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Life Cycle Assessment of sustainable construction materials: A Comparative Study with a Case Analysis on Fly Ash Concrete Mixes

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Abstract: *The construction industry is one of the largest contributors to global carbon dioxide (CO_2) emissions, primarily due to the use of energy-intensive materials like cement and steel. As the demand for infrastructure rises, it becomes essential to adopt sustainable construction practices that minimize environmental impacts. Life Cycle Assessment (LCA) is an effective tool for evaluating the environmental footprint of construction materials across various stages, from raw material extraction to production. This study focuses on a cradle-to-gate LCA to quantify CO_2 emissions associated with both conventional and alternative materials in the Indian construction sector.*

An experimental investigation was conducted on M25 concrete mixes containing 0%, 10%, 20%, 25%, and 30% fly ash as a partial replacement for cement. The results showed that a 30% fly ash mix led to approximately 28% reduction in cradle-to-gate CO_2 emissions compared to ordinary Portland cement (OPC) concrete. In addition, secondary data from the literature was used to assess the emissions of fly ash bricks, bamboo panels, recycled concrete aggregates (RCA), and geopolymer concrete. Among these, bamboo panels and fly ash bricks demonstrated the lowest embodied carbon.

The findings of this study emphasize the significant role of material selection in reducing the carbon footprint of construction projects. Adoption of sustainable alternatives such as fly ash concrete, bamboo panels, and geopolymer concrete can help the construction industry align with global sustainability goals. Future work could include cradle-to-grave assessments, integration of water and energy footprints, and cost analyses to provide a holistic view of environmental performance.

Key Words: *Life Cycle Assessment, Cradle-to-Gate, CO_2 Emissions, Fly Ash Concrete, Bamboo Panels, Geopolymer Concrete, Sustainable Materials, Construction Industry*

1. INTRODUCTION:

The construction sector plays a vital role in the economic development of any nation, but it is also one of the largest contributors to environmental pollution and climate change. The production of construction materials, particularly cement and steel, is highly energy-intensive and results in significant carbon dioxide (CO_2) emissions. According to global estimates, cement production alone accounts for nearly 7% of the world's CO_2 emissions. As urbanization and infrastructure demands increase, especially in developing countries like India, it becomes imperative to adopt sustainable construction practices that minimize environmental harm while meeting the growing needs of society. Life Cycle Assessment (LCA) has emerged as a powerful tool for quantifying the environmental impacts of construction materials and systems.

By analyzing the entire life cycle of a product — from raw material extraction, production, use, to end-of-life— LCA provides comprehensive insights into its ecological footprint. In particular, a cradle-to-gate LCA focuses on the stages up to the point where the material is ready for delivery and use, thereby helping stakeholders make informed decisions about material selection and sourcing.

Cradle-to-gate life cycle assessments are particularly valuable for evaluating construction materials, as they allow stakeholders to compare the environmental impacts of materials before actual construction commences. In recent times, both researchers and industry experts have increasingly focused on environmentally friendly materials to curb the carbon emissions associated with buildings and infrastructure. Materials such as fly ash bricks, recycled concrete aggregates (RCA), bamboo-based panels, and geopolymer concrete have emerged as promising alternatives. These materials offer the potential to either partially or fully replace traditional options like ordinary Portland cement (OPC) and fired clay bricks. Fly ash, a residue generated from coal-fired power plants, can be utilized in various forms, including as a partial replacement in cement-based products and as a raw material in brick manufacturing. Bamboo, a fast-growing renewable resource, offers high strength-weight ratios and low embodied carbon, making it a promising material for structural and non-structural applications. Despite the availability of such alternatives, their adoption in mainstream construction remains limited due to gaps in awareness, policy support, and technical standardization. Moreover, few studies comprehensively compare the cradle-to-gate emissions of these materials under Indian conditions, where material sourcing, energy mix, and construction practices differ from global averages.

This study aims to address that gap by conducting both experimental and literature-based assessments of selected sustainable materials, quantifying their cradle-to-gate CO_2 emissions and comparing them against conventional options. By highlighting the carbon savings achievable through material choice, the study seeks to support the transition toward greener construction practices in India.

2. LITERATURE REVIEW:

Life Cycle Assessment (LCA) has been widely adopted to evaluate the environmental impacts of construction materials and systems. A cradle-to-gate approach, in particular, focuses on the impacts generated during the production stages — from raw material extraction to the point at which materials are ready for construction use. Numerous studies have examined how alternative materials can help reduce embodied carbon in buildings and infrastructure, particularly in the Indian context.

