

## LIFE CYCLE ENERGY AND CARBON FOOTPRINT ASSESSMENT OF PRECAST CONCRETE VS CAST-IN-SITU SYSTEMS

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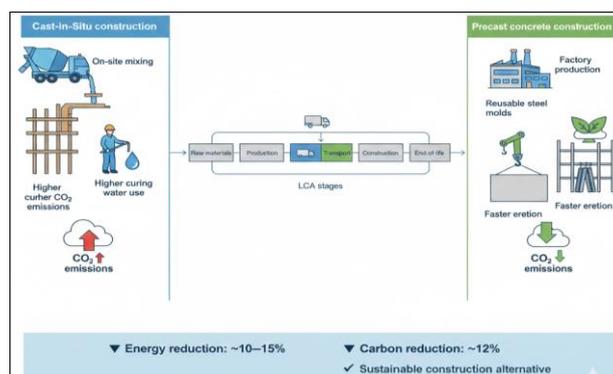
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### ABSTRACT

The construction industry significantly contributes to global energy consumption and greenhouse gas emissions, primarily due to extensive use of cement-based materials. This study presents a comparative Life Cycle Assessment (LCA) of Precast Concrete (PC) and Cast-in-Situ (CIS) construction systems with emphasis on embodied energy and carbon footprint. A cradle-to-grave approach is adopted considering material production, transportation, construction, and end-of-life stages. Results indicate that precast concrete systems demonstrate lower life cycle energy demand and reduced carbon emissions owing to controlled manufacturing, reduced material wastage, and improved construction efficiency. The study highlights precast construction as a sustainable alternative for low-carbon infrastructure development.

**KEYWORDS:** Life Cycle Assessment; Precast Concrete; Cast-in-Situ; Embodied Energy; Carbon Emissions; Sustainable Construction.

### Graphical Abstract:



## 1. INTRODUCTION

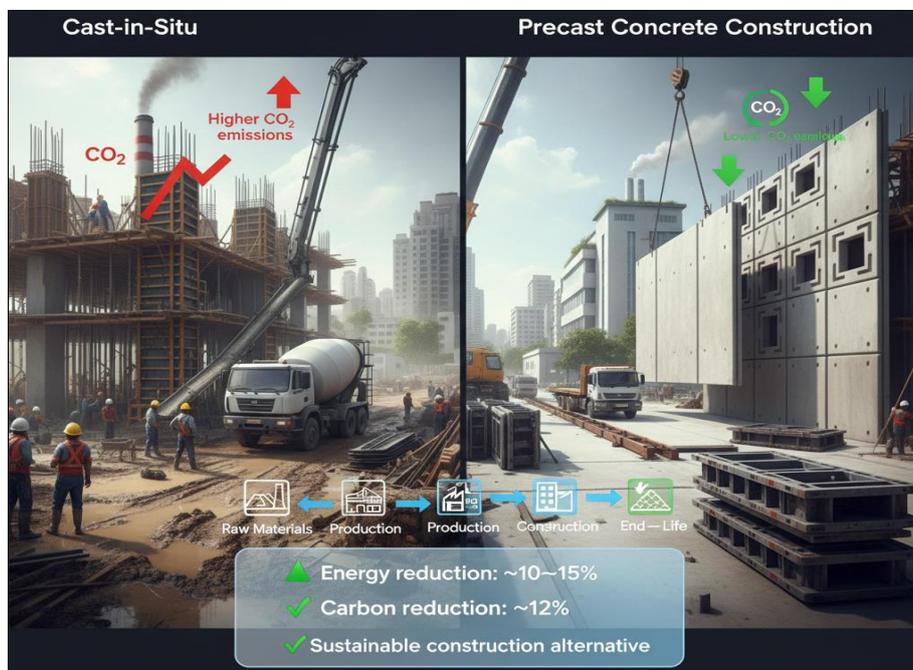
Rapid urbanization and accelerated infrastructure development across the globe have significantly intensified the environmental burden of the construction sector. With increasing demand for residential, commercial, and transportation infrastructure, the consumption of energy and natural resources has risen sharply, leading to higher greenhouse gas emissions. Among construction materials, concrete is the most widely used due to its versatility, durability, and structural performance. However, concrete production is highly energy-intensive and is responsible for nearly 8% of global carbon dioxide emissions, primarily due to cement manufacturing processes (Andrew, 2018). Cement production involves the calcination of limestone and high-temperature kiln operations, both of which contribute substantially to CO<sub>2</sub> emissions and fossil fuel consumption.

