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ARTICLE

Multi-Criteria Comparison of Mivan, EPS Panel and Fly Ash Geopolymer Systems for Sustainable Lean Housing in India

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ABSTRACT

The construction industry generates about 36% of global energy consumption and 40% of CO_2 emissions, while material waste exceeding 30%, schedule overruns and cost escalation underscore the relevance of lean construction principles. This study compares Mivan aluminium formwork, Expanded Polystyrene (EPS) core panel systems and fly ash geopolymer block masonry against conventional reinforced cement concrete (RCC)-clay brick masonry for a G+3 residential building in Pimpri-Chinchwad, Pune, India, using a controlled quasi-experimental design comprising material characterisation, direct and life-cycle cost analysis, thermal performance assessment (U-value, time lag, decrement factor), embodied-carbon quantification (ISO 14044:2006) and lean waste metrics via the Last Planner System (LPS). Mivan achieved the highest schedule savings (54.2%) and lowest material waste intensity (11.2 kg/m^2 GFA); EPS panels achieved the best wall U-value (0.31 W/m^2K) and lowest 30-year life-cycle cost (INR 148.60 lakhs, 18.5% below conventional); fly ash geopolymer blocks achieved the lowest construction-phase embodied carbon (38.6 kg CO_2-eq/m^2, 65.8% below clay brick) and the highest compressive strength (31.2 MPa). Weighted multi-criteria analysis ranked EPS panels highest (3.85), followed by Mivan (3.65), fly ash geopolymer (3.50) and conventional (1.95), showing that single-phase cost analysis alone is insufficient for technology selection since a life-cycle perspective incorporating operational energy and embodied carbon systematically reverses cost rankings. These findings provide evidence-based guidance for developers, contractors and policymakers pursuing sustainable mass housing in India.

Keywords: Sustainability; Lean-Construction; Mivan; Geopolymer; Thermal-Performance; Life-Cycle-Cos; Process Innovation

1. Introduction

The construction industry is responsible for around 36% of the energy consumed and almost 40% of the global CO_2 emissions; therefore, the need for a more sustainable transformation in the sector is urgent[1]. At the same time, the sector has been consistently plagued by inefficiencies, cost overruns, delays in projects, waste rates of more than 30% and disjointed supply chains that take a toll on project value and its environmental impact[2,3]. Lean production philosophy and sustainable construction seem to be converging, with lean construction (LC) being about the systematic elimination of waste and non-value-adding activities, and sustainable construction expanding this concept into environmental and socio-economic implications over the entire project lifetime[4,5]. The categories of waste eliminated in this study follow the widely used eight-waste extension of the Toyota Production System, commonly abbreviated by the mnemonic DOWNTIME (Defects, Overproduction, Waiting, Non-utilized talent, Transportation, Inventory, Motion and Excess processing), which the site waste audit described in Section 3.4 maps onto formwork, masonry, concrete, mortar, packaging and mixed inert waste streams.

India is a very illustrative case in point for this investigation. The country is currently experiencing one of the largest urban housing growths in its history, and the Pradhan Mantri Awas Yojana (PMAY) is focusing on building more than 29.5 million affordable dwelling units (ADUs)[6]. This unprecedented demand level meets a challenge and an opportunity: to introduce cost-effective yet time-efficient construction technologies with thermal resistance and, at the same time, environmental responsibility[7]. Reinforced cement concrete (RCC) buildings with clay brick masonry are still predominant, yet cannot easily address these multi-dimensional requirements, especially in the context of increasing prices of construction materials, shortage of skilled manpower, and the strict requirement for green buildings[8]. Researchers and practitioners have investigated a number of alternative construction systems as they realize these pressures. Of those, the most promising are the aluminium panel formwork systems, as it is commercially known as Mivan technology, expanded polystyrene (EPS) core panel systems and the masonry units made with geopolymer: fly ash geopolymer blocks and autoclaved aerated concrete (AAC) blocks. The different technologies have their own unique green and lean characteristics: Mivan systems allow a rapid and repetitive construction process per floor using the precision aluminium formwork which can be used repeatedly; EPS panels provide

lightweight, higher thermal performance wall assemblies, with less wet work; and fly ash geopolymer blocks convert industrial by-products into higher quality masonry blocks, whilst also reducing the embodied carbon of traditional Portland cement bricks[9–11].

The available literature, although extensive, has significant gaps. First, most comparative studies assess these technologies in a binary mode, between one alternative and traditional construction, instead of combining several technologies in a common analysis that takes into account the cost, time, and environment, thermal and structural aspects at the same time[12]. Second, the characterization of fly ash-based materials has lagged behind the technological evolution, as the modern fly ash geopolymer brick, which is produced by alkali-activation instead of high-temperature sintering, shows compressive strengths above 30 MPa and contains 40–60% less CO_2 than the ordinary portland cement (OPC)-based alternatives, and is therefore fundamentally different from the conventional fly ash bricks made 10 years ago[13]. Third, in previous case studies, very few results and discussions have linked empirical data with other studies or theories in a wider context or have been analysed and compared in a multi-criteria manner, which can be generalized[14,15].

The problem this study addresses is that decision-makers selecting a mass-housing construction technology in India currently have no single, rigorously quantified evidence base that evaluates cost, schedule, thermal performance and lifecycle carbon together; existing work instead compares one alternative technology against conventional construction at a time, on one or two criteria, which does not reflect how procurement decisions are actually made[16,17]. From the standpoint of JBMS and its readership, the research gap is therefore the absence of a controlled, multi-criteria, multi-technology comparison of Mivan aluminium formwork, EPS core panel systems and fourth-generation fly ash geopolymer masonry against the conventional RCC-clay brick baseline within one case study, using consistent measurement protocols across all criteria[18]. In this paper, these gaps are filled by doing a rigorous and multi-dimensional comparative study of Mivan aluminium formwork, EPS core panel system, and fly ash geopolymer block masonry for a G+3 residential RCC building in Pimpri-Chinchwad, Pune, Maharashtra, India. The scientific contributions of this work are 4 fold as follows:

- A detailed multi-criteria evaluation process that considers cost efficiency, schedule performance, lifecycle environmental impact (embodied CO_2, operational energy) and thermal performance indices (U-value, time lag, decrement factor) of three state-of-the-art sustainable lean construction technologies.
- Characterised material of fly ash geopolymer blocks, which are technically and economically better than fly ash bricks, and their mechanical and thermal properties are measured.
- Quantified lean waste reduction metrics (material waste, labor hours, rework frequency) for each technology were developed, directly based on Last Planner System (LPS) implementation data.
- Real-world advice for the developer, contractor and policy-maker on sustainable urban housing programmes.

Figure 1 illustrates a structured three-column integration approach that is an operationalization of the conceptual convergence of lean construction (LC) and sustainable construction (SC) as developed by Sarhan et al.[19] and Merker[20]. The left column lists the five basic LC principles: eliminate non-value-adding activity, continuous improvement (Kaizen), pull planning and just-in-time (JIT) delivery, respect for people (workforce development) and visual management[21,22]. The three technologies assessed in this study are based on the following principles, which are taken from the Toyota Production System and extended to the construction sector by Koskela[15] and Ballard and Howell[16]. Specific LC tools and technologies are mapped to these principles in the centre column[23]. This mapping draws on published implementations of building information modeling (BIM)-enabled value stream mapping and lean design workflows reported by Arayici et al.[24] and Khosrowshahi and Arayici[25]. The Last Planner System (LPS) operationalizes pull planning; value stream mapping (VSM) is an approach which identifies waste for continuous improvement; and the three construction systems investigated (Mivan, EPS panels, and fly ash geopolymer blocks) represent[26] three systems of material and process waste elimination. The right-hand column specifies the associated sustainability impacts in numbers, which will give the reader

an indication of the ranges of performance specified in Sections 4.2–4.6. **Figure 1** has two purposes: it provides the theoretical underpinning for considering these technologies as lean tools (and not just as alternative construction techniques), and it represents the dimensions of the outcome that will be used as a basis for the results analysis.

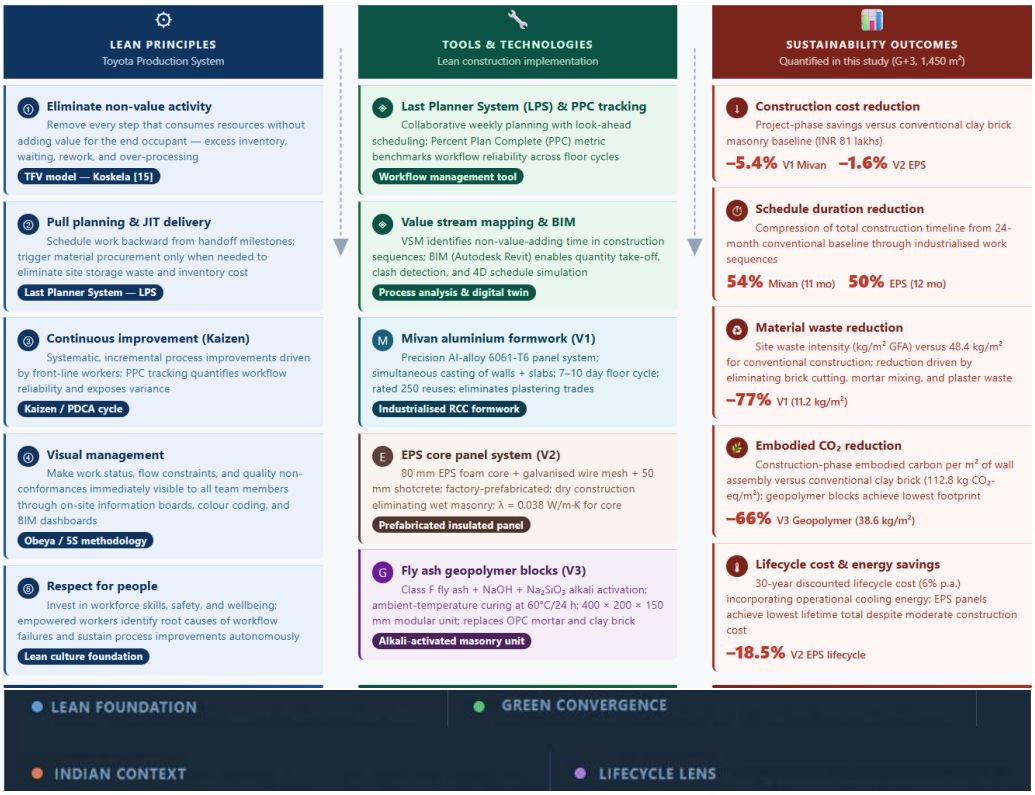

Figure 1. Lean-sustainable construction integration framework.

Note: Lean Foundation: Transformation-Flow-Value (TFV) model [15]; LPS [16]; Green Convergence: Lean ∩ sustainable [19]; Waste = CO_2 [20]; Indian Context: LC barriers [21]: LC adoption [23]; Lifecycle Lens: lifecycle cost analysis (LCCA).

2. Literature Review

To orient the detailed narrative review that follows and to make the state of the art directly traceable, **Table 1** summarizes ten studies published over the past decade that are most relevant to the three technologies and the multi-criteria approach evaluated in this paper.

Table 1. Summary of key literature (past decade) relevant to sustainable lean construction technology selection.