- Deshmukh and Kulkarni (2023) investigated the role of fly ash as a partial cement replacement in concrete production. Their study demonstrated that fly ash replacements up to 30% could significantly lower cementrelated CO_2 emissions without compromising strength or durability. The authors emphasized the importance of mix design optimization to balance environmental benefits and structural performance.
- NTPC internal studies (2023) examined the industrial application of geopolymer concrete in flooring and precast elements. These studies confirmed that geopolymer concrete could achieve CO_2 emission reductions of 40–50% compared to ordinary Portland cement (OPC) concrete, aligning with national goals for low-carbon construction.
- Sharma and Gupta (2022) conducted an LCA of green building materials in India, focusing on alternatives such as fly ash bricks, recycled concrete aggregates (RCA), and bamboo panels. Their findings indicated that fly ash bricks could reduce CO_2 emissions by 30–40% compared to clay bricks due to the elimination of firing processes and the use of industrial waste. The study also highlighted the environmental advantages of bamboo panels, citing their renewability and low processing energy.
- Sabnis (2015) studied low-carbon concrete options and found that geopolymer concrete substantially reduces CO_2 emissions relative to OPC concrete. The reduction is largely attributed to the lower energy requirements of geopolymer binder production and the use of by-products such as fly ash and slag. The study supported the viability of geopolymer concrete as an eco-friendly alternative for various structural applications.

Collectively, these studies demonstrate that sustainable materials — including fly ash concrete, fly ash bricks, bamboo panels, RCA, and geopolymer concrete — offer considerable potential for reducing the carbon footprint of the construction sector. However, widespread adoption is still constrained by challenges such as market acceptance, lack of standardization, and limited policy incentives. The present work builds on this literature by comparing cradle-to-gate CO_2 emissions of selected conventional and alternative materials through a combination of experimental and secondary data analyses.

3. OBJECTIVES :

The main aim of this study is to find out how using different sustainable construction materials can help reduce carbon dioxide (CO_2) emissions in the building industry. By comparing traditional materials with options like fly ash concrete, fly ash bricks, bamboo panels, and recycled aggregates, this work shows how better material choices can make construction more eco-friendly.

4. RESEARCH METHOD :

The methodology of this study consists of two main components:(a) an experimental program involving concrete mix design with partial replacement of cement by fly ash, and(b) cradle-to-gate CO_2 emission estimation for selected construction materials using experimental quantities and literature data.

4.1 Experimental Procedure

Concrete mixes were designed for M25 grade concrete, with varying levels of fly ash replacing ordinary Portland cement (OPC) by weight. The mix design followed **IS 10262:2019** guidelines. Five mix proportions were considered:

- 0% fly ash (or OPC)
- 10% fly ash
- 20% fly ash
- 25% fly ash
- 30% fly ash

The materials used in the concrete mixes were:

- OPC 43 grade cement
- Fly ash
- Crushed granite coarse aggregate
- Natural river sand as fine aggregate

Table 1: Material quantities for different fly ash concrete mixes (kg/m³)

Fly Ash %	Cement	Fly Ash	Fine Aggregate	Coarse Aggregate
0%	400	0	650	1200
10%	360	40	650	1200
20%	320	80	650	1200
25%	300	100	650	1200
30%	280	120	650	1200

4.2 CO_2 Emission Calculation

This study employed a standard method to estimate cradle-to-gate CO_2 emissions, where emissions were calculated by multiplying the material quantity by its corresponding emission factor, expressed in kilograms of CO_2 per kilogram of material.

Emissions=Material Quantity× Emission Factor

This is a standard formula used in Life Cycle Assessment (LCA) studies, as given in IPCC Guidelines for National Greenhouse Gas Inventories (2006) and is consistent with approaches in ISO 14040. The emission factors (constants) for each material were taken from standard literature relevant to Indian conditions, including Sharma & Gupta (2022), Sabnis (2015), and national inventory data.