In the context of climate change mitigation and sustainable development goals, reducing the environmental footprint of construction activities has become a critical priority. Governments, policymakers, and industry stakeholders are increasingly emphasizing low-carbon construction practices, energy-efficient building systems, and environmentally responsible material selection. Consequently, evaluating alternative construction systems that can reduce life cycle energy demand and carbon emissions is essential for transitioning toward sustainable infrastructure development (Cabeza et al., 2014). Traditionally, cast-in-situ construction has been the predominant method for constructing reinforced concrete structures, particularly in developing countries. In this method, concrete is mixed, poured, and cured directly at the construction site. Cast-in-situ construction offers flexibility in design and ease of execution for complex structural geometries. However, it is often associated with prolonged construction durations, extensive use of temporary formwork, higher material wastage, increased water consumption for curing, and significant on-site labor dependency. These factors collectively contribute to increased energy use and carbon emissions over the construction life cycle.

In contrast, precast concrete construction systems have gained increasing attention as a modern and efficient alternative to conventional cast-in-situ methods. Precast construction involves manufacturing structural components such as beams, columns, slabs, and wall panels in controlled factory environments, followed by transportation and assembly at the construction site. This approach offers several advantages, including improved quality control, enhanced material efficiency, reduced construction time, and minimized on-site activities. Factory-controlled production enables optimized mix designs, precise reinforcement placement, and reduced material wastage, thereby contributing to improved

environmental performance (Marinković et al., 2010). The adoption of precast systems is particularly advantageous in large-scale housing projects, urban infrastructure, and repetitive structural layouts where standardization and speed of construction are critical. Moreover, reduced dependence on on-site labor and formwork results in improved safety and productivity. Despite these benefits, precast construction is sometimes perceived as environmentally unfavorable due to concerns related to transportation energy and emissions, especially when precast plants are located far from project sites. Therefore, a systematic and quantitative environmental assessment is required to evaluate whether the benefits of precast systems outweigh their associated impacts across the entire life cycle.

Life Cycle Assessment is widely recognized as a comprehensive and scientifically robust methodology for evaluating the environmental impacts of products, processes, and systems throughout their entire life span. In the context of construction, LCA enables the assessment of energy consumption and carbon emissions associated with various stages, including raw material extraction, material processing, transportation, construction, and end-of-life disposal. By adopting a life cycle perspective, LCA helps identify critical stages that contribute most significantly to environmental impacts and facilitates informed decision-making for sustainable construction practices (ISO 14040, 2006).



**Fig.1: Comparative Life Cycle Assessment (LCA) of Precast vs. Cast-in-Situ Concrete Systems.**

Several previous studies have applied LCA to assess the environmental performance of concrete materials and construction systems. Research indicates that material production, particularly cement manufacturing, dominates the embodied energy and carbon footprint of reinforced concrete structures. Flower and Sanjayan (2007) reported that cement content significantly influences greenhouse gas emissions in concrete production. Studies comparing precast and cast-in-situ systems have reported potential reductions in energy consumption and CO<sub>2</sub> emissions for precast construction due to reduced waste generation, optimized production processes, and shorter construction periods. Despite the growing body of literature, there remains a need for comprehensive comparative studies that quantitatively evaluate precast and cast-in-situ construction systems under similar functional and structural conditions. In particular, studies focusing on the Indian construction context are limited, even though India is one of the fastest-growing construction markets globally. The predominance of cast-in-situ construction in India, coupled with increasing urban housing demand and sustainability concerns, necessitates a detailed assessment of alternative construction systems using locally relevant data and assumptions.