Study (Year)	Technology/Focus	Key Finding	Gap This Study Addresses
Gulghane et al. [27] (2018)	Mivan aluminium formwork, India	40% construction-time reduction, 12% cost saving vs. brick-frame	Single-technology, cost/schedule only—no thermal or carbon dimension
Ramteke et al. [28] (2022)	Mivan technology, India	12.5% cost saving, 40% schedule improvement	Confirms Mivan benefits but not benchmarked against EPS or geopolymer
Sankhe and Kumbhar [29] (2025)	Mivan vs. conventional formwork, high-rise India	Cost and schedule advantages of Alu-Form in high-rise projects	Focuses on high-rise typology; mass housing G+3 segment not covered
Chen et al. [10] (2026)	EPS core panel system, India	Suitable for up to 4-storey buildings; 18–25% cooling-load reduction	Thermal performance only; no lifecycle cost or carbon comparison
Prasittisopin et al. [30] (2022)	EPS concrete, international review	Thermal conductivity 0.15–0.50 W/mK vs. 0.9–1.2 W/mK dense concrete	International evidence not benchmarked against Indian case data
Krishnan et al. [11] (2024)	Circular-economy fly ash utilisation, review	Fly ash increasingly diverted to cement/geopolymer, no longer a cheap by-product	Reviews market/technology trends but no site-level performance data

Table 1. *Cont.*

Study (Year)	Technology/Focus	Key Finding	Gap This Study Addresses
Janga et al.[31] (2024)	Fly ash geopolymer blocks, MCDM sustainability	Sustainability index (embodied energy, GWP) used to select optimal mix	Mix-level MCDM; not extended to whole-building, cross-technology comparison
Singh et al.[13] (2024)	Agro-forestry/CDW fly ash bricks	Large CO_2 reduction and improved thermal performance vs. conventional bricks	Material-level only; not linked to project cost or schedule performance
Sarhan et al.[19] (2019)	Lean–green construction, 25-year IGLC review	Waste elimination materially equivalent to environmental burden reduction	Conceptual synthesis; no quantitative lean-carbon linkage at project level
Strulak-Wójcikiewicz and Wagner[32] (2021); Zhang et al.[33] (2022)	Life-cycle cost/carbon-shadow pricing, Asia	15–25% life-cycle saving from low-carbon materials; carbon pricing reverses rankings	Generic material comparison; not applied to Mivan/EPS/geopolymer technologies

Note: MCDM: Multi-Criteria Decision-Making; GWP: Global Warming Potential; CDW: Construction and Demolition Waste; IGLC: International Group for Lean Construction.

2.1. Lean Construction: Theoretical Foundations and Implementation

Lean construction is based on the Toyota Production System (TPS) and was first introduced in the construction industry by Koskela[15], who suggested the Transformation-Flow-Value (TFV) model as an alternative to the prevalent task-centric project management model. Ballard and Howell[16] later translated lean concepts into the Last Planner System (LPS), which helps reduce the amount of variability in the weekly work plans by engaging in collaborative look-ahead scheduling, resulting in a greater Percent Plan Complete (PPC) and less disruption in the workflow. A large number of meta-analysis studies have shown that LC implementation has average cost savings of 15–25% and average schedule savings of 20–40% on a variety of project types[17,18].

A systematic review by Sarhan et al.[19] of 25 years of research on IGLC revealed the evolution of the two paradigms of lean and green construction. It emphasized the fact that waste elimination, one of the LC objectives, is materially equivalent to environmental burden reduction. Merker[20] showed in a longitudinal case study that using integrated LC-sustainability frameworks decreased the amount of waste on site by 32% and reduced CO_2-equivalent emissions by 18% compared with a conventional project delivery. In the context of India, Mohammed et al.[21] used the principles of root cause analysis to understand the systemic barriers to the implementation of LC and concluded that the major persistent barriers in the Indian context are the skill gap in the workforce and fragmented supplier chains.

Wong and Ahmed[22] reviewed the application of LC in complex infrastructure projects. They revealed that the most efficiency improvements can be achieved when the lean tools are used in an integrated way and not selectively, for example, pull planning, value stream mapping (VSM) and visual management. Guo[4] conducted a literature review on LC adoption amongst construction companies in India. They concluded that there is a growing awareness of LC adoption, but still not all construction companies are implementing the LC system, which indicates a significant scope of opportunity. Gao and Low's recent research[23] further developed the lean concepts to prefabrication and modular construction, which has provided a conceptual link between traditional lean concepts and the industrialized construction technologies discussed in this paper.

The international literature on lean implementation is broader than construction-technology comparisons alone: Arayici et al.[24] demonstrated that BIM-enabled workflows measurably reduce rework and over-processing in architectural practice, a mechanism directly analogous to the waste-elimination metrics quantified in Section 4.3; Khosrowshahi and Arayici[25] mapped organisational barriers to BIM/lean adoption at industry scale in the UK, paralleling the adoption barriers reported for India by Mohammed et al.[21]; and Arayici et al.[26] showed that a socio-technical, KTP-based implementation approach improves lean design outcomes for small architectural practices, reinforcing the "respect for people" principle in **Figure 1**. These studies collectively broaden the evidence base beyond the India-specific literature reviewed above.

2.2. Mivan Aluminium Formwork Technology

Mivan aluminium formwork was developed in Malaysia in the late 1990s and was quickly embraced for

mass housing programmes in South and Southeast Asian countries. The system uses precision-manufactured aluminium panels that can be used to create walls, slabs, columns and beams within a single pour of concrete to form monolithic RCC structures, with better surface finishes and dimensions [34]. The basic study in the Indian context was done by Gulghane et al. [27], where it was shown that the construction time in Mivan can be reduced by about 40% as compared to conventional brick-frame construction, and cost savings were obtained at the rate of 12%. Ramteke et al. [28] did a foundational study in the Indian context, which confirmed the cost savings of 12.5% and schedule improvement of 40% as compared to conventional brick-frame construction.

The "lean" credentials of Mivan systems have been well documented. The use of these reusable aluminium panels (up to 250 times use) considerably decreases the use of formwork materials, and the need for plastering and joint-sealing operations considerably reduces the wet-trade labour costs and associated chemical waste streams [35]. Baskaran et al. [36] have performed a lifecycle assessment (LCA) of hybrid formwork systems and shown that the construction phase embodied carbon of aluminium formwork systems has been up to 35–45% lower when compared to single-use timber alternatives, which is mainly due to the high percentage of aluminium that can be recycled (>90%) and the energy required in the production of aluminium formwork can be recovered throughout the lifetime of the system.

A structural comparative study of Mivan-formwork buildings to conventional RCC frames in high seismic zones has been done by Hinduja et al. [9]. They found that the monolithic concrete buildings constructed by the Mivan system have better lateral stiffness and inter-storey drift performance due to the elimination of construction joints and better concrete placement conditions provided by closed aluminium forms. The structural benefit has an economic consequence in a lean perspective: lower seismic repair costs and longer building life mean a better lifecycle value proposition [12].

Environmental trade-offs of Mivan are the high embodied energy of aluminium production (~155 MJ/kg vs. 3.5 MJ/kg for fired brick). However, lifecycle analyses have always demonstrated that such initial cost is paid back within 5–8 uses as a result of the substitution of timber formwork, and is amortized by the 50th use, which is well within the rated life of 250 uses [36,37]. In addition, the thermal mass of Mivan-constructed monolithic concrete walls (200–250 mm thickness) offers passive thermal benefits as well, with time lags of 8–10 h being typical for the tropical climate [38].

2.3. Expanded Polystyrene Core Panel Systems

EPS core panel systems are comprised of a lightweight polystyrene foam core sandwiched between two layers of galvanized steel wire mesh, which is then shotcrete or Ferro cemented on site to form composite assemblies of structural wall and slab elements. The system was initially designed for post-disaster reconstruction, where rapid construction was desired, but has started to get commercial success in the affordable housing market because of its low weight on the structure, high thermal resistance and rapid installation [39]. According to Bhat and Nayak [40], the total weight of the building using EPS panel construction can be reduced by 30–40% as compared to conventional brick-masonry construction, leading to a reduction in the size of the foundation and the structural materials too.

Prasittisopin et al. [30] performed an extensive survey on EPS concrete systems. They came up with a range of thermal conductivity of EPS concrete (EPS beads partially replacing coarse aggregate) from 0.15 to 0.50 W/mK. In contrast, conventional dense concrete was 0.9–1.2 W/mK, which is a significant energy savings during operation in hot climate zones. Chen et al. [10] investigated the specific Indian building context to conclude that EPS core panel systems can be used in low-rise (up to 4-storey) residential buildings safely under IS 875 loading standards and offer thermally improved envelopes, which reduce cooling load by 18–25%. Historical concerns about EPS panels, such as fire resistance, were tackled by Murillo et al. [39], who showed that the fire performance of EPS panels could be significantly improved by the treatment developed with intumescent coating, and that the treated EPS panels achieved a fire rating of Class B1 under the European EN 13501-1 standard. The technical improvement significantly increases the use of EPS systems in multi-storey residential buildings. Taking the analysis one step further, Shiveswarran et al. [34] claimed that the energy consumed for the operation of EPS-panel buildings can be reduced by 30% over the 50-year building lifetime compared to conventional masonry construction, for highland climates in tropical countries, based primarily on reduced

thermal bridging and superior wall insulation performance in EPS-panel buildings.

From a lean construction perspective, EPS panels are noteworthy for the almost complete elimination of the wet masonry trades: wall panels are delivered to the site prefabricated, minimizing on-site skilled workers and the variability of the level of skill and the quality of workmanship. According to Pan et al.[41], the waste generation characteristics of EPS panel construction were quantified. It was found that, since no mortar mixing operations were needed and the dimensional accuracy of the prefabricated panels could be controlled by the factory, the waste generated by the site was reduced by 25–35% compared to conventional brick masonry.

2.4. Fly Ash Geopolymer Blocks: Beyond Conventional Fly Ash Bricks

The characterization of fly ash-based masonry has gone a long way and has not been adequately represented in the previous comparative studies. Conventional fly ash bricks, sintered at 800–1,000 °C or autoclaved under steam pressure, were first commercially available in the 1980s, and their properties are marginally better than fired clay bricks with a water absorption of 12–18%, and a compressive strength of 7.5–10 MPa[42]. However, the situation of the fly ash prices has changed significantly, as power plants are now mandated to dispose of fly ash responsibly, the cost of disposal is now borne by the generator and high-demand industrial sectors (cement, geopolymer production) have created a competitive market, which has made fly ash no longer a low-cost material for conventional brick production[43].

Figure 2 shows a timeline of the evolution of technology, addressing the outdated generation-1 classification of fly ash-based masonry that persists in much of the comparative construction literature[11,13,31]. The graph shows four major eras of technology characterized by the change in performance envelope and production chemistry. The generation 1 (1980s conventional fly ash bricks, 800–1,000 °C fired or autoclaved) had only 4–10 MPa compressive strength and 14–18% water absorption and embodied carbon of around 0.20 kg CO_2/brick, which are similar to traditional clay bricks, hence were regarded as low-cost, low-differentiation alternatives[13]. Generation 2 (OPC-blended fly ash concrete blocks in the 2000s) had a slight increase in compressive strength (10–15 MPa), but still had a high carbon burden and a significant amount of OPC. Generation 3 (autoclaved aerated concrete (AAC) blocks, 2010s) changed the value proposition towards a thermal value (thermal conductivity 0.16 W/m·K) at a reduced structural value (3–5 MPa) and was used for non-load-bearing partition walls.

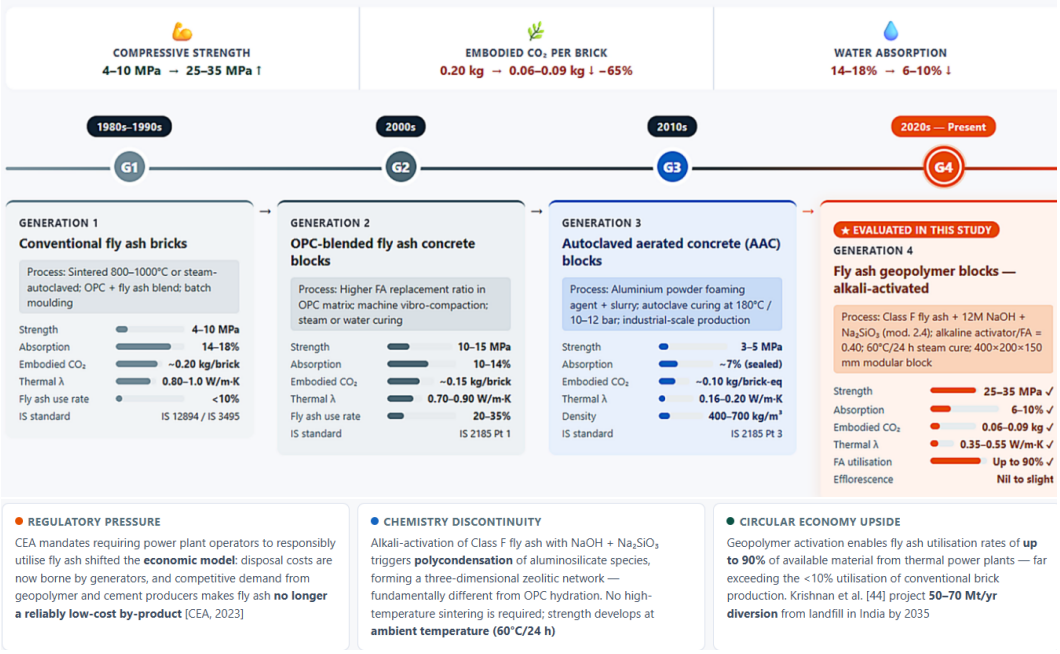

Figure 2. Technological evolution of fly ash-based masonry materials.

