impacts and Thermal Insulation Performance of Innovative Composite Solutions for Building Applications," *Construction and Building Materials*, vol. 55, pp. 406-414, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[7] Sameer Maithel, Rajan Rawa, and Yash Shukla, "Thermal Properties of Indian Masonry Units & Masonry for Eco-Niwas Samhita Implementation," pp. 1-9, 2023. [Google Scholar]

[8] H.L. Gauch et al., "What Really Matters in Multi-Storey Building Design? A Simultaneous Sensitivity Study of Embodied Carbon, Construction Cost, and Operational Energy," *Applied Energy*, vol. 333, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[9] Payam Nejat et al., "A Global Review of Energy Consumption, CO_2 Emissions and Policy in the Residential Sector (With an Overview of the Top Ten CO_2 Emitting Countries)," *Renewable and Sustainable Energy Reviews*, vol. 43, pp. 843-862, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[10] "*Net Zero by 2050: A Roadmap for the Global Energy Sector*," International Energy Agency, Report, pp. 1-224, 2021. [Google Scholar] [Publisher Link]

[11] Peng Zhou et al., "Energy Transition Management towards a Low-Carbon World," *Frontiers of Engineering Management*, vol. 9, pp. 499-503, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[12] Ruijun Chen, Yaw-Shyan Tsay, and Shiwen Ni, "An Integrated Framework for Multi-Objective Optimization of Building Performance: Carbon Emissions, Thermal Comfort, and Global Cost," *Journal of Cleaner Production*, vol. 359, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[13] Changhai Peng, "Calculation of a Building's Life Cycle Carbon Emissions based on Ecotect and Building Information Modeling," *Journal of Cleaner Production*, vol. 112, pp. 453-465, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[14] Rahman Azari, and Narjes Abbasabadi, "Embodied Energy of Buildings: A Review of Data, Methods, Challenges, and Research Trends," *Energy and Buildings*, vol. 168, pp. 225-235, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[15] Vitor Sousa, and José Alexandre Bogas, "Comparison of Energy Consumption and Carbon Emissions from Clinker and Recycled Cement Production," *Journal of Cleaner Production*, vol. 306, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[16] Sabbie A. Miller et al., "Carbon Dioxide Reduction Potential in the Global Cement Industry by 2050," *Cement and Concrete Research*, vol. 114, pp. 115-124, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[17] Omer Damdelen, *Measuring Thermal Mass of Sustainable Concrete Mixes*, Computing in Civil and Building Engineering, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[18] P. Shafigh et al., "Thermal Properties of Cement Mortar with Different Mix Proportions," *Materiales De Construcción*, vol. 70, no. 339, pp. 1-12, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[19] *Energy Conservation Building Code for Residential Buildings: Part I: Building Envelope*, Bureau of Energy Efficiency, pp. 1-40, 2017. [Publisher Link]

[20] Mohamed Abdel Latif Ahmed, "Building Technology in Achieving Thermal Comfort within Buildings," *International Journal of Advances Engineering and Civil Research*, vol. 1, no. 1, pp. 38-48, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[21] *Life Cycle Assessment for Buildings. Why it Matters and how to Use it*, One Click LCA Ltd, 2021. [Google Scholar] [Publisher Link]

[22] Roni Rinne, Hüseyin Emre Ilgın, and Markku Karjalainen, "Comparative Study on Life-Cycle Assessment and Carbon Footprint of Hybrid, Concrete and Timber Apartment Buildings in Finland," *International Journal of Environmental Research and Public Health*, vol. 19, no. 2, pp. 1-24, 2022. [CrossRef] [Google Scholar] [Publisher Link]