For this study, we applied the above formula individually to each material in the concrete mix. To determine the overall CO_2 emissions for each fly ash concrete mix, the individual emissions from all constituent materials were calculated and then aggregated. This approach resulted in the following working formula:

CO_2 emissions (kg)= (Cement quantity×0.90) + (Fly ash quantity×0.03) + (Fine aggregate quantity×0.005) + (Coarse aggregate quantity×0.005) Where:

- The quantities of each material were calculated per 1 m³ of concrete based on the mix design.
- The emission factors were:
- Cement: 0.90 kg CO_2/kg
- Fly ash: 0.03 kg CO_2/kg
- Fine aggregate: 0.005 kg CO_2/kg
- Coarse aggregate: 0.005 kg CO_2/kg

These constants were chosen based on published LCA studies for construction materials in India and conform to values recommended in IPCC (2006) and ISO 14040 for cradle-to-gate analyses.

4.3 Compilation of Literature Data for Sustainable Materials

Alongside the fly ash concrete mixes, this study incorporated secondary data on other sustainable construction materials, sourced from existing Life Cycle Assessment (LCA) literature and relevant technical publications. This data was used to compare their cradle-to-gate CO_2 emissions with those of conventional materials.

Table 2: CO_2 emission factors for selected materials

Material	CO_2 Emissions	Source
Fly ash bricks	70–100 kg/m³	Sharma & Gupta (2022)
Bamboo panels	50–80 kg/m³	Sharma & Gupta (2022), NTPC (2023)
Recycled concrete aggregate	100–150 kg/m³	Literature reports
Geopolymer concrete	200–250 kg/m³	Sabnis (2015), NTPC (2023)
OPC	850–950 kg/ton	Sabnis (2015)
Steel	1700–2000 kg/ton	Sharma & Gupta (2022)
Traditional concrete (M25)	300–350(per-m³)	Madurwar&Verma(2023);
Conventional precastconcrete	~280-320(per m³)	Madurwar (2023)
Natural-aggregates (gravel)	5–10	Arukala (2020); Jain (2021)
Burnt Clay Bricks	200–250	Majumder (2024); Jain (2021);NTZR 2024

These values were used to enable direct comparison of the environmental performance of sustainable materials with conventional options.

4.4 Functional Unit and System Boundary:

The functional unit for this study was:

- **1 m³ of concrete** (for mixes)
- **1 tonne of material** (for comparison across materials)

The system boundary was defined as **cradle-to-gate**, covering all processes from raw material extraction to manufacturing, up to the point the material is ready for delivery to the construction site. Transport to site, construction activities, usage phase, and end-of-life were excluded from this study.

5. RESULTS:

The CO_2 emissions of different fly ash concrete mixes were calculated using the material quantities and emission factors.

Table 3:CO_2 Emissions of Fly Ash Concrete Mixes

Fly Ash %	CO_2 Emissions (kg/m³)
0%	369.25
10%	334.45
20%	299.65
25%	282.25
30%	264.85

The results indicate that increasing the proportion of fly ash in the mix leads to a reduction in CO_2 emissions. This trend is attributed to the significantly lower emission factor of fly ash compared to that of cement.

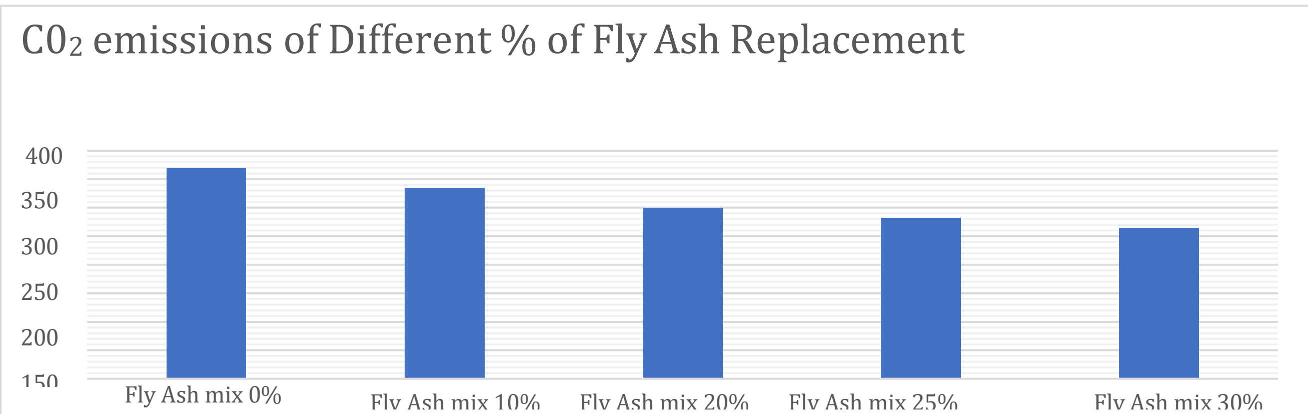

Figure 1. Graphical Representation of Different % of Fly Ash Replacements

5.1 Comparison of Fly Ash Mixes, Sustainable Materials, and Conventional Materials

The CO_2 emissions of sustainable materials and conventional materials (as identified in the literature used in this study) are presented below.