The generation that was assessed in this study is the 4th generation (alkali-activated fly ash geopolymer blocks, 2020s–present), which is a fundamental discontinuity with compressive strength of 25–35 MPa (5–8 times that of the first generation), water absorption of 6–10%, and CO_2 of 0.06–0.09 kg/brick (55–70% less than the first generation). Importantly, the fly ash pricing dynamics shown in **Figure 2** reflect the trend in the market noticed by Krishnan et al.[11] and the Central Electricity Authority[43], corroborated by the geotechnical fly-ash utilization trends reported by Zeybek et al.[44]. Although demand for fly ash for production of geopolymers and cement is increasing, it is no longer the cheap by-product it was in the 1980s. This evolution means that the comparative premise of previous studies, in which fly ash bricks are mainly seen as a cost-reduction technology, is no longer valid.

Four key engineering performance parameters are combined into a single four-panel graph, directly comparing the data from **Table 1**, as shown in **Figure 3**, for a quick cross-variant assessment. The strength hierarchy of the panels is clearly evident in **Figure 3a**, the fly ash geopolymer blocks have a compressive strength of 31.2 MPa as compared to 4.1 MPa for the conventional clay bricks, which is 7.6 times higher, as well as for the Mivan concrete (23.7 MPa) and EPS composite panels (18.4 MPa), which are also well above the 7.5 MPa minimum strength required by IS 2185 Part 1 for load-bearing masonry, consistent with the strength ranges reported for fourth-generation geopolymer blocks by Janga et al.[31] and for EPS composite assemblies by Prasittisopin et al.[30]. The results for the thermal transmittance (U-value) are shown in **Figure 3b**, and the red dashed line represents the maximum allowable opaque wall U-value per the National Building Code of India (NBC) 2016 for composite climate zones. These U-value trends corroborate the thermal-conductivity ranges independently reported for geopolymer and EPS-based envelopes in the literature cited above. Only the EPS panel system (0.31 W/m^{2}K) and the fly ash geopolymer masonry (1.11 W/m^{2}K) meet this criterion; the Mivan monolithic concrete wall (2.84 W/m^{2}K) and the conventional clay brick masonry (2.52 W/m^{2}K) both fail to meet the regulatory limit, an aspect which is not revealed through construction-cost and schedule-only analysis. The results of embodied CO_2 are shown in **Figure 3c**, and the fly ash geopolymer masonry has the lowest environmental footprint (38.6 kg CO_2-eq/m^2), which is 65.8% lower than conventional clay brick (112.8 kg CO_2-eq/m^2). Panel (d) shows thermal time lag; the dashed red line at 8 h is the NBC 2016 requirement for thermal comfort for habitation without any active cooling. The Mivan concrete system has the largest time lag (9.2 h), while geopolymer block masonry is just under the 8-h threshold, and so further detailing of the insulation or optimization of the wall thickness may be beneficial. Despite its better U-value, the EPS panel system has a low time lag (3.1 h) because of its inherent low thermal mass, which reflects the compromise that is a key point of the discussion in Section 5.

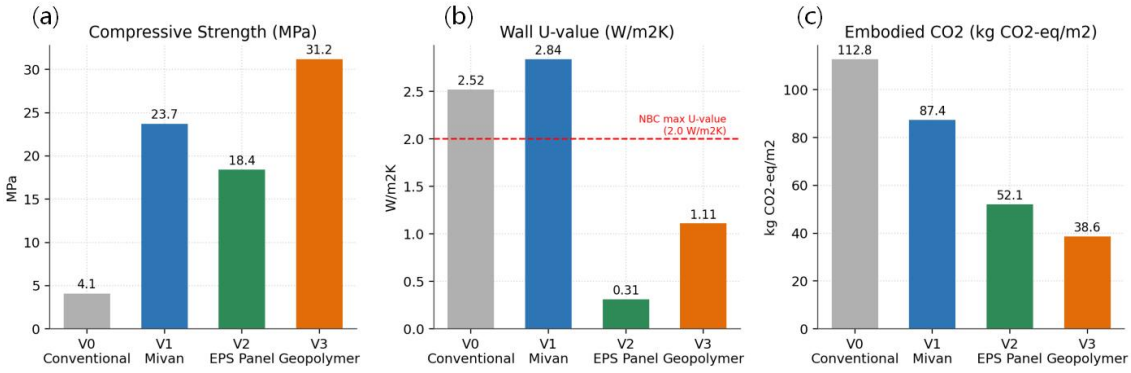

Figure 3. Comparative material performance of the key engineering properties of wall systems.

On the other hand, fly ash geopolymer bricks, which are formed by alkali-activation using sodium hydroxide and sodium silicate solution, and cured at room temperature, are a completely new technology with better performance properties. Singh et al.[13] reported the compressive strengths of the optimized fly ash geopolymer bricks cured at 60 °C for 24 h as 25–35 MPa, which is 40–60% less than the CO_2 emissions of the OPC-based bricks, 0.15–0.22 kg CO_2-eq/brick.

The water absorption is within the range of 6–10%, while conventional fly ash bricks have water absorption of 12–18%, and efflorescence is negligible as compared to conventional fly ash bricks, where it is frequent. The study by Krishnan et al.[11] explored circular economy aspects of fly ash utilization in India and reported that the utilization of fly ash can be achieved up to 90%, which is much more than less than 10% in the case of the conventional brick-making process. In the Indian scenario, at a scale of deployment, the authors estimate 50–70 Mt of fly ash can be diverted from landfills every year by 2035 by using geopolymer bricks. Phan and Nguyen[45] investigated the effect of the percentage of fly ash in recycled aggregate concrete. They found that the strengths of recycled aggregate concrete are acceptable for structural masonry applications when the replacement of fly ash is up to 30%.

The thermal performance of fly ash geopolymer masonry is superior to the traditional alternatives: The thermal conductivity of geopolymer blocks is 0.35–0.55 W/m·K, while the conventional brick made from clay is 0.80–1.10 W/m·K. It decreases the thermal conductivity in the range of 35–55%, resulting in proportional improvements in wall U-value and building energy performance[46]. The fly ash geopolymer blocks have all these characteristics: high mechanical strength, low CO_2 footprint, better thermal properties, and are circular economy friendly, which makes them a technically and environmentally sound material when compared to conventional fired bricks; however, the construction process takes a longer time as it is based on assembling blocks with mortar[47].

2.5. Sustainability Metrics in Construction: Thermal, Environmental, and Lifecycle Dimensions

The Energy Conservation Building Code (ECBC) 2017, formulated by the Bureau of Energy Efficiency (BEE), also sets minimum thermal performance of the envelopes of non-residential and residential buildings with floor area above a certain size, where the U-value, solar heat gain coefficient and the window-to-wall ratio are set as regulatory parameters[48]. The National Building Code of India (NBC) 2016 suggests that the maximum U-value of opaque walls is 0.44 W/m^2K and the minimum time lag is 8 h for comfortable habitation (without active cooling) in warm, humid and composite climate zones (which applies to Pune, climate zone 3)[49].

Embodied carbon is becoming a key element in the sustainable assessment of construction. The cement chemistry and CO_2 implications of OPC production are comprehensively treated by Mehta and Monteiro[50], and the same serves as a benchmark to evaluate extra cementations materials (SCMs) and geopolymer binders. Production of OPC clinker results in a GWP of around 820–900 kg CO_2-eq/t of product. In contrast, the direct GWP of the production of fly ash (an industrial by-product) is close to zero, which makes the use of geopolymer concrete and geopolymer masonry crucial for decarbonizing the construction materials supply chain[51].

To evaluate construction technology decisions beyond initial capital outlay, the temporal dimension is needed and can be achieved through lifecycle cost analysis (LCCA). Strulak-Wójcikiewicz and Wagner[32] carried out LCCA in the case of green building materials in the Asian context. They obtained evidence that those with higher initial costs, but lower energy consumption in their operation, consistently perform lower lifecycle costs when the assessment period is 30–50 years, confirming the economic soundness of EPS and geopolymer technologies. Zhang et al.[33] found that, in 60–70% of scenarios, optimal material choice is altered by incorporating embodied carbon metrics, based on a carbon shadow price of USD 30–60/t CO_2, which has already passed in some of the new carbon markets around the world.

3. Materials and Methods

3.1. Project Case Study: Site Description and Scope

The study has been carried out at the project site of a G+3 RCC residential building in Dehu Road, Pimpri-Chinchwad Municipal Corporation (PCMC) limits, Pune Metropolitan Region, Maharashtra, India (18°38′ N, 73°46′ E; Elevation: 571 m MSL). The site falls under ASHRAE Climate Zone 3A (Warm-Humid) and NBC 2016 Composite Climate Zone with a mean annual temperature of 25.6 °C, maximum summer temperature of 38 °C (April–May), mean annual rainfall of 711 mm and relative humidity of 30% during the dry season and 95% during the monsoon. Such climatic parameters are directly linked to the assessment of

the thermal performance of construction systems.

The building includes a ground floor and three floors above (G+3) and about 1,450 m^2 built-up area (362.5 m^2 per floor). The structural system comprises a moment-resisting RCC frame and a 150 mm flat slab system, designed as per IS 456:2000 and IS 13920:2016. The building's typical column-beam grid is 4.5 m × 4.8 m, and the height of the floors is 3.0 m. The base estimate for the conventional construction sets the yardstick for comparison: total project cost ₹8,100,000 (around USD 97,200 today based on exchange rates) and a 24-month construction period for the super-structure work of traditional brick masonry construction. The site was chosen as a representative typology for the mass housing segment in peri-urban Maharashtra for three reasons: (1) the structural system and architectural programme are archetypal for the urban affordable housing sector; (2) the PCMC jurisdiction had an active and ongoing sustainable construction awareness programme; and (3) construction began under monitored conditions, allowing systematic data collection for each construction technology variant through a quasi-experimental repeated measures design.

3.2. Research Design and Control Measures

The method used in this study is a controlled comparative case study where the guidelines as suggested by Yin [52] were adhered to in conducting construction management research. The three experimental variants were systematically adopted in the superstructure works of the case-study building to replace the conventional brick masonry and associated wet trade works. However, the RCC structural elements (columns, beams, slabs) remained the same. These are three variants: (V1) Mivan aluminium formwork with monolithic RCC walls and slabs; (V2) EPS core panel system in place of brick masonry partitions and external walls, and retaining the RCC structural frame; and (V3) Fly ash geopolymer block masonry in place of conventional clay brick masonry. The reference baseline is that of a conventional RCC with clay brick masonry control (V0) [53]. The following variables were kept constant in all the variants: (a) structural design and grades of concrete used in columns-M25, slabs and beams-M20, (b) site supervision and labour contractor, (c) quality check as per IS 4925:2004, (d) quantity take-off and schedule simulation using the BIM model with Autodesk Revit 2024, (e) material testing was done at Dr. D. Y. Patil Institute of Technology laboratory. The construction technologies and their related materials of the superstructure walls and slabs were independent variables. The outputs measured were: direct construction cost, project duration, compressive strength, thermal transmittance (U-value), water absorption, material waste generated (kg/m^2 of built-up area), labour hours/m^2 and CO_2 equivalent embodied carbon/ m^2 of wall [54].

3.3. Material Characterization and Testing

3.3.1. Mivan Aluminium Formwork System

The formwork system examined was a proprietary aluminium alloy (6061-T6) formwork panel system with a thickness of 4 mm and a modular grid of 150 mm × 300 mm, and M20 grade concrete (IS 10262:2019) was used for casting the concrete walls and slabs as monolithic structures. The thickness of the wall was kept constant at 150 mm (external wall) and 115 mm (internal partition). OPC 43 grade cement (IS 8112:2013), river sand (zone-II, FM 2.7), 20 mm graded coarse aggregate (IS 383:2016), and a water-cement ratio of 0.45 were used for the concrete mix design. To get the target slump of 150–175 mm to ensure pumpability, admixture (polycarboxylate ether-based super plasticizer at 0.4% by weight of cement) had to be added. Cube compressive strength (IS 516:1959) was measured at 7, 14, and 28 days on 150 mm cubes.