Furthermore, many existing studies focus on either energy consumption or carbon emissions in isolation rather than integrating both indicators within a unified life cycle framework. A combined assessment of life cycle energy demand and carbon footprint provides a more holistic understanding of environmental performance and supports the development of low-carbon construction strategies. Such integrated evaluations are essential for aligning construction practices with national sustainability policies and global climate commitments. Against this backdrop, the present study aims to quantitatively compare the life cycle energy consumption and carbon footprint of precast concrete and cast-in-situ construction systems using a cradle-to-grave life cycle approach. The assessment considers key stages such as material production, transportation, construction, and end-of-life processes. By adopting a consistent functional unit and comparable system boundaries, the study ensures a fair and transparent comparison between the two construction methods. The findings are expected to provide valuable insights for engineers, planners, policymakers, and construction practitioners, supporting evidence-based decision-making for sustainable infrastructure development.

## 2. Previous researches

Several studies have applied life cycle assessment techniques to evaluate the environmental impacts of construction systems, particularly focusing on reinforced concrete structures.

Research consistently indicates that cement production is the dominant contributor to environmental impacts, accounting for approximately 70–80% of the total embodied carbon in reinforced concrete due to the energy-intensive clinker production process and associated process emissions (Andrew, 2018). As a result, strategies that reduce cement consumption or improve material efficiency play a crucial role in lowering the carbon footprint of construction projects. Comparative studies between precast concrete (PC) and cast-in-situ (CIS) construction systems have reported that precast construction can reduce carbon emissions by approximately 10–30%, primarily due to optimized material usage, controlled production processes, and reduced construction waste (Cabeza et al., 2014). Factory-controlled environments allow for precise batching, improved curing conditions, and effective quality control, which minimize material losses and rework during construction.

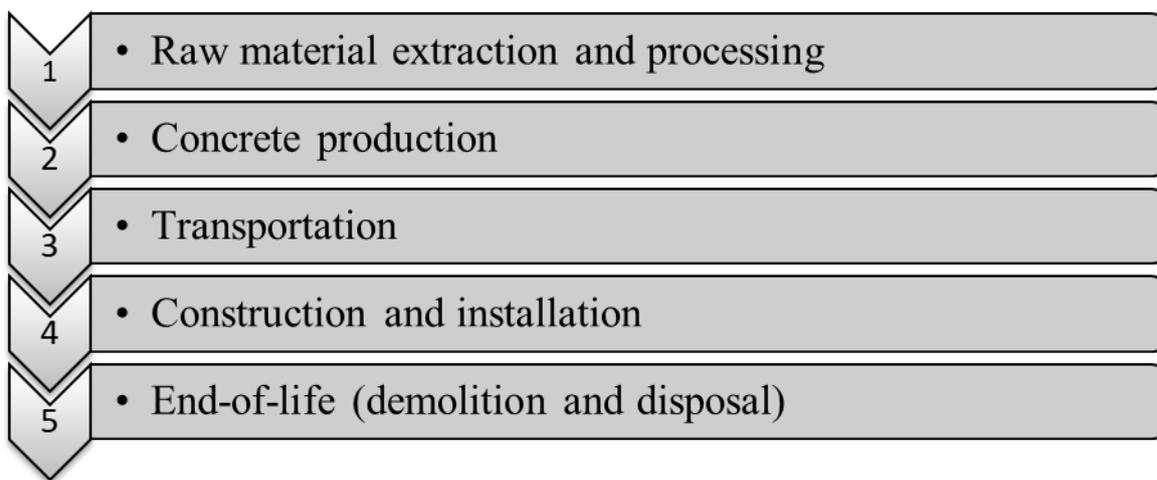
Marinković et al. (2010) emphasized that the reuse of steel molds and standardized components in precast systems further contributes to improved environmental performance. Several researchers have also highlighted that precast construction leads to reduced on-site energy consumption due to shorter construction durations, lower labor intensity, and minimized curing requirements (Kellenberger & Althaus, 2009). These benefits are particularly evident in large-scale and repetitive building projects where standardized precast elements can be efficiently utilized. Additionally, the reduction in formwork materials and on-site equipment usage further lowers embodied energy and emissions. Despite these advantages, transportation energy and associated carbon emissions remain a critical concern in precast construction, especially when precast manufacturing plants are located far from construction sites. Studies by Goggins et al. (2010) reported that transportation impacts can partially offset the environmental benefits of precast systems if logistics are not optimized. However, most cradle-to-grave life cycle assessments indicate that, even when transportation impacts are considered, precast concrete systems generally outperform conventional cast-in-situ construction in terms of overall environmental indicators. Overall, the literature suggests that precast concrete offers significant potential for reducing life cycle energy consumption and carbon emissions. However, the extent of these benefits is influenced by factors such as transportation distance, project scale, material composition, and regional construction practices, highlighting the need for context-specific assessments.

