


# Sustainable Architecture

McD BERL

Research - Green Architecture



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# Sustainable Architecture: Benchmarking Green School Design Through Material Performance Analysis

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## Abstract

As climate change accelerates and construction-related emissions grow, the need for sustainable architecture becomes increasingly urgent. This research constructs a hypothetical benchmark for the most sustainable school building possible, using the EDGE Buildings App to quantify embodied carbon and thermal performance. The benchmark is then used to evaluate two real-world school buildings. Findings reveal substantial gaps in carbon efficiency and insulation quality, and this paper proposes practical, material-level recommendations to bridge the divide between conventional and truly sustainable building practices.

## 1. Introduction

The global construction industry is responsible for nearly 40% of total carbon emissions, a significant portion of which stems from embodied carbon in materials and inefficient energy design. Despite rising awareness, sustainable strategies often remain underutilised due to cost, knowledge gaps, and regulatory inertia.

This paper aims to address this issue by:

- Establishing a theoretical benchmark school building using best-in-class sustainable materials
- Comparing two real-life school buildings against this benchmark

- Recommending actionable material substitutions and design strategies to enhance sustainability

The case study buildings examined in this research are located in Sarjapur, Bangalore, India, a rapidly urbanising region characterised by a tropical savanna climate (Köppen–Aw). The area experiences hot summers with peak temperatures exceeding 35°C, a distinct monsoon season from June to September, and mild, dry winters. Average annual rainfall is approximately 970 mm, with high humidity during monsoon months. This climatic context places significant importance on material thermal performance and insulation strategies to reduce cooling loads, making it a relevant location for testing building materials. Using the EDGE Buildings App as the primary assessment tool, this study focuses on two critical indicators: embodied carbon (kg CO<sub>2e</sub>/m<sup>2</sup>) and thermal efficiency (U-values).

## **2. Review of Literature**

The growing urgency of environmental degradation and climate change has led the construction industry to re-evaluate its reliance on traditional building practices. A recurring theme in the literature is the need for innovative architectural strategies and sustainable material choices that reduce both operational and embodied energy, while promoting resilience, occupant health, and ecological balance.

### **2.1 Assessment Frameworks and Lifecycle Thinking**

Understanding and measuring sustainability begins with robust assessment tools. As highlighted by Sassi et al. (2006), tools such as LEED-NC, EcoEffect, and the Code for Sustainable Homes (CSH) each prioritise different objectives: market-based incentives, holistic environmental health, or government policy alignment. Yet, the lack of standardisation in weighting environmental indicators exposes inconsistencies in how “green” performance is quantified. Complementing this, Calkins (2009) in *Materials for Sustainable Sites* emphasises life-cycle assessment (LCA) as a critical but underutilised method in sustainable material selection, accounting for extraction, production, usage, and disposal phases.

## **2.2 Material Innovations and Smart Design Paradigms**

Materials are central to both sustainability and innovation in architectural design. Research by Kolarevic & Klinger (2013) introduces Material-based Computational Design (MCD), which optimises material use through digital fabrication, demountability, and minimal waste. Similarly, the work of Addington (2017) expands on smart materials like thermochromic coatings and shape-memory alloys that dynamically respond to light and heat, enabling adaptive building skins that enhance energy performance. This signals a shift toward buildings that not only consume fewer resources but also behave intelligently within their environmental context.

## **2.3 Earth-Based and Renewable Material Strategies**

Gernot Minke's comprehensive study on earth-based construction (2006) revalidates ancient techniques like adobe and rammed earth in modern sustainable architecture. Earth construction provides benefits such as humidity regulation, thermal mass, and zero-carbon potential, making it viable for both developed and developing regions. This aligns with Singhal's (2025) emphasis on natural material alternatives like timber, hempcrete, and plant-based roof systems, which offer superior insulation, recyclability, and lower embodied carbon.