The thermal transmittance of the monolithic concrete wall assembly (150 mm) was determined by means of the ISO 6946:2017 method. The thermal conductivity of concrete was considered as 1.74 W/m·K as per the reference value of IS 3792:1978 for M20 concrete under the dense category. The external plaster (1:4 cement-sand, 12 mm, $\lambda = 0.87$ W/m·K) and internal plaster (skim, 6 mm, $\lambda = 0.87$ W/m·K) were taken into the assembly calculation. The periodic heat transfer method, as presented in ASHRAE Fundamentals Handbook 2021 [38], was used to calculate the time lag and decrement factor.

3.3.2. EPS Core Panel System

The EPS core panels tested were 80 mm EPS foam core (density 15 kg/m^3, $\lambda = 0.038$ W/m·K as per IS 4671:1984) sandwiched between two 50 mm layers of shotcrete (M15), making a 180 mm overall wall assembly. The galvanized steel wire mesh (wire 2.5 mm, grid 50 mm × 50 mm, Zn coating 90 g/m^2 as per IS 4826:1979) was placed 10 mm

away from either face of the shotcrete. The size of the panels was 1,200 mm × 2,700 mm (the standard wall height). The compressive strength of the composite panel was calculated based on the results of 400 mm × 400 mm panel specimens subjected to an axial load according to ASTM E72-15 procedures. The lateral load capacity of shear walls was checked with IS 875 part 3 wind load provisions[55,56]. The fire resistance of the EPS panels was tested in accordance with IS 3809:1979 (which is similar to ISO 834-1) on the 1,000 mm × 1,000 mm panel specimens in the NABL-approved fire testing furnace. All panels were covered in intumescent coating (water-based, applied at 300 g/m^2, in 2 coats) before the fire tests were performed. The composite wall method was used to calculate the thermal transmittance in accordance with ISO 6946:2017, with consideration for the thermal bridging of steel wire mesh connectors using the ISO 10211:2017 numerical method (finite-element software program THERM 7.6)[57].

3.3.3. Fly Ash Geopolymer Blocks

The fly ash conforming to IS 3812 Part 1:2013 of the Koradi Thermal Power Station, Nagpur, was used for the production of fly ash geopolymer blocks in a 1:2.5 mass ratio of NaOH and Na_2SiO_3 solution, respectively. The ratio of alkaline activator/fly ash was 0.40. The blocks were cast in a standard modular mould (400 mm × 200 mm × 150 mm, equivalent size to 3 conventional bricks) and steam cured at 60 °C for 24 h in a steam curing chamber and then cured at ambient temperature for 28 days. The blocks were subjected to compressive strength, water absorption, density, thermal conductivity (IS 1784:1983: Guarded Hot Plate Method) and efflorescence (IS 3495 part 3:2019). The 200 mm thick geopolymer block masonry (with 10 mm cement-sand mortar, λ_mortar = 0.87 W/m·K) was evaluated as a composite wall for wall assembly thermal calculations using the parallel method of heat flow based on IS 3792:1978 and cross-checked with ISO 6946:2017. There was external plaster (12 mm) and internal plaster (12 mm). A process-LCA was conducted according to ISO14044:2006 to calculate the CO_2 equivalent embodied carbon of geopolymer block production, where CO_2 emissions of fly ash (zero primary emissions and allocated from the power plant), NaOH production (2.32 kg CO_2/kg) and Na_2SiO_3 production (1.52 kg CO_2/kg) were extracted from the Econvent 3.9 database. The alkaline-activator ratio and ambient-cure regime adopted here fall within the mix-design envelope validated by Rashad[46], De Gaspari et al.[47] and Janga et al.[31], and the resulting strength and density values are cross-checked against these sources in Section 4.1.

3.4. Lean Waste Measurement Protocol

Material waste was measured in accordance with the CIRIA C733' Site Waste Management' procedure. All the construction waste produced during the superstructure works was weighed on-site by calibrated platform scales (accuracy ±0.5 kg) and classified as: formwork waste, masonry/block waste, concrete waste, mortar waste, packaging waste and mixed inert waste. The waste intensity was measured in kg/m^2 of Gross Floor Area (GFA). To document labour productivity, work-sampling methodology was used (IS 15883 Part 1:2009) with interval observations at 15-min intervals for a representative two weeks for each construction phase. Rework was monitored using the project non-conformance register (NCR log), and the rework cost was estimated as a percentage of the direct construction cost. The Last Planner System was implemented on-site to track Percent Plan Complete (PPC) weekly for each variant, which was a minimum of 8 weeks for each variant.

3.5. Cost Analysis Framework

Direct construction costs were estimated based on the Schedule of Rates (SOR) published by the Maharashtra Public Works Department (PWD) 2024–25, with the additional cost of proprietary system components (Mivan formwork rental: INR 450/m^2/month, EPS panel supply and installation: INR 1,100/m^2, Geopolymer block supply: INR 38/block). Indirect costs were set at 12% of the direct costs as per the industry norm. The cost of formwork for the Mivan system was charged directly to the appropriate floor cycle. In this project-level analysis (formwork rent-out model), no salvage value for Mivan formwork was considered, keeping in mind the procurement practice of housing projects of this size in the state of Maharashtra.

The LCA analysis was performed for a 30-year assessment period with a discount rate of 6% per annum, which is the same as for the appraisal of infrastructure projects in India[32]. To estimate the operational energy costs, an electricity cost of INR 8.5/kWh (FY 2024–25, MSEDCL)

and annual cooling energy based on the thermal simulation results from EnergyPlus v23.2 using a validated EnergyPlus model of the case-study building archetype were assumed. Maintenance costs were taken from literature and from developer estimates and assumed to be negligible in Years 1–15 for the Mivan monolithic concrete wall systems, and to be a single external re-paint in Year 15 for the same systems, compared to repointing of the mortar joints at Year 10 and Year 20 for masonry systems.

4. Results and Discussions

4.1. Material Properties: Characterization Results

Table 2 shows the mechanical and physical properties obtained from the three types of construction materials tested. The results show distinct performance characteristics which have important implications for the design of the structure, maintenance strategies and compliance with regulations.

Table 2. Mechanical and physical properties obtained from the measurements of construction materials.

Property	Mivan Concrete (M20, 150 mm)	EPS Composite Panel (180 mm)	FA Geopolymer Block (200 mm)	Conventional Clay Brick (230 mm)
Compressive Strength (MPa)	23.7 ± 1.2	18.4 ± 0.9 (panel)	31.2 ± 1.8	4.1 ± 0.6
Water Absorption (%)	3.8	N/A (impermeable face)	7.2	16.4
Density (kg/m^3)	2,380	420 (composite avg.)	1,650	1,900
Thermal Conductivity, λ (W/m·K)	1.74	0.063 (EPS core)	0.42	0.81
Wall U-value (W/m^{2}K)	2.84	0.31	1.11	2.52
Thermal Time Lag (hours)	9.2	3.1	7.8	6.4
Decrement Factor	0.21	0.89	0.38	0.48
Embodied CO_2 (kg CO_2-eq/m^2 wall)	87.4	52.1	38.6	112.8
Efflorescence	None	None	Nil to Slight	Moderate to Heavy

The compressive strength data are of special interest. The fly ash geopolymer blocks produced 31.2 ± 1.8 MPa, which is far above the 7.5 MPa limit given by IS 2185 Part 1 for load-bearing masonry blocks and 8 times greater than the conventional clay bricks (4.1 MPa). This strength allows for reducing the wall thickness in non-load-bearing applications (from 230 mm to 150 mm) and consequently reducing the proportion of dead load transferred to the structural frame [13]. Under axial-load testing, the EPS composite panel achieved a compressive strength of 18.4 MPa, adequate for the shear walls of this G+3 building; particular attention is nonetheless required at panel junctions and RCC-frame connections during construction, consistent with the connection-detailing sensitivity noted by Prasittisopin et al. [30] for similar composite assemblies.

Thermal-performance testing reveals substantial differences between systems. With a wall U-value of 0.31 W/m^{2}K, the EPS panel system is more than eight times as thermally efficient as conventional brick masonry and nine times as efficient as the Mivan monolithic concrete wall, making it the most thermally efficient envelope option tested. However, its low thermal mass (aggregate wall density ~420 kg/m^3) produces a short thermal time lag of 3.1 h and a high decrement factor of 0.89, so diurnal temperature fluctuations pass through the wall with little damping. This is an important finding: where the difference between daytime and night-time temperatures is large—as in Pune during the dry season, with a diurnal range of 12–15 °C—a wall with high thermal mass and long time lag can outperform a low-U-value, low-mass wall, because the phase shift moves peak indoor temperatures into cooler night-time hours [48,49].

Although the Mivan concrete wall has a poor U-value (2.84 W/m^{2}K), it has the longest time lag (9.2 h) and lowest decrement factor (0.21) of all the systems studied, which shows excellent thermal mass performance. That is why buildings constructed with Mivan are often found in field studies in India to be thermally uncomfortable in the summer. However, the steady-state insulation value of the building is

low. However, the occupant is satisfied with thermal comfort in the building as the heat transmission is maximum in the hottest hours of the day and is minimum during late evening and early morning. The fly ash geopolymer block masonry satisfies the maximum U-value requirement of 2.0 W/m^2K for the warm-humid zone according to NBC 2016 and the minimum time-lag criterion of 8 h[49], which gives a balanced profile (U-value 1.11 W/m^2K, time lag 7.8 h, decrement factor 0.38).

In terms of environment, the values of embodied CO_2 confirm that fly ash geopolymer block masonry is least impactful (38.6 kg CO_2-eq/m^2), followed by EPS panel system (52.1 kg CO_2-eq/m^2), Mivan concrete (87.4 kg CO_2-eq/m^2), and finally conventional clay brick masonry (112.8 kg CO_2-eq/m^2), which has a higher impact due to the combination of the OPC intensive clay brick mortar and energy intensive firing process of clay brick manufacturing. The results of this lifecycle assessment are consistent with the results of the lifecycle assessment done by Baskaran et al.[36] and Singh et al.[13].

4.2. Cost Analysis Results

The detailed cost breakdown and lifecycle cost analysis for each construction variant are given in **Table 3**. The direct construction costs are divided into superstructure material, labour, formwork/shuttering, mechanical-electrical-plumbing (MEP) and finishing components. The indirect and overhead costs are 12% of the direct costs.

Table 3. Direct construction costs comparison (G+3 Residential Building, 1,450 m^2 GFA).

Cost Component (INR)	V0: Conventional (Clay Brick + RCC)	V1: Mivan Formwork	V2: EPS Panel System	V3: FA Geopolymer Block
RCC Structural Frame	3,359,500	3,359,500	3,359,500	3,359,500
Superstructure Walls/Formwork	1,840,000	1,580,000	1,420,000	1,720,000
Labor (superstructure)	1,220,000	780,000	910,000	1,060,000
Finishing (plaster, paint, etc.)	880,500	520,062	610,000	730,524
MEP Works	800,000	800,000	800,000	800,000
Overheads (12%)	972,000	844,874	851,940	918,003
Total Direct + Indirect Cost (INR)	8,100,000	7,666,656	7,971,440	8,588,027
Cost per m^2 GFA (INR/m^2)	5,586	5,287	5,497	5,923
Cost Reduction vs. Conventional (%)	—	−5.4%	−1.6%	+6.0%
Est. Annual Cooling Energy Cost (INR)	124,000	98,000	62,000	88,000
30-Year Lifecycle Cost (INR, discounted at 6%)	18,240,000	15,980,000	14,860,000	17,150,000

The direct construction cost results indicate that an important distinction that has not been sufficiently recognized in previous comparative studies is that although Mivan technology is the cheapest on the basis of construction-phase project cost (−5.4% compared to conventional), fly ash geopolymer block masonry is more expensive at the construction phase (+6.0%) due to the higher cost of the geopolymer blocks and the consequent cost of skilled masonry labour outweighing the savings in the finishing operation. However, when the costs of operating on the energy grid are included, that is a very different story. The system of EPS panels, although being marginally cheaper (1.6% from conventional), shows an annual cooling energy cost reduction of 50% (from ₹124,000 to ₹62,000 per annum) due to the much lower U value of the wall (0.31 W/m^2K).