### 3. METHODOLOGY

#### 3.1 Life Cycle Assessment Approach

This study adopts a Life Cycle Assessment (LCA) methodology in accordance with the ISO 14040 and ISO 14044 standards, which provide internationally recognized principles and frameworks for assessing the environmental impacts of products and systems throughout their life cycle (ISO, 2006a; ISO, 2006b). The LCA approach enables a comprehensive evaluation of both energy consumption and carbon emissions associated with precast concrete (PC) and cast-in-situ (CIS) construction systems.

The life cycle stages included in the assessment are as follows:



**Fig.2: life cycle stages in building construction methods.**

A cradle-to-grave system boundary is considered to capture the complete life cycle of reinforced concrete structural elements. This boundary includes all stages from raw material extraction to end-of-life disposal, ensuring that upstream and downstream impacts are accounted for. The selected system boundary allows for an objective comparison between the two construction systems and avoids shifting environmental burdens from one stage to another (Guinée et al., 2011). Environmental impact categories evaluated in this study include cumulative energy demand (CED) and global warming potential (GWP), expressed in terms of CO<sub>2</sub>-equivalent emissions. These indicators are widely used in building LCA studies due to their relevance to climate change mitigation and energy efficiency assessment (Cabeza et al., 2014).

### 3.2 Functional Unit

The functional unit is defined as 1 m<sup>3</sup> of reinforced concrete structural element, which serves as the basis for comparison between precast and cast-in-situ systems. The selection of this functional unit enables normalization of energy and emission values and ensures consistency across life cycle stages. Similar functional units have been widely adopted in previous LCA studies of concrete structures to facilitate meaningful comparisons (Marinković et al., 2010; Goggins et al., 2010). Both PC and CIS systems are assumed to deliver equivalent structural performance, durability, and service life. Any differences in material composition, production methods, and construction processes are therefore reflected only in the environmental performance and not in functional output.