Table 4:CO_2 Emissions of Selected Materials

Material	CO_2 Emissions (kg/m³ or kg/ton)
Fly Ash Concrete (0%)	369.25
Fly Ash Concrete (10%)	334.45
Fly Ash Concrete (20%)	299.65
Fly Ash Concrete (25%)	282.25
Fly Ash Concrete (30%)	264.85
Fly Ash Bricks	70–100
Bamboo Panels	50–80
Recycled Concrete Aggregate (RCA)	100–150
Geopolymer Concrete	200–250
Traditional Concrete (M25)	300–350
Conventional Precast Concrete	280–320
Burnt Clay Bricks	200–250
OPC	850–950
Natural Aggregate (Gravel)	5-10
Steel (reinforcing)	1,700–2,000

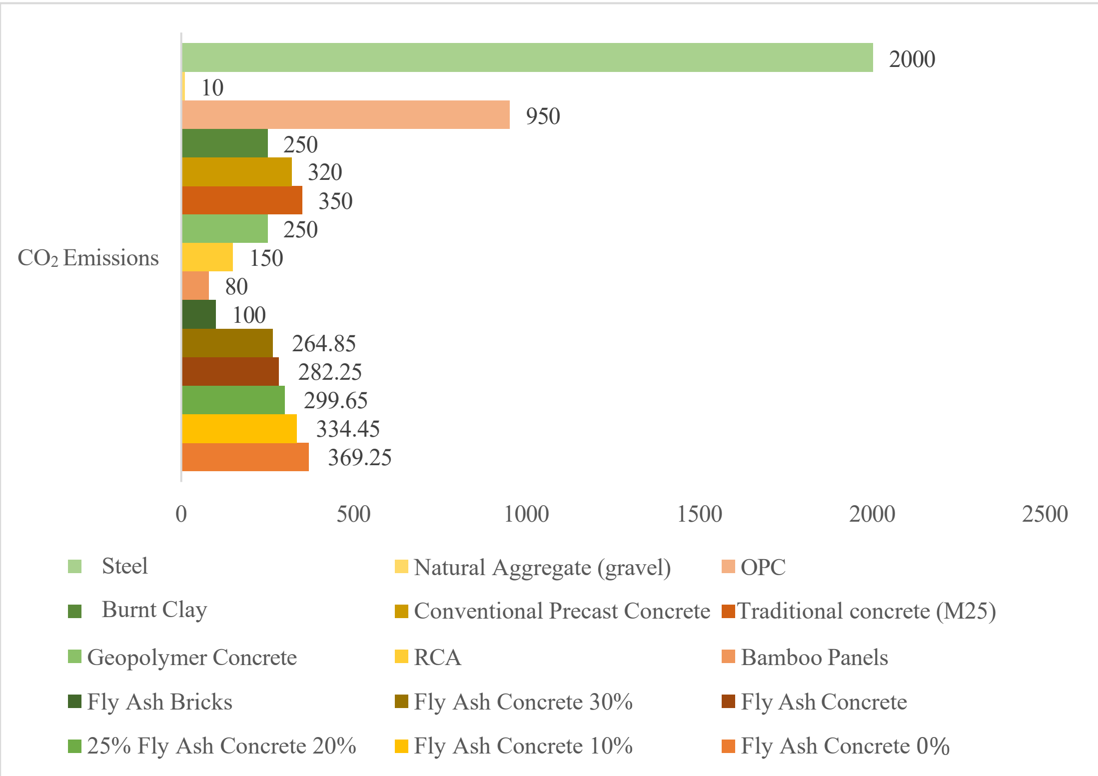

Figure 2. Graphical Representation of Comparison of Fly Ash Concrete, Sustainable Materials, and Conventional-Materials

6.ANALYSIS

- Fly ash concrete mixes showed a clear reduction in CO_2 emissions as fly ash content increased.
- Sustainable materials like fly ash bricks and bamboo panels had much lower emissions compared to conventional materials such as clay burnt bricks, OPC, and steel.
- Geopolymer concrete, RCA, and precast concrete demonstrated emissions savings over traditional materials.