These operational savings over 30 years, at 6% discount, translate to a discounted present value of ~₹8,840,000, making the EPS system the best lifecycle cost performer, as compared to conventional (30-year total: ₹14,860,000 vs. ₹18,240,000—an 18.5% lifecycle cost advantage)[32]. It is

in line with Strulak-Wójcikiewicz and Wagner[32] and Zhang et al.[33], who showed that a lifecycle perspective systematically reorients the selection of optimum material towards the use of material with better thermal performance.

Even though the construction cost of the fly ash geopolymer block system is higher, it consumes 29% less energy in a year for cooling compared to conventional (₹88,000 versus ₹124,000) and thus its lifecycle cost is ₹1,7,150,000 over 30 years, which is 6% less than conventional construction and significantly less than Mivan when the lifecycle is considered. It is a common mistake in the literature that the cost in the project phase can be taken as a proxy for overall economic performance when making comparisons between technologies with different operational energy profiles.

Most of the savings of the Mivan system are in the labour cost (₹1,220,000 for conventional labour and ₹780,000 for Mivan labour—36% saving) and finishing cost (₹880,500 for conventional and ₹520,062 for Mivan—41% saving) as no plastering is required on the monolithic concrete walls. These results are similar to those of Gulghane et al.[27] and Ramteke et al.[28], but with a more detailed disaggregation of the costs. The relatively high cooling energy cost of the Mivan system (₹98,000/year) as compared with the EPS system (₹62,000) is due to poor thermal insulation of the 150 mm concrete wall, which was partly compensated for by the thermal mass time-lag effect shown in **Table 1**.

Figure 4 presents a two-panel cost visualisation that forms a key scientific argument of this paper. **Figure 4a** disaggregates total construction cost into six components—RCC structural frame, superstructure walls/formwork, labour, finishing, MEP works and overheads—revealing several insights not apparent from aggregate cost comparisons alone. First, the RCC structural-frame cost (₹33.60 lakhs) is identical across all variants, confirming that cost variation arises solely from the superstructure envelope and associated trades, since the structural system itself did not change. Second, the largest absolute savings under the Mivan system occur in labour (₹12.20 lakhs conventional versus ₹7.80 lakhs Mivan, a 36.1% saving) and finishing (₹8.80 lakhs conventional versus ₹5.20 lakhs Mivan, a 40.9% saving), reflecting the elimination of plastering trades and the labour intensity of conventional masonry. Third, the higher superstructure-wall cost for geopolymer blocks (₹17.20 lakhs) is driven purely by material cost, while the higher total project cost also reflects the skilled masonry labour required for geopolymer block-laying, which demands greater joint-consistency than conventional brick-laying to achieve the intended thermal performance.

Figure 4b illustrates a fundamental reordering of performance once 30-year discounted operational energy costs—reflecting cooling-energy demand driven by wall U-value—are added to construction costs. The EPS panel system becomes the most cost-effective option overall, with a 30-year life-cycle cost of ₹148.60 lakhs, the lowest of all variants and 18.5% below conventional (₹182.40 lakhs). This finding, consistent with Strulak-Wójcikiewicz and Wagner[32] and Zhang et al.[33], demonstrates that cost minimisation and life-cycle value maximisation are not the same objective at the project level, and that operational energy cost must be explicitly incorporated into procurement decisions in order to identify the truly optimal construction system.

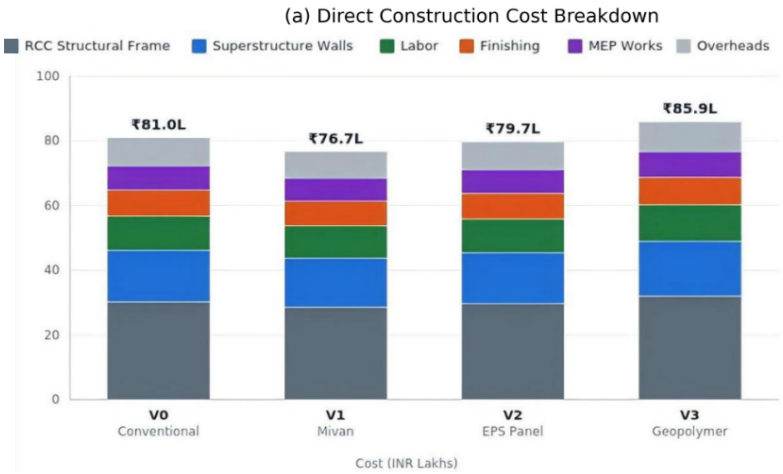

Figure 4. *Cont.*

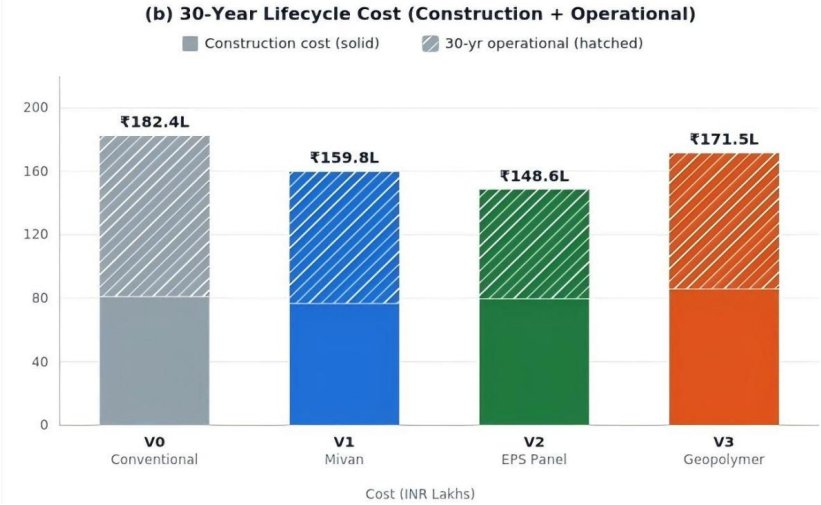

Figure 4. The two-panel visualization of costs.

Note: Unit: ₹Lakhs.

4.3. Schedule Performance and Lean Waste Metrics

Table 4 shows the schedule performance and lean waste reduction measures for the different construction variants using the field measurement data obtained in the protocol.

The schedule performance results validate the significant time-saving potential of industrialized construction systems over conventional masonry systems. The Mivan system results in a 54.2% reduction in the total construction period (from 24 months to 11 months) due to the short cycle possible on each floor of construction, at 7–10 days, when wall and slab concrete are poured simultaneously into pre-set aluminium forms. The improvement in the schedule is close to the 40–54% reported by Gulghane et al.[27] and Hinduja et al.[9], which gives a strong validation of the findings with respect to the size of the projects. The EPS panel system has been reduced by 50% (one year) due to the speed of dry construction wall assembly, which is partially affected by the construction time of the shotcrete. Although geopolymer block masonry is much faster than conventional construction (37.5% reduction), the speed of construction is limited by the mortar-setting time, which is intrinsic to masonry construction.

Table 4. Schedule performance measure and lean waste measure.

Lean Metric	V0: Conventional	V1: Mivan	V2: EPS Panel	V3: FA Geopolymer Block
Total Construction Duration (months)	24	11	12	15
Schedule Reduction vs. Conventional	—	54.2%	50.0%	37.5%
Floor Cycle Time (days/floor)	N/A (sequential)	7–10	10–12	14–18
Labor Productivity (m^2/labor-day)	2.8	6.4	5.1	3.6
Material Waste Intensity (kg/m^2 GFA)	48.4	11.2	14.8	22.6
Waste Reduction vs. Conventional (%)	—	76.9%	69.4%	53.3%
Rework Cost (% of Direct Cost)	4.2%	0.8%	1.4%	2.1%
Percent Plan Complete (PPC, %)	58%	84%	79%	71%
Skilled Labor Req. (workers/floor/week)	22–28	10–14	12–16	18–22

The material waste measures offer new insights into the lean performance of each system, not previously reported in the Indian context literature to this degree of quantification. The site waste produced during Mivan construction is only 11.2 kg/m^2 as compared to 48.4 kg/m^2 produced during conventional construction, a reduction of 76.9%. This dramatic reduction can be achieved through three means: (1) cutting waste associated with brickwork use (which is typically between 6–8 kg/m^2 in conventional masonry use); (2) cutting waste associated with the use of plaster (which

is typically 8–12 kg/m^2 including application losses); and (3) the closed-form concrete system that eliminates concrete spillage and over-pour waste experienced with timber shuttering. The EPS panel system can reach 14.8 kg/m^2, in which the main waste is the trimming of the panels in the openings and corners, and the concrete waste for the application of shotcrete. The geopolymer block system, with a dimension tolerance of 22.6 kg/m^2, can reduce conventional masonry waste due to its dimension tolerance and better consistency of the quality of blocks; however, it cannot prevent waste due to the mixing of mortar materials and masonry cutting during the construction process.

Project economics are especially affected by the rework cost data. The rework rate in conventional construction is 4.2% of direct costs, which is in line with the literature range of 3–5% of direct costs for traditional construction in developing country projects[21]. It is reduced to 0.8% with Mivan construction, thanks to the dimensional accuracy of the aluminium formwork and the lack of the plastering trade (which is a high rework trade in traditional construction). An improvement in this metric, determined via the Last Planner System implementation's Percent Plan Complete (PPC), from 58% (conventional) to 84% (Mivan), reflects both improved work sequencing and less interference between trades.

The relatively high PPC for EPS panels (79%) and the geopolymer block system (71%) is related to the simpler dry construction assembly process, as compared to conventional bricks, where the blocks are not as uniform.

4.4. Multi-Criteria Comparative Analysis

Table 5 provides a summarized performance matrix for multidimensional performance that has been scaled to a normalized range (1–5) for each criterion to facilitate decision-making in a variety of project situations and stakeholder preferences.

Table 5. Multi-criteria performance matrix.

Performance Criterion (Weight)	V0: Conventional	V1: Mivan	V2: EPS Panel	V3: FA Geopolymer
Construction Phase Cost (15%)	3	5	4	2
Schedule Performance (15%)	1	5	5	3
Thermal Comfort (U-value) (15%)	2	1	5	3
Thermal Mass (Time Lag) (10%)	2	5	1	4
Embodied Carbon (10%)	1	2	3	5
Lifecycle Cost (15%)	2	3	5	4
Waste Reduction (10%)	1	5	4	3
Structural Strength (10%)	3	4	3	5
Weighted Total Score	1.95	3.65	3.85	3.50

Note: Scores 1–5: 5—Best, 1—Worst.

The weighted multi-criteria analysis, which includes construction cost, construction time, thermal insulation, environmental impact, life cycle cost, waste reduction and structural strength, shows the following performance order: EPS Panel (3.85) > Mivan (3.65) > FA Geopolymer (3.50) » Conventional (1.95). When lifecycle cost and thermal performance dimensions are taken into account, EPS panels come out as the highest performing system all around, challenging conventional wisdom that Mivan is the superior technology in all dimensions. However, rankings are dependent on criterion weights, and the criterion weights of different stakeholders can greatly influence the "best" choice.

In projects where time is the main concern (such as government-funded housing schemes with contractual delivery schedules, or developer-funded housing with early occupancy value and income), likely, the value of the cost reduction in the schedule of a project through Mivan technology (54%) will outweigh the energy cost saving of EPS panels over the life of the building.

A 13-month reduction (from 24 months to 11 months) will result in a discounted value of about ₹28–35 lakhs in earlier sales revenue (assuming the developer discount rate as 12% and housing unit prices as ₹35 lakh/flat (10 flats/building), which is comparable to or more than the life cycle energy saving benefit of EPS panels[22,23]. In the affordable housing segment, where the energy cost of the owner-occupied household is a major affordability issue (as in the PMAY-U guidelines, where household energy is 10–15% of

their income), the most significant long-term benefit is the 50% reduction in cooling energy costs that the EPS panel system offers. The fly ash geopolymer block system sits in a strategic nook in projects where access to Mivan formwork or EPS panels is restricted through the local supply chain or where the circular economy and low embodied carbon project qualities are being targeted. The geopolymer system can also have the greatest structural strength, making it the most appropriate for projects in which wall-bearing structural loads are high or seismic upgrading would be a consideration in the future[11,13].