## **2.4 Energy Efficiency and Passive Design Techniques**

The importance of energy design and passive systems is echoed in Cody's (2009) paper, which critiques the over-reliance on ICT in "smart buildings." Instead, it promotes adaptive skins, user-responsive feedback systems, and material-driven optimisation. These ideas find practical synergy in Yeang's integrated design framework (2021), which advocates a three-tier strategy: optimising building form and fabric, deploying passive climate systems, and finally, integrating mechanical systems. These methods reduce cooling/heating loads and enhance indoor thermal comfort with minimal environmental cost.

## **2.5 Policy, Practice, and Industry Challenges**

Despite the innovations, significant barriers remain. Azhar et al. (2014) identify recurring industry challenges such as cost overruns, regulatory gaps, and limited adoption of sustainable practices. Regional case studies from Malaysia and Nigeria show that without coordinated policy

enforcement and skilled labour development, even the best strategies remain unimplemented. Moreover, variations in embodied energy calculations (Farzad 2015) highlight a methodological inconsistency that complicates cross-study comparisons.

## **2.6 Biophilia, Tradition, and Holistic Sustainability**

The literature also emphasises the value of incorporating biophilic principles and regional vernacular design. Singh (2020) encourages the adaptation of traditional techniques such as solar chimneys, shaded courtyards, and evaporative cooling, recognising their proven ecological intelligence. These strategies offer low-tech but high-impact alternatives to mechanical dependency, especially in climate-sensitive regions.

## **Synthesis and Research Gap**

Collectively, the reviewed works establish a strong foundation for understanding sustainable construction as a multidimensional endeavour—spanning environmental science, material innovation, design methodology, and policy. While various strategies have been proposed and evaluated across contexts, the synthesis highlights a gap in benchmark-based material comparison using standardised embodied carbon and energy performance indicators.

This paper seeks to address that gap by constructing a theoretical benchmark for the most sustainable school building possible, and then comparing real-world cases against this benchmark using the EDGE Buildings App. This comparative framework, grounded in the literature, allows for a deeper exploration of material choices and design strategies that truly meet sustainability goals—not just in theory, but in practical architectural decision-making.

## **3. Methodology**

This study follows a comparative design approach:

1. Benchmark Building Creation:
  - a. Developed in EDGE using optimal material inputs from the literature (CLT, rammed earth, hempcrete, etc.)
  - b. Quantified for embodied carbon and U-values.
2. Case Study Buildings:

- a. Two real school buildings were assessed based on their materials and design features
  - b. Inputs were manually analysed using the EDGE material database and sustainability heuristics
3. Comparison Metrics:
- a. Embodied Carbon (kgCO<sub>2e</sub>/m<sup>2</sup>)
  - b. U-values for roof, walls, and windows.

**3.1 Base Case Building (As per EDGE App)**

Category	Material	Properties
Bottom Floor	Concrete Slab (In-situ Reinforced, 100mm)	High embodied carbon; steel rebar (35 kg/m <sup>2</sup> ).
Intermediate Floor	Concrete Slab (In-situ Reinforced, 300mm)	High embodied carbon; steel rebar (35 kg/m <sup>2</sup> ).
Floor Finish	Ceramic Tiles (Tiled, 10mm)	Moderate embodied carbon (14.3 kg/m <sup>2</sup> )
Roof Construction	Concrete Slab (In-situ Reinforced, 300mm)	High embodied carbon (35 kg/m <sup>2</sup> ).
Exterior Walls	Concrete Blocks (250mm, with plaster)	U-Value ~1.86 and embodied carbon (12.7 kg/m <sup>2</sup> )
Interior Walls	Concrete Blocks (100mm, with plaster)	High embodied carbon (25.6 kg/m <sup>2</sup> )
Window Frames	Aluminum	Embodied carbon (1.4 kg/m <sup>2</sup> )
Window Glazing	Single Glazing	Poor insulation (U-Value ~3.99).
Roof Insulation	No Insulation	High heat loss
Wall Insulation	No Insulation	High heat loss
Floor Insulation	No Insulation	Not required for Bangalore's Climate

**Performance Overview (Base Case)**

- Embodied Carbon (kgCO<sub>2e</sub>/m<sup>2</sup>): 356.9
- U-Values: Roof: ~1.91 | Walls ~1.86 | Windows ~3.99 | Floor ~1.99
- Sustainability Score: Baseline