7.CASE STUDIES

- **PMAY Housing with Fly Ash Bricks:** In government housing schemes under the Pradhan Mantri Awas Yojana (PMAY), fly ash bricks have been adopted in place of traditional clay burnt bricks. The use of fly ash bricks has resulted in approximately 30–35% reduction in CO_2 emissions compared to conventional clay bricks, as the firing process is eliminated and waste material (fly ash) is utilized.
- **Smart City Roads Using Recycled Concrete Aggregate (RCA):** Recycled concrete aggregate has been used in road sub-base and pavement layers in smart city infrastructure projects. The replacement of natural aggregates with RCA has contributed to a 15–20% reduction in embodied CO_2 emissions compared to conventional aggregates, while also promoting circular economy principles.
- **Bamboo Housing in Northeast India:** Bamboo panels have been used in traditional and modern housing solutions in parts of Northeast India. The use of bamboo, a fast-growing and renewable resource, has resulted in low embodied carbon structures, contributing to a significant reduction in overall building CO_2 emissions

8. CONCLUSION :

This research evaluated the environmental performance of selected sustainable construction materials using Life Cycle Assessment (LCA), with a focus on cradle-to-gate CO_2 emissions. A comparative analysis was conducted for materials such as fly ash concrete mixes, bamboo panels, recycled concrete aggregates, fly ash bricks, and geopolymer concrete, benchmarked against conventional construction materials like Ordinary Portland Cement (OPC), clay bricks, and steel.

Experimental data was generated for M25 grade concrete with varying percentages of fly ash (0% to 30%) replacing cement. The results demonstrated that increasing the proportion of fly ash significantly reduces embodied carbon. Specifically, a 30% fly ash replacement reduced CO_2 emissions by approximately 28% compared to conventional concrete. In addition to fly ash concrete, literature-based emission factors for other sustainable materials confirmed their potential for reducing carbon footprints. Bamboo panels and fly ash bricks emerged as particularly low-emission alternatives due to their use of renewable resources and industrial by-products. The study underscores the importance of thoughtful material selection in promoting low-carbon and environmentally responsible construction practices.

While this study focused on CO_2 emissions, it also highlighted the need for future LCA research to include broader environmental indicators and leverage emerging technologies like BIM and AI. Overall, the findings advocate for the wider adoption of sustainable materials as a practical pathway toward greener construction and climate-resilient infrastructure development.

9. FUTURE WORK/SCOPE

While this study focused on the cradle-to-gate CO_2 emissions of selected sustainable construction materials using Life Cycle Assessment (LCA), future work can expand both the scope and depth of analysis in several important ways:

- Cradle-to-Grave Assessment: Future studies should extend the system boundary beyond production to include transportation, construction, use-phase emissions, maintenance, and end-of-life disposal or recycling. This would provide a more comprehensive understanding of the total environmental footprint.
- Integration with Emerging Technologies: The incorporation of Building Information Modeling (BIM) and Digital Twin technologies can allow real-time tracking of material choices and environmental impacts. This integration would help automate sustainability assessments during the design and construction phases.
- Artificial Intelligence and Machine Learning: Advanced algorithms could be used to predict the environmental performance of materials under different mix designs, site conditions, or regional manufacturing practices. AI-based models may also help optimize material combinations for low-carbon construction.
- Inclusion of Additional Environmental Indicators: Future studies can incorporate a broader range of sustainability indicators such as embodied energy, water footprint, acidification potential, human toxicity, and resource depletion to provide a holistic sustainability evaluation.
- Regional Emission Data: Using region-specific or manufacturer-specific emission factors can increase the accuracy and relevance of the analysis, especially in a geographically diverse country like India.
- Development of Simplified Tools: User-friendly tools or mobile apps based on LCA principles could be developed to assist architects, engineers, and builders in selecting environmentally sustainable materials during the design phase.
- Life Cycle Costing (LCC) and Social Impact Assessment: Combining LCA with LCC and social dimensions will enable a more complete Life Cycle Sustainability Assessment (LCSA), helping stakeholders balance environmental, economic, and social factors in material selection.

10. LIMITATIONS:

- The study only evaluates CO_2 emissions (Global Warming Potential); other factors like water usage, energy demand, or durability are not considered.
- The cradle-to-gate boundary excludes transport and end-of-life phases.
- Material strength, durability, and cost were not analyzed.

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