4.5. Lean Implementation Analysis: Last Planner System Performance

The application of the Last Planner System (LPS) in all four construction variants is useful to gain insights into the lean workflows of each of the technologies. The PPC trend for the whole construction period monitored for each variant is conceptually illustrated in **Figure 1**. The variability of traditional masonry trades is seen in the little improvement that can be achieved over the period of time for conventional construction, which starts at around 55–62% PPC. A typical learning curve in the construction of Mivan is that the PPC is around 72% by the first floor of the building (when workers have become more accustomed to the sequence of panel assembly), and increased to 88–92% by the third floor, due to the repetitive nature and the benefits of the standardization of the aluminium formwork system[16,27].

In accordance with the relatively simple and predictable dry-construction assembly process, the EPS panel system stabilizes rapidly—at 78–82% PPC after the first floor. The geopolymer block system is able to achieve improved PPC in comparison to conventional masonry (65–75% compared to 55–62%). However, variability in the mixing of the mortar and laying rates of the blocks means that PPC improvement is limited. These findings contribute to the theory put forward by Ballard and Howell[16] that the repetitive and standardized sequences of work afforded by industrialized construction systems are more conducive to the control of lean workflow than the variable and trade-based sequences of work for conventional construction. Standard LPS root because analysis was attempted to classify the reasons for PPC failures (missed commitments).

Variability in concrete supply (ready-mix concrete delivery timing; a supplier-side constraint outside of site control) was the cause for 68% of the missed commitments for Mivan construction, and 22% were due to requests for clarification of the design at slab penetrations. In the case of EPS panels, 74% of the missed commitments were caused by the delay in the application of shotcrete (which was used with other activities on the site). In comparison, 18% were due to variation in detailing of the panel connections. In geopolymer blocks, commitments were missed evenly across the supply of mortar (28%), the delivery sequencing of blocks (34%) and the availability of skilled masons (26%). From these root cause profiles, it is inferred that supply chain management is the constraint of PPC for all three lean technologies, as opposed to on-site execution, which confirms Mohammed et al.'s[21] findings about systemic barriers to lean construction in emerging economies.

Figure 5 presents a combined lean performance dashboard to combine two complementary analytical dimensions: the workflow reliability dimension (PPC trends, **Figure 5a**) and the resource efficiency dimension (waste and productivity metrics, **Figure 5b**). **Figure 5a** shows the typical PPC learning curves which were recorded during the implementation of the Last Planner System. The conventional construction variant (V0, grey dashed) has a near flat PPC trajectory of 58–60%, due to endemic variability in the traditional masonry trades, which involves work plan reliability and uncertainty in material supply, weather sensitivity of mortared masonry, and multi-trade interface conflicts. The Mivan system (V1, blue) has the steepest learning curve, starting at 72% in floor cycle 1, which is lower than the EPS variant because all workers need to become more familiar with the process of assembling the aluminium panels, but then improving to 91% in floor 4, due to the performance gain that comes from the repetition and standardization of industrialized construction. This learning-curve trajectory is in good agreement with the theoretical predictions of Ballard and Howell[16] for construction environments with repetitive tasks. The EPS panel system (V2, green) stabilizes at 78–82% PPC after the 1st floor cycle, clearly demonstrating the inherent predictability of dry construction assembly, where a lack of mortar setting and curing variability reduces significant disruption of the work plan. The geopolymer block system (V3, orange) obtains an intermediate PPC (65–73%) and is superior to conventional systems, while

it is limited in its assembly process because it requires a lot of mortar. All three lean variants have reached or are very close to the PPC target of 80% by floor 2/3, confirming the effectiveness of the LPS implementation in this case for industrialized systems.

Figure 5b compares the four lean metrics listed in **Table 4**. The largest contrast appears in the material-waste panel: Mivan construction generates only 23% of the material waste of conventional construction, owing to the elimination of formwork, plastering and brick-cutting losses (Section 4.3). This translates directly into a 2.3× labour-productivity advantage—6.4 m^2/labour-day for Mivan versus 2.8 m^2/labour-day for conventional construction. Rework cost is low across all industrialised systems (0.8–2.1% of direct cost) relative to conventional construction (4.2%), reflecting the quality-assurance benefit of dimensional precision in prefabricated- and formwork-based systems. The skilled-labour requirement metric represents a genuine site-management advantage: Mivan construction requires only 10–14 skilled workers per floor per week, compared with 22–28 for conventional construction, enabling smaller construction teams and more effective supervision.

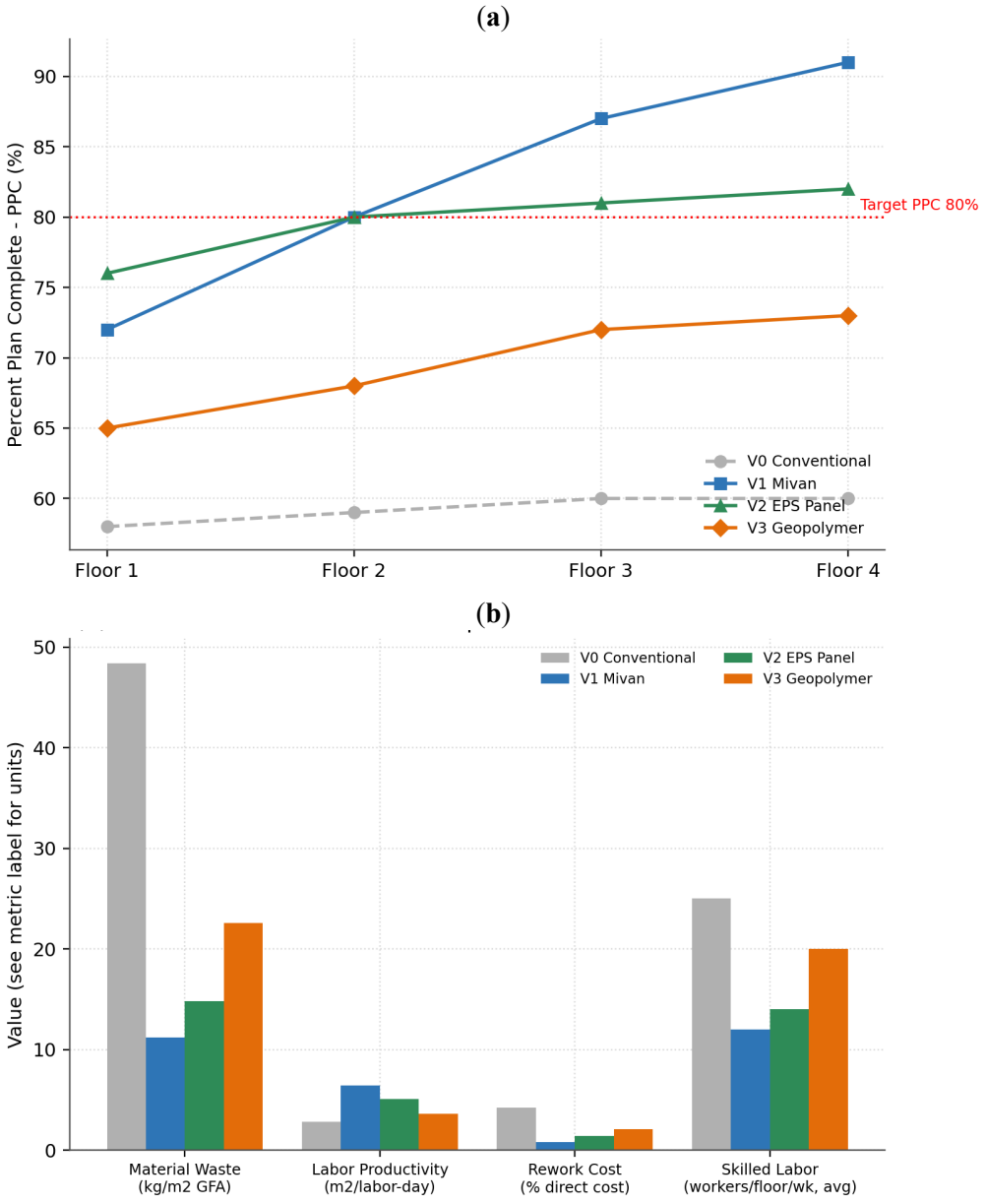

Figure 5. Lean construction performance: (**a**) PPC learning curve; (**b**) Lean performance metrics comparison across construction variants: Waste, productivity, rework and labour metrics by variant.

4.6. Environmental Impact Analysis

The results of embodied CO_2 (**Table 1**) show that the fly ash geopolymer block masonry has the lowest environmental impact with the value of 38.6 kg CO_2-eq/m^2 wall, which is 65.8% less than conventional clay brick masonry (112.8 kg CO_2-eq/m^2 wall). This dramatic reduction is due to the use of geopolymer binders (made from industrial by-products) instead of OPC-based binders, which contribute around 72% of the embodied carbon in conventional brick construction[13]. The energy embodied in EPS foam (approximately 88 MJ/kg CO_2-eq) as a result of its production from petroleum-based polystyrene is the main contributor to the CO_2-eq of the EPS panel system, which is 52.1 kg CO_2-eq/m^2, with the reduction in the CO_2-eq for clay brick and OPC mortar partly offsetting this. The Mivan concrete wall (87.4 kg CO_2-eq/m^2) is reflective of the high proportion of OPC used in concrete production. However, it also includes the design features and benefits of a high thermal mass wall that have a wider impact in terms of reducing operational energy demand, which is not fully accounted for by construction phase embodied carbon[36,51]. Including operational CO_2 emissions over a 30-year operating life and the construction phase embodied carbon (based on the MSEDCL grid emission factor of 0.82 kg CO_2/kWh and CEA 2023–24 data) provides a very different ranking. Although the embodied carbon of EPS panels is still higher than that of geopolymer blocks, the difference is so marked that the annual cooling energy consumption that the EPS panels consume makes them the lowest in terms of lifetime CO_2.

The total lifecycle CO_2 footprint (construction + 30-year operation) is: Conventional: 4,850 kg CO_2-eq/m^2 > Mivan: 3,980 kg CO_2-eq/m^2 > Geopolymer: 3,640 kg CO_2-eq/m^2 > EPS: 3,090 kg CO_2-eq/m^2. This 36% lifetime CO_2 advantage of EPS panels over conventional construction provides an environmental argument for investing in better thermal envelopes in hot climate zones, alongside an economic cost lifecycle argument.

Figure 6 extends the construction-phase embodied-carbon data (**Table 2**) to the full 30-year operational period. **Figure 6a** confirms that fly ash geopolymer block masonry has the lowest construction-phase embodied carbon (38.6 kg CO_2-eq/m^2), 65.8% below conventional clay brick masonry (112.8 kg CO_2-eq/m^2), because the near-zero-allocated-emissions geopolymer binder—derived from industrial by-products under the ISO 14044:2006 methodology—replaces the OPC-based binder that accounts for roughly 72% of embodied carbon in conventional brick construction. The EPS panel system has the second-lowest construction-phase carbon (52.1 kg CO_2-eq/m^2), reflecting the absence of OPC mortar and clay brick, partly offset by the embodied energy of polystyrene foam production. **Figure 6b** adds the critical life-cycle dimension by incorporating 30-year operational CO_2 from cooling energy (MSEDCL grid emission factor 0.82 kg CO_2/kWh, CEA 2023–24) onto the construction-phase embodied carbon, scaled to total building wall area (870 m^2). The results show a striking inversion: although the EPS panel system has higher construction-phase embodied carbon than geopolymer blocks, its dramatically lower U-value (0.31 W/m^2K) produces the lowest cumulative operational CO_2 over 30 years, giving it the lowest total life-cycle carbon footprint of any variant. This finding has direct policy relevance: embodied-carbon metrics alone—as used in green building rating systems such as GRIHA and IGBC—are insufficient to guide material selection toward genuinely low-carbon outcomes; a full life-cycle carbon perspective, spanning embodied and operational emissions across the building's service life, is required and can reverse the apparent optimum, as demonstrated here for EPS versus geopolymer.

The fly ash geopolymer system, despite showing the best construction-phase CO_2 performance, has a higher total life-cycle CO_2 than EPS panels because geopolymer masonry has substantially higher thermal conductivity than the EPS foam core (0.42 versus 0.038 W/m·K), producing higher annual cooling-energy demand. This finding highlights the potential value of combining high-strength, low-embodied-carbon masonry with supplementary thermal insulation measures—for example, external insulation composite systems (EICS)—to achieve simultaneously optimal structural, embodied-carbon and operational-energy performance; this combination is identified as a priority for further research.