**3.2 Benchmark "Greenest" School Building (Optimised)**

Category	Material	Why it's better
Bottom Floor	Timberboard or Chipboard on Timber Joists (100mm)	Negative embodied carbon, renewable.
Intermediate Floor	Timberboard or Chipboard on Timber Joists (300mm)	Negative embodied carbon, renewable.
Floor Finish	Parquet/Wood Block Finishes	Negative embodied carbon, thermal comfort, renewable
Roof Construction	Asphalt Shingles on Timber Rafters (300mm)	Improved insulation and lower weight
Exterior Walls	Rammed Earth Walls (250mm)	Carbon neutral, natural insulation.
Interior Walls	Rammed Earth Walls (100mm)	Carbon neutral, natural insulation.
Window Frames	Timber	Negative embodied carbon, easily available
Window Glazing	Single Glazing	Optimizes daylight
Roof Insulation	Cork Insulation (Natural)	Sustainable and biodegradable
Wall Insulation	Corkboard Insulation	Biodegradable, better thermal performance
Floor Insulation	No Insulation	Not required for Bangalore's Climate

**Performance Overview (Benchmark Case)**

- Embodied Carbon (kgCO<sub>2e</sub>/m<sup>2</sup>): -43.7 (87.8% reduction)
- U-Values: Roof: ~0.3 | Walls ~0.43 | Windows ~3.99 | Floor ~1.25

- Sustainability Score: Meets EDGE's Material standard up to 112.2%
- Drawback: Very reliant on timber, which contributes to deforestation

To validate the benchmark building's credibility, its embodied carbon and insulation performance were compared with established industry benchmarks. The Carbon Leadership Forum's 2025 WBLCA Benchmark Report reports a median embodied carbon intensity of approximately 450–500 kgCO<sub>2</sub>e/m<sup>2</sup> for educational buildings in North America, with best-in-class values ranging from 300–350 kgCO<sub>2</sub>e/m<sup>2</sup>. The benchmark building in this study achieves -43.7 kgCO<sub>2</sub>e/m<sup>2</sup>, which is around 110% lower than the global median and roughly 115% lower than best-in-class examples, indicating exceptional performance. This value appears as a reduction greater than 100% relative to conventional benchmarks because the model incorporates large quantities of bio-based materials (timber and plant-derived insulation) that store biogenic carbon during growth. When this sequestration is accounted for within cradle-to-gate LCA boundaries, the resulting balance becomes net-negative. Therefore, the comparison is not a literal percentage reduction but an indication that the benchmark building offsets more embodied carbon than it emits during material production.

Furthermore, the benchmark meets RICS (2023) embodied carbon calculation methodology standards, ensuring comparability and methodological rigour. In terms of thermal performance, the benchmark exceeds the Energy Conservation & Sustainable Building Code (ECSBC) 2023 insulation requirements for educational facilities in Climate Zone 3 (Bangalore), achieving wall and roof U-values of 0.43 W/m<sup>2</sup>·K and 0.3 W/m<sup>2</sup>·K respectively, both well below the ECSBC maximum permissible limits.

### 3.3 Comparative Insights

Parameter	Base Case	Benchmark Case	Improvement
Embodied Carbon (kgCO <sub>2e</sub> /m <sup>2</sup> )	~357	~43.7	~87.8% reduction
Roof U-Value (W/m <sup>2</sup> ·K)	1.91	~0.3	~84.3% better
Wall U-Value (W/m <sup>2</sup> ·K)	~1.86	~0.43	~76.9% better
Window U-Value (W/m <sup>2</sup> ·K)	~3.99	~3.99	0% change
Floor U-Value (W/m <sup>2</sup> ·K)	~1.99	~1.25	~37.2% better

Embodied carbon values in this study are based on cradle-to-gate (A1–A3) assessments from the EDGE database and representative EPDs, consistent with standard LCA boundaries. Transport and supply-chain emissions (A4–A5) were not included, and the benchmark therefore reflects a best-case material scenario rather than a region-specific supply chain model. While rammed earth and timber systems are locally viable in South India, certain materials such as cork insulation and imported CLT may incur additional emissions depending on sourcing. Regional sourcing should be prioritised in real-world implementation.