### 3.3 System Boundary Definition

#### 3.3.1 Raw Material Extraction and Processing

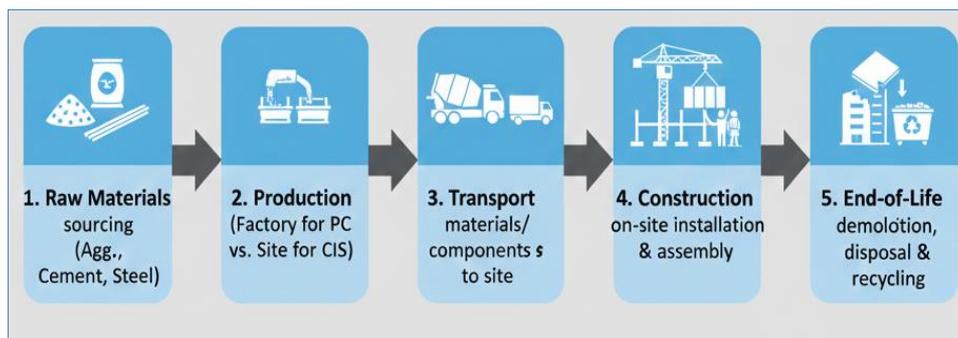
This stage includes the extraction, processing, and preparation of raw materials such as cement, fine aggregates, coarse aggregates, reinforcing steel, and water. Cement production is modeled as the most energy- and carbon-intensive process due to clinker production and fuel combustion in rotary kilns. Emission factors for cement are adopted from Indian production data and literature sources, accounting for both process and energy-related emissions (Andrew, 2018). Aggregate extraction and processing include quarrying, crushing, and grading operations. Reinforcing steel impacts include iron ore extraction, steelmaking, and rolling processes. Electricity and fuel consumption during these processes are included in the life cycle inventory.

#### 3.3.2 Concrete Production

Concrete production differs significantly between PC and CIS systems. In the CIS system, concrete is produced either on-site or at nearby ready-mix plants and transported to the construction site. Energy consumption includes batching, mixing, and pumping operations. On-site losses due to over-ordering, spillage, and quality-related rework are also considered (Kellenberger & Althaus, 2009). In contrast, precast concrete elements are manufactured in factory-controlled environments. The PC system benefits from optimized mix design, controlled curing conditions, and efficient batching processes. Energy inputs include mixing, vibration, steam or accelerated curing (if applicable), and internal material handling. The reuse of steel molds and reduced material wastage are explicitly accounted for, resulting in improved material efficiency compared to CIS construction (Marinković et al., 2010).

### 3.3.3 Transportation

Transportation impacts include the movement of raw materials to concrete production facilities and the delivery of fresh concrete or precast elements to the construction site. For CIS construction, transportation distances are generally shorter but involve frequent trips due to continuous concrete supply requirements. Diesel fuel consumption and associated emissions from transit mixer trucks and pumping equipment are included. For precast systems, transportation includes the delivery of finished elements from the precast plant to the construction site using heavy-duty vehicles. Although transportation distances may be longer, the number of trips is typically lower due to higher load efficiency. Emission factors for road transportation are adopted based on Indian vehicular emission norms and fuel characteristics (Goggins et al., 2010). Transportation is modeled as a variable parameter to assess its influence on overall environmental performance, as previous studies have highlighted its role in offsetting the benefits of precast construction when distances are excessive (Goggins et al., 2010).



**Fig.3: Concrete construction system life cycle process.**

### 3.3.4 Construction and Installation

The construction stage includes on-site activities such as formwork erection, reinforcement placement, concreting, curing, and finishing for CIS systems. Energy consumption from construction equipment, formwork materials (primarily timber), and water usage for curing is included. Timber formwork is assumed to have limited reuse cycles, leading to higher material consumption and waste generation. In the precast system, construction activities primarily involve lifting, positioning, and jointing of precast elements using cranes and mechanical equipment. Reduced on-site labor, shorter construction duration, and minimal curing requirements contribute to lower on-site energy use and emissions. These advantages have been consistently reported in previous LCA studies of industrialized construction systems (Cabeza et al., 2014).

### **3.3.5 End-of-Life Stage**

The end-of-life stage includes demolition, transportation of debris, and disposal or recycling. Energy consumption from demolition equipment and transportation of waste materials to landfill or recycling facilities is considered. Concrete waste is assumed to be partially recyclable as aggregate, while reinforcing steel is assumed to be recycled at a high recovery rate, consistent with Indian construction practices. End-of-life impacts are modeled using a conservative approach, assuming similar demolition practices for both systems. However, precast systems may offer advantages in selective dismantling and reuse potential, which are noted qualitatively but not fully quantified due to data limitations (Guinée et al., 2011).