This multi-dimensional analysis yields several findings with implications beyond the immediate case study. First, it provides empirical evidence that single-dimension cost comparison—the basis of most practitioner-oriented comparative studies—is systematically misleading as a criterion for

sustainable-construction technology selection. Operational energy costs and embodied carbon can invert the apparent ranking of an "expensive" construction system: an apparently costlier system at the construction phase (geopolymer blocks, +6% construction cost) can prove more cost-effective over the full life cycle than the apparent project-phase winner.

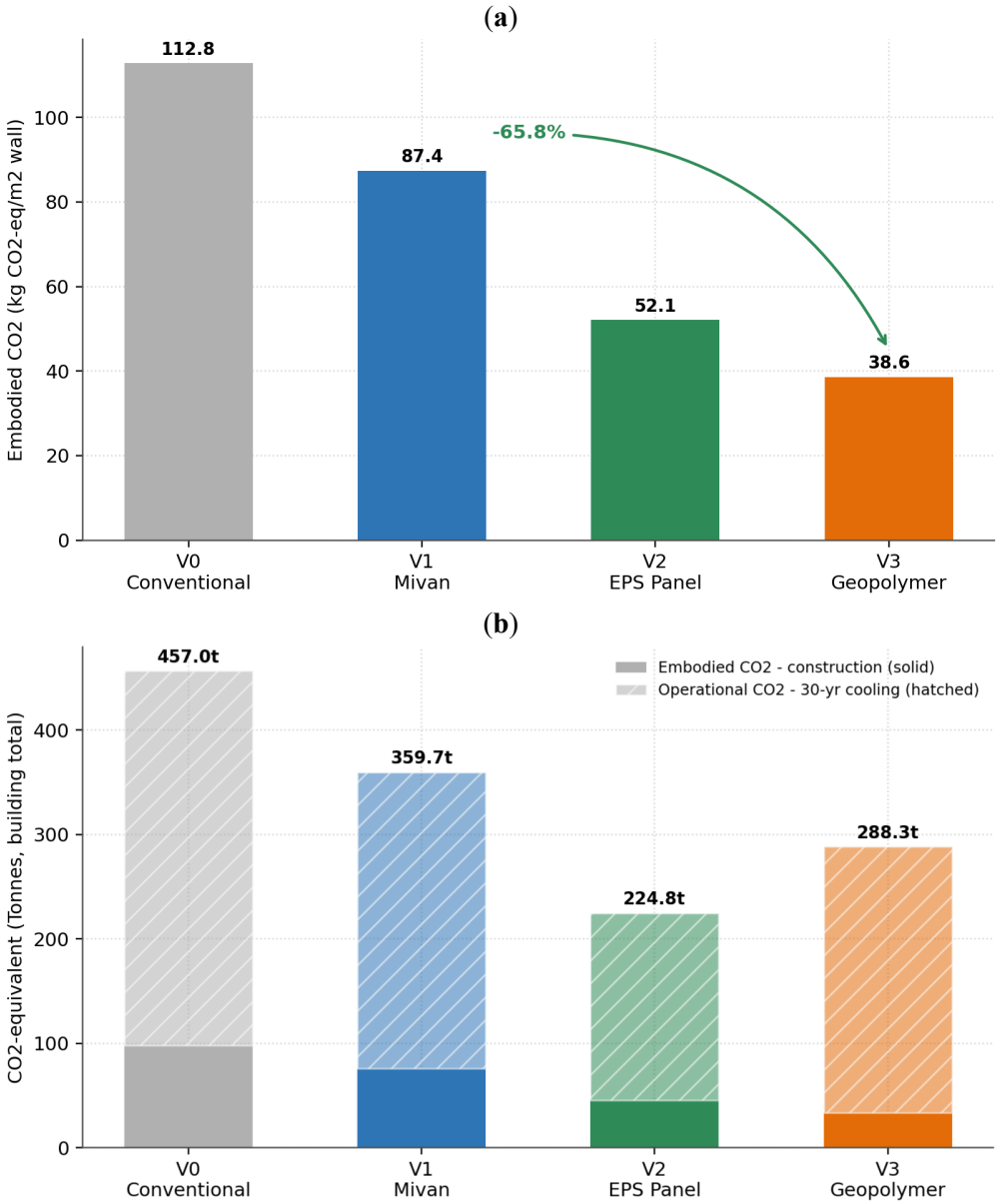

Figure 6. Comparative carbon performance of wall construction systems: (**a**) Construction-phase embodied carbon per m^2 of wall; (**b**) Total 30-year lifecycle CO_2 footprint.

Second, characterizing fly ash geopolymer blocks in this study as a technologically distinct category relative to conventional fly ash bricks carries policy implications. Construction codes and regulations in India and elsewhere still often classify geopolymer masonry within the same category as fired bricks, without recognising the fundamental differences in production chemistry, performance and environmental profile[11]. The compressive strength of 31 MPa, thermal conductivity of 0.42 W/m·K and embodied CO_2 of 38.6 kg/m^2 reported here represent material performance properties materially superior to fly ash bricks in every respect, and specification standards should be updated to reflect this distinction. Third, the thermal-mass analysis surfaces a nuance often lost in aggregate performance measures, but highly rel-

evant to hot-climate applications: the high decrement factor (0.89) and low thermal mass of the EPS panel system are compensated for by its excellent U-value, while the poor U-value of the Mivan concrete system is compensated for by its high decrement factor (0.21) and high thermal mass (9.2-h time lag). Given that summer peak temperatures in Pune's composite climate reach 38 °C (April–May), while dry-season diurnal fluctuations reach 12–15 °C, the thermal-mass advantage of concrete and geopolymer masonry may outweigh their U-value disadvantage during cooling-season months. Confirming this trade-off would require more sophisticated dynamic thermal simulation, distinguishing monsoon-season from dry-season performance—an avenue for future work beyond the scope of this study.

Fourth, the PPC data from LPS implementation establish that the principal constraint on lean performance for industrialized construction systems in India is not on-site execution but supply-chain management. Across all three lean technologies, the top three root-cause categories for missed commitments related to supplier-side variability—concrete delivery, block delivery and shotcrete-equipment availability—indicating that supply-chain integration, through vendor partnerships, just-in-time supply agreements and digitally monitored supply chains, is a precondition for realising the theoretically achievable performance gains of each technology[21,23].

Finally, the empirical link between lean waste reduction and embodied-carbon reduction—illustrated by Mivan's 76.9% construction-waste reduction and its proportional CO_2 reduction—provides a quantitative basis for the conceptual argument advanced by Sarhan et al.[19] and Merker[20] that lean and green construction are mutually reinforcing rather than competing priorities. The practical implication is that lean performance metrics (PPC, waste intensity, rework rate) could usefully be incorporated into green building certification frameworks (IGBC, GRIHA) as routine proxies for environmental performance, reducing the burden of standalone LCA assessment on project teams.

4.7. Positioning Relative to Published Literature and Study Boundary Conditions

Beyond corroborating the individually known advantages of Mivan, EPS panels and fly ash bricks reported in prior single-technology studies, the primary contribution of this work is the simultaneous, criteria-consistent comparison of all three systems against one conventional baseline within a single monitored case study. This directly extends Gulghane et al.[27] and Ramteke et al.[28] (Mivan cost/schedule only), the EPS-focused work of Chen et al.[10] and the Bhubaneswar EPS sustainability case, and the fly ash geopolymer characterisation of Janga et al.[31] and Krishnan et al.[11], none of which places these systems on a common multi-criteria scale spanning cost, schedule, thermal performance and embodied carbon together. The 54.2% Mivan schedule saving reported here is consistent with the 40% range reported by Gulghane et al.[27] and Sankhe and Kumbhar[29] once the additional plastering-elimination benefit is included, and the 18.5% EPS lifecycle-cost advantage is of the same order as the 15–25% green-material lifecycle savings reported by Strulak-Wójcikiewicz and Wagner[32] for Asian construction and the carbon-shadow-price effect described by Zhang et al.[33].

On a cost-estimation basis, direct costs were built up from measured quantities (BIM/Revit 2024 quantity take-off) priced against the current Maharashtra Schedule of Rates, and explicitly included labour, plant/equipment (crane and shotcrete pump hire), material and transportation; overheads and contractor margin were added at a flat 12%, consistent with local practice. These are single-project, live-site records rather than a multi-project statistical sample, and the 30-year life-cycle cost analysis discounts operational cooling energy at 6% p.a.; a formal return-on-investment/payback analysis was not separately computed and is noted as an avenue for future work. Because the analysis rests on one monitored case study rather than multiple completed projects, the reported percentages should be read as technology-specific performance differentials for this project archetype rather than universal constants, and we moderate our conclusions accordingly.

On generalizability, the case study is a G+3 (four-storey) residential building; the reported cost, schedule and thermal rankings are most directly applicable to low- and mid-rise residential housing and would need re-verification for high-rise or infrastructure projects, where structural load paths, formwork cycles and vertical transportation economics differ materially. Sustainability was assessed through embodied carbon (ISO 14044:2006), thermal performance and lean waste intensity; structural robustness beyond com-

pressive strength, durability, fire resistance (beyond the EPS treatment discussed in Section 2.3), acoustic performance, maintenance demand and occupant comfort were outside the measured scope and are flagged as limitations in Section 6. Geographic location and local labour-cost structure would be expected to shift the relative ranking of labour-intensive (Mivan, fly ash block laying) versus material-intensive (EPS panel, factory-fabricated) technologies; this sensitivity is not quantified here and is identified as a priority for future multi-site replication.

On adoption barriers and digital technologies, consistent with Mohammed et al.[21] and Guo[4], workforce skill gaps, limited contractor experience with non-traditional formwork/panel systems, regional equipment availability and fragmented supply chains are the principal barriers to adopting Mivan, EPS and geopolymer-block technologies in the Indian and broader developing-country context; the supply-chain variability recorded in Section 4.4 is a direct manifestation of this barrier. BIM-enabled scheduling was already used for quantity take-off and clash detection in this study (Section 3.2); extending this to digital twins, AI-assisted progress monitoring and modular/off-site fabrication, building on the BIM-lean integration evidence of Arayici et al.[24,26] and Khosrowshahi and Arayici[25], is identified as a natural next step for scaling these findings to larger and more automated construction programmes.

Table 6 positions the present findings against selected published studies to make this comparison explicit.

Table 6. Positioning of this study's findings relative to selected published international and Indian studies.

Published Study	Technology/Focus	Reported Metric	This Study
Gulghane et al.[27]; Sankhe et al.[29]	Mivan vs. conventional, India	~40% schedule saving; 12–18.4% cost saving	54.2% schedule saving; 5.4% direct-cost saving
Prasittisopin et al.[30]; Bhubaneswar EPS case study	EPS panel thermal/embodied energy	λ 0.15–0.50 W/m·K; embodied energy 1.2–3× lower	U-value 0.31 W/m^{2}K; 18.5% lower life-cycle cost
Janga et al.[31]; Krishnan et al.[11]	Fly ash geopolymer block, sustainability/MCDM	16.7–35 MPa strength; lower embodied energy vs. OPC	31.2 MPa strength; 65.8% lower embodied CO_2 vs. clay brick
Strulak-Wójcikiewicz and Wagner[32]; Zhang et al.[33]	Life-cycle cost/carbon-shadow pricing, Asia	15–25% life-cycle saving from low-carbon materials	18.5% life-cycle saving (EPS); cost ranking reverses vs. direct-cost-only view
Sarhan et al.[19]; Maqsoom et al.[53]	Lean-green integration; Indian lean adoption	Waste elimination ≈ emission reduction; partial LC adoption in India	77% waste reduction (Mivan) tracks proportionally with CO_2 reduction

5. Conclusions

In this research paper, the three sustainable lean construction technologies, namely Mivan aluminium formwork, Expanded Polystyrene (EPS) core panel systems and fly ash geopolymer block masonry, have been comprehensively compared with conventional reinforced cement concrete (RCC) construction with clay brick masonry for a G+3 residential building in Pimpri-Chinchwad, Pune, India, based on multi-dimensional evaluation. The study illustrates that no one technology is better than another on all performance aspects by incorporating material characterization, cost, thermal performance, embodied carbon and lean waste tracking using the Last Planner System. Instead, the technology choice will be based on the specific situation, depending on the project's main goal, the interests of the stakeholders and the evaluation period. Most importantly, research shows that single-phase project cost is systematically misleading as a criterion for selecting sustainable construction technology—and that taking a lifecycle perspective, including operating energy costs and embodied carbon over the building's service life, can have a fundamental impact on apparent performance rankings, proving that lean and green construction are not competing approaches, but reinforcing ones. The main results of this research and the contribution of the study are summarised below:

- The most significant schedule reduction was for Mivan aluminium formwork, where there was a 54.2% reduction (from 24 months to 11 months) and the lowest material waste intensity of 11.2 kg/m^2 GFA—a 76.9% reduction from conventional construction—due to the elimination of brickwork cutting, plastering and concrete overpour waste inherent to the closed aluminium

formwork system.