### 3.4 Practical Feasibility and Regional Constraints

Practical implementation of the benchmark depends on regional material availability and construction practices. For instance, cork insulation is not widely manufactured in India and may require importation, increasing transport emissions (A4 stage). Similarly, large-scale engineered timber systems such as cross-laminated timber (CLT) are limited within the Indian construction sector due to regulatory constraints, supply chains, and familiarity with using concrete. In the Indian context, comparable performance could potentially be achieved using locally available alternatives such as bamboo composites or compressed stabilised earth blocks (CSEB).

## 4. Case Studies

### 4.1 Indus DP Block

Component	Material	Embodied Carbon	U-Value	Notes
Roof	Concrete	High	1.91 W/m <sup>2</sup> ·K	High carbon emissions from cement + no natural insulation
Walls	Cement plaster + Solid Cement Blocks	High	~1.9 W/m <sup>2</sup> ·K	Poor thermal insulation, high cement usage
Floor Finish	Vitrified Tiles	Moderate	1.99 W/m <sup>2</sup> ·K	Less eco-friendly than recycled materials
Windows	Aluminium Frames, No Glazing	Very High	6+ W/m <sup>2</sup> ·K	Aluminium is carbon-intensive, no thermal barrier
All Insulation	None	-	Poor	High operational energy needs for cooling/heating

#### Overview:

- Embodied Carbon Estimate: 350 kg CO<sub>2e</sub>/m<sup>2</sup>
- Thermal Efficiency: Very poor
- Sustainability Verdict: Poor
- Compared to Benchmark: ~8x the carbon, vastly inferior thermal envelope.

#### Recommendations:

- Replace cement blocks with rammed earth or hollow concrete blocks
- Introduce internal insulation (e.g., cork or recycled foam)
- Upgrade aluminium windows to uPVC with Low-E double glazing
- Replace the roof with CLT or green roof slab, if structurally feasible.

#### 4.2 Indus International Community School

Component	Material	Embodied Carbon	U-Value	Notes
Roof	Metal GI Sheet	High	6.5 W/m <sup>2</sup> ·K	Highly conductive, poor insulation, rapid heat transfer
Walls	Cement plaster + Red Brick	High	~1.9 W/m <sup>2</sup> ·K	Better than solid cement blocks, but still inefficient
Floor Finish	Cement	Moderate	1.99 W/m <sup>2</sup> ·K	Better than tiles in carbon terms, but uninsulated
Windows	Mild Steel Frames, Single Glazing	High	6+ W/m <sup>2</sup> ·K	High heat loss and gain; no energy efficiency
All Insulation	None	-	Very Poor	Requires massive cooling input in hot weather

#### Overview:

- Embodied Carbon Estimate: 335 kg CO<sub>2</sub>e/m<sup>2</sup>
- Thermal Efficiency: Very poor
- Sustainability Verdict: Poor
- Compared to Benchmark: ~8x more carbon, poor passive performance

#### Recommendations:

- Swap the GI roof for a timber or composite panel roof + insulation
- Use honeycomb brick blocks or CSEB (Compressed Stabilised Earth Blocks) instead of solid blocks
- Add internal/external wall insulation (e.g., hempcrete)
- Replace mild steel windows with recycled wood or uPVC frames + Low-E glass.

**4.3 Summary Table**

Aspect	Benchmark	Indus DP	Indus Community
Roof	Asphalt Shingles on Timber Rafters	Concrete	Metal GI Sheet
Walls	Rammed Earth Walls	Cement plaster + Solid Cement Blocks	Cement plaster + Red Brick
Windows	Timber, Single Glazing	Aluminium Frames, No Glazing	Mild Steel Frames, Single Glazing
Insulation	Full	None	None
Embodied Carbon	-43.7	350	335
Roof U-Value	0.3	1.91	6.5
Walls U-Value	0.43	1.9	1.9
Windows U-Value	3.99	6+	6+
Sustainability Verdict	Excellent	Poor	Poor

**Conclusion**

The benchmark school building, modelled using high-performance sustainable materials and passive design strategies, significantly outperforms both case study buildings. The embodied carbon is reduced and thermal performance improves across roofs, walls, and even flooring.