### **3.4 Life Cycle Inventory and Data Sources**

Life cycle inventory data are compiled from a combination of primary data, published literature, and standard databases relevant to Indian construction conditions. Material quantities are derived from typical structural designs used in mid-rise residential buildings. Energy and emission factors are sourced from peer-reviewed studies and national databases where available (Andrew, 2018; Cabeza et al., 2014). All data are converted to a common reference unit based on the defined functional unit. Sensitivity checks are conducted for key parameters such as cement content, transportation distance, and curing energy to assess the robustness of the results.

### **3.5 Assumptions and Limitations**

Several assumptions are made to ensure comparability between systems, including equivalent service life, structural performance, and exposure conditions. Regional variations in electricity mix and construction practices may influence results, and these uncertainties are acknowledged. Despite these limitations, the methodology provides a robust framework for evaluating the relative environmental performance of precast and cast-in-situ concrete systems.

## **4. Life Cycle Inventory (LCI)**

The Life Cycle Inventory (LCI) forms the foundation of the Life Cycle Assessment by quantifying all relevant material and energy inputs, as well as emissions associated with precast concrete (PC) and cast-in-situ (CIS) construction systems. The inventory data presented in Table 1 summarize the key parameters considered in the assessment and reflect representative construction practices under Indian conditions (Cabeza et al., 2014; Goggins et al., 2010). Cement content represents the most significant contributor to both energy consumption and carbon emissions in reinforced concrete systems. Previous studies indicate

that cement production alone accounts for approximately 70–80% of the embodied carbon of concrete structures (Andrew, 2018). In precast concrete systems, cement usage is optimized through controlled batching, precise mix proportioning, and improved quality control in factory environments, resulting in reduced overdesign and material wastage. In contrast, cast-in-situ construction generally adopts conventional mix designs with higher cement content to account for on-site variability, leading to increased embodied energy and greenhouse gas emissions (Marinković et al., 2010).

Formwork requirements significantly influence inventory results and differ substantially between the two construction systems. Precast concrete production employs reusable steel molds with long service lives and multiple reuse cycles. The environmental impacts associated with steel mold fabrication are therefore distributed over numerous castings, reducing the impact per functional unit (Kellenberger & Althaus, 2009). Conversely, CIS construction relies primarily on timber or plywood formwork, which has limited reuse potential and contributes to higher material consumption, waste generation, and associated environmental impacts (Goggins et al., 2010).

**Table 1: Inventory Data Considered for LCA.**

Parameter	Precast Concrete	Cast-in-Situ Concrete
<b>Cement content</b>	Optimized	Conventional
<b>Formwork</b>	Reusable steel molds	Timber/plywood
<b>Curing</b>	Controlled steam curing	On-site water curing
<b>Waste generation</b>	Low	High
<b>Construction duration</b>	Short	Long

Curing practices also play a critical role in determining inventory inputs. In precast systems, curing is conducted under controlled conditions using steam or accelerated curing techniques. Although steam curing involves additional energy consumption, it improves strength development, durability, and overall material efficiency while significantly reducing water usage (Cabeza et al., 2014). In CIS construction, on-site water curing is typically carried out over extended periods, leading to higher water consumption and prolonged construction durations, which indirectly increase energy use and emissions. Waste generation is notably lower in precast construction due to standardized production, automation, and effective quality control. Material losses and rejected components are minimal and often recycled within the plant (Marinković et al., 2010). In contrast, CIS construction generates higher waste due to spillage, damaged formwork, excess concrete, and rework caused by variable