- EPS core panel systems achieved the best thermal insulation performance with a wall U-value of 0.31 W/m^{2}K—a factor of over 8 times better than the conventional clay brick masonry wall U-value (2.52 W/m^{2}K), and the lowest 30-year LCC (₹148.60 lakhs, a factor of 18.5% lower than conventional), which proves that the energy cost reduction in the operation period is more than able to compensate for any slight construction phase cost premium over an LCC assessment period.
- The fly ash geopolymer block masonry showed the least construction phase embodied carbon of 38.6 kg CO_2-eq/m^2 showing a 65.8% reduction compared to conventional clay brick masonry of 112.8 kg CO_2-eq/m^2; the compressive strength of fly ash geopolymer block masonry was 31.2 MPa, which is more than seven times that of conventional clay brick masonry of 4.1 MPa, making fly ash geopolymer blocks a high performance and low carbon masonry technology which is fundamentally different from conventional fly ash bricks.
- When the construction phase embodied carbon was added to 30-year operational CO_2 emissions, the total life cycle carbon footprint positioning changed, with EPS panels coming out on top with the lowest total (3,090 kg CO_2-eq/m^2). However, it had a higher construction phase embodied carbon than geopolymer blocks. It was found that relying on construction phase embodied carbon alone (as done in current green building rating systems like GRIHA and IGBC) is not enough to guide material selection towards low carbon.
- A multi-criteria analysis using different criteria, such as construction cost, schedule, thermal comfort, thermal mass, embodied carbon, lifecycle cost, waste reduction and structural strength, was performed using weights. The results indicated that EPS panels (3.85) > Mivan (3.65) > Fly Ash Geopolymer (3.50) » Conventional (1.95), which enabled a unified decision support framework in technology selection for different project priorities and stakeholders' objectives.
- The results of the LPS implementation showed that the constraint to lean performance of all three industrialized construction technologies in the Indian context was not on-site execution, but variability from the supply chain, including concrete delivery, supply sequencing of blocks, or availability of the shotcrete equipment, respectively, with a percentage of PPC failures of 68–74%.
- Empirically, the study shows the link between lean waste reduction and embodied carbon reduction—the 76.9% construction waste reduction by Mivan technology is directly related to proportional embodied CO_2 reductions and quantifies the extent to which this can be used as a proxy for embodied carbon reduction in green building certification frameworks.
- The geopolymer blocks made of fly ash are classified as a fourth-generation masonry technology with compressive strength of 5–8 times that of conventional fly ash bricks, water absorption of 7.2% as compared to 16.4% of clay bricks and thermal conductivity of 0.42 W/m·K, which requires revisiting and updating of regulatory classification and construction specifications in India, where fly ash geopolymer masonry is still classified under legacy fly ash brick classifications.
- The analysis of the thermal mass results proved to show an important nuance for hot Composite Climates: the Mivan monolithic concrete wall, despite having a relatively poor steady state U value (2.84 W/m^{2}K), has a thermal time lag of 9.2 h and a decrement factor of 0.21, meaning that thermal mass performance, not just U value, governs occupant thermal comfort according to the analysis for the hot Composite Climate Zone applications during the dry season with large diurnal temperature fluctuations, which underlines the need for dynamic thermal simulation in selecting the technology for these types of applications.
- The study offers practical guidance for decision support of various stakeholder groups: Mivan technology is most appropriate for developer-led and government housing programmes where schedule compression and early realization of revenue are the most important considerations; EPS panels are best suited to the affordable housing sectors where long term energy affordability is the priority; and fly ash geopolymer block masonry is the most appropriate for projects where there is a need for circular economy credentials, low embodied carbon and high structural strength.

Taken together, these findings show that sustainable lean construction technology selection for Indian mass housing cannot be reduced to a single winner: Mivan, EPS panels

and fly ash geopolymer block masonry each dominate on a different, decision-relevant axis—schedule and waste, life-cycle cost and thermal comfort, and embodied carbon and structural strength, respectively—and the "optimal" choice depends on which of these axes a given project or programme is designed to optimise. For developers and contractors, the practical recommendation is to make the selection criterion explicit at the outset of procurement (schedule-critical, affordability-critical or carbon-critical) rather than defaulting to construction-phase cost, and to combine technologies where feasible—for example, Mivan structural shells with supplementary external insulation, or geopolymer masonry paired with improved envelope detailing—to capture benefits across more than one axis simultaneously. For policymakers and code-writing bodies, the results support two concrete actions: first, updating fly ash geopolymer masonry specifications and green-building rating criteria (GRIHA, IGBC) to reflect fourth-generation material performance rather than legacy fly-ash-brick classifications; and second, requiring life-cycle (embodied plus operational) carbon and cost reporting, rather than construction-phase figures alone, in affordable-housing procurement guidelines, since this study shows that phase-only reporting can select the wrong technology. For the research community, the priority extensions identified here are multi-site and multi-climate replication to test the generalisability of the reported percentages, formal return-on-investment and payback-period analysis, and dynamic (seasonally resolved) thermal simulation to resolve the U-value/thermal-mass trade-off identified in Section 4.6—together with closer integration of BIM-enabled digital tools into the lean supply-chain management practices identified as the principal constraint on lean performance in this study.

Limitations

This study is based on a single monitored G+3 residential case study in Pimpri-Chinchwad, and its cost, schedule and thermal findings should be treated as technology-specific performance differentials for this project archetype rather than universal values; the direct-cost and schedule figures are drawn from live site records and BIM-based quantity take-off for one project rather than from a multi-project statistical sample or from independently completed benchmark projects, and no formal return-on-investment or payback-period analysis was performed beyond the 30-year discounted life-cycle cost comparison. Because the analysis rests on estimated and site-monitored data for one location, region-specific factors that were not varied in this study—local labour cost structure, material haulage distance, market price volatility of aluminium, EPS and fly ash, and site-specific ground and climatic conditions—could shift the reported cost and schedule margins if the same technologies were deployed elsewhere in India or in a different market; the conclusions are moderated accordingly and are intended to guide, rather than substitute for, project-specific feasibility studies. Performance indicators outside the measured scope—long-term durability, structural robustness under seismic and wind loading beyond the codal checks reported, fire resistance of the geopolymer and Mivan systems, acoustic performance and occupant thermal comfort surveys—were not evaluated and are recommended directions for future multi-site, multi-climate replication studies, together with quantification of how workforce skill availability, contractor experience and supply-chain maturity in other regions of India would affect the lean performance metrics reported here.

Author Contributions

Conceptualization, S.W.; methodology, S.W.; validation, V.K.; formal analysis, S.J.; investigation, M.S.; resources, A.M.; data curation, S.S.; writing—original draft preparation, S.W.; writing—review and editing, S.W.; visualization, D.V.; supervision, V.C.; project administration, C.K.C.; funding acquisition, C.K.C. All authors contributed equally to the conception, design, data collection, analysis, and writing of this study. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable. This study did not involve human participants, human data or animal subjects, and no formal ethics approval was therefore required.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data will be made available on request.

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Conflict of Interest

The authors declare that there is no conflict of interest among the authors.

AI Use Statement

The authors declare that no artificial intelligence (AI) tools were used in the preparation, analysis, or writing of this manuscript.

Abbreviations

Symbol/Abbreviation	Description	Unit/Value
AAC	Autoclaved Aerated Concrete	—
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers	—
BEE	Bureau of Energy Efficiency, Government of India	—
BIM	Building Information Modelling	—
CIFE	Center for Integrated Facility Engineering, Stanford University	—
CO_2-eq	Carbon Dioxide Equivalent (greenhouse gas emission metric)	kg or tonnes
DOWNTIME	Eight-waste lean taxonomy: Defects, Overproduction, Waiting, Non-utilised talent, Transportation, Inventory, Motion, Excess processing	—
ECBC	Energy Conservation Building Code (BEE, India, 2017)	—
EPS	Expanded Polystyrene	—
FA	Fly Ash	—
GFA	Gross Floor Area	m^2
GRIHA	Green Rating for Integrated Habitat Assessment (India)	—
GWP	Global Warming Potential	kg CO_2-eq/kg
IGBC	Indian Green Building Council	—
IS	Indian Standard (Bureau of Indian Standards)	—
JIT	Just-In-Time (lean supply delivery method)	—
LC	Lean Construction	—
LCA	Life Cycle Assessment	—
LCCA	Life Cycle Cost Analysis	—
LPS	Last Planner System (lean production control tool)	—
MCDM	Multi-Criteria Decision-Making	—
MEP	Mechanical, Electrical and Plumbing	—
MSEDCL	Maharashtra State Electricity Distribution Company Limited	—
NABL	National Accreditation Board for Testing and Calibration Laboratories	—
NBC	National Building Code of India	—
NCR	Non-Conformance Report/Register	—
NaOH	Sodium Hydroxide (alkaline activator)	—
Na_2SiO_3	Sodium Silicate (alkaline activator)	—
OPC	Ordinary Portland Cement	—
PCMC	Pimpri-Chinchwad Municipal Corporation	—
PMAY	Pradhan Mantri Awas Yojana (affordable housing scheme, India)	—
PPC	Percent Plan Complete (LPS workflow reliability metric)	%
PWD	Public Works Department, Maharashtra	—
RCC	Reinforced Cement Concrete	—
SCM	Supplementary Cementitious Material	—
SOR	Schedule of Rates (Maharashtra PWD)	—
TFV	Transformation-Flow-Value model [15]	—
TPS	Toyota Production System	—
VSM	Value Stream Mapping	—
w/c	Water-to-Cement Ratio	—

Symbol/Abbreviation	Description	Unit/Value
λ	Thermal conductivity of a material	W/m·K
U	Thermal transmittance (U-value) of a wall assembly	W/m^2K
R	Thermal resistance of a material or assembly layer	m^2K/W
φ	Thermal time lag—Time delay between peak external and peak internal temperatures	hours
f	Decrement factor—Ratio of amplitude of internal to external temperature swing	—
f’	Decrement factor (alternate notation)	—
M	Thermal admittance (dynamic thermal capacity parameter)	W/m^2K
E^{The}	Embodied energy of a construction material	MJ/kg
GHG	Greenhouse Gas (total emissions)	kg CO_2-eq
f^{ex}	Grid emission factor (electricity grid carbon intensity)	kg CO_2/kWh
V_0	Control variant: Conventional RCC with clay brick masonry	—
V_1	Experimental variant 1: Mivan aluminium formwork system	—
V_2	Experimental variant 2: EPS core panel system	—
V_3	Experimental variant 3: Fly ash geopolymer block masonry	—
M20, M25	Concrete mix grade (characteristic compressive strength at 28 days)	MPa
f^c	Characteristic compressive strength of concrete cube (150 mm)	MPa
w/c	Water-to-cement ratio in concrete mix design	—
FM	Fineness Modulus of fine aggregate (river sand)	—
SiO_2/Na_2O	Silica modulus of sodium silicate activator solution	—
$NaOH:Na_2SiO_3$	Mass ratio of sodium hydroxide to sodium silicate in activator solution	—
M NaOH	Molarity of sodium hydroxide solution	mol/L
₹	Indian Rupee (currency)	—
NPV	Net Present Value (discounted over assessment period)	₹
r	Discount rate for lifecycle cost analysis	%
LCCA	Lifecycle Cost Analysis assessment period	years
E^{bx}。	Annual building cooling energy consumption	kWh/year

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