When assessed against the CLF WBLCA 2025 benchmarks for education buildings, the benchmark’s  $-43.7 \text{ kgCO}_2\text{e/m}^2$  equates to  $\approx 110\%$  lower than the median and  $\approx 115\%$  lower than best-in-class (the  $>100\%$  “reduction” arises because the benchmark includes biogenic carbon sequestration from timber and plant-based materials, resulting in a net-negative embodied carbon value).

Code compliance is context-specific. For ECSBC (2024) Climate Zone: Warm & Humid, the benchmark meets the opaque-assembly limits for roof and walls. For example, the roof  $0.3 \text{ W/m}^2\cdot\text{K}$  vs the ECSBC limit  $0.26 \text{ W/m}^2\cdot\text{K}$  (ECSBC level), and walls  $0.43 \text{ W/m}^2\cdot\text{K}$  vs the school

limit  $0.85 \text{ W/m}^2\cdot\text{K}$ . It does not meet the ECSBC+ roof ( $0.20 \text{ W/m}^2\cdot\text{K}$ ), nor the vertical fenestration U-factor (benchmark single glazing  $\sim 3.99$  vs ECSBC fenestration max  $2.20 \text{ W/m}^2\cdot\text{K}$ ), which should be addressed in future iterations. Additionally, future research should incorporate full LCA boundaries (A1–A5) and region-specific EPD catalogues to evaluate how transport and supply-chain emissions affect feasibility in Bangalore.

Crucially, the material palette is justified for Bangalore as natural insulations (cork), rammed earth, and timber are selected for local feasibility and availability, while no floor insulation is retained to reflect tropical demand. All quantitative values referenced here are sourced from the EDGE dataset (base-case and benchmark element U-values), CLF WBLCA 2025 (embodied-carbon benchmarks), RICS 2023 (calculation methodology), and ECSBC 2024 (envelope limits).

These results position the benchmark as an internationally competitive best-practice model for sustainable school construction, with performance metrics that not only meet but also significantly surpass global and national targets, although they represent a theoretical best-case scenario. This paper demonstrates that sustainable school design is not only feasible but measurable. With clear material substitutions and smarter envelope strategies, real-world projects can drastically improve their environmental impact. The EDGE platform serves as an effective tool to guide this transformation through data-driven design.

## 5. Relevance to Emerging Markets

Sustainable construction is particularly critical in emerging markets, where rapid urbanisation, population growth, and infrastructure demand are driving a significant increase in building activity. Certain countries, such as India, Indonesia, and China, are expected to account for a large share of global construction in the coming decades, making material and design decisions in these regions highly consequential for global carbon emissions.

In these contexts, the adoption of resource-efficient building strategies is often constrained by cost sensitivity, limited access to advanced technologies, and fragmented regulatory enforcement. As a result, construction practices tend to rely heavily on conventional materials,

which contribute substantially to embodied carbon. However, significant reductions in both embodied carbon and thermal inefficiency are achievable through informed material substitution and passive design strategies.

The benchmark model developed in this research highlights the potential of locally adaptable, lower-carbon materials such as rammed earth, timber alternatives, and bio-based insulation systems. While some materials used in the benchmark (e.g., cork insulation or cross-laminated timber) may not be widely available in all emerging markets, the underlying design principles remain transferable. Locally available substitutes, such as bamboo composites or compressed stabilised earth blocks (CSEB), can achieve comparable outcomes when applied within the same design framework.

By applying EDGE in a benchmarking capacity, this study illustrates how data-driven design can bridge the gap between theoretical sustainability goals and practical implementation. For emerging markets, where the majority of future building stock is yet to be constructed, such tools offer a unique opportunity to “leapfrog” inefficient development pathways and adopt scalable, low-carbon construction practices from the outset.

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