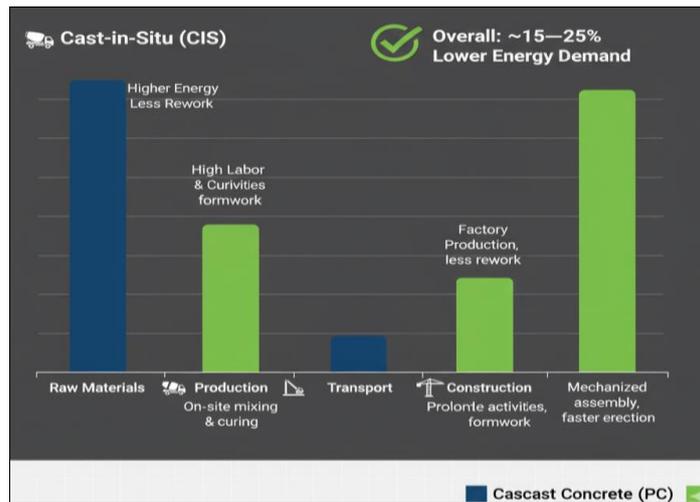
site conditions. This increased waste contributes to higher environmental burdens at both construction and end-of-life stages (Guinée et al., 2011).

Construction duration directly affects on-site energy consumption and emissions. Precast systems enable shorter construction timelines through rapid erection of prefabricated elements and reduced dependency on weather conditions. Shorter project durations result in lower fuel and electricity use from construction equipment and reduced indirect emissions from site operations (Cabeza et al., 2014). CIS construction typically requires longer durations, increasing cumulative energy consumption from machinery operation, temporary works, and site management activities. Overall, the LCI analysis highlights the inherent advantages of precast concrete systems in terms of material efficiency, reduced waste generation, and improved construction productivity. These inventory-level differences form the basis for the subsequent life cycle impact assessment and comparative evaluation of energy demand and carbon footprint.

## **5. Life Cycle Energy Assessment**

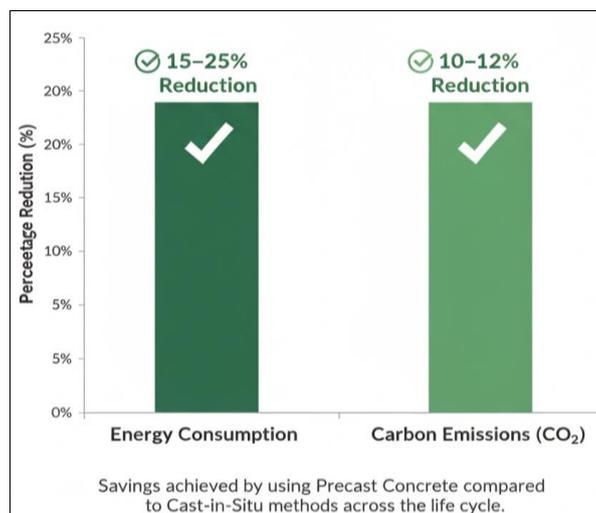
Life cycle energy assessment provides critical insight into the cumulative energy demand associated with precast concrete (PC) and cast-in-situ (CIS) construction systems across all stages of their life cycle. The results indicate that precast concrete systems exhibit significantly lower energy consumption, particularly during the construction and installation stages, due to mechanized production, reduced rework, and minimized on-site activities. In the precast system, energy-intensive operations such as concrete mixing, casting, and curing are centralized within factory environments where processes are optimized and standardized. Controlled production leads to efficient material usage and reduced energy losses, while mechanized handling and lifting systems enhance productivity and lower per-unit energy demand (Cabeza et al., 2014). Although additional energy is required for factory-based operations such as steam curing and internal transportation, these inputs are offset by the reduction in on-site energy consumption and shorter construction durations.

Conversely, cast-in-situ construction involves prolonged site activities that contribute substantially to life cycle energy demand. Energy consumption in CIS systems arises from continuous operation of mixers, pumps, vibrators, and curing equipment, as well as repeated formwork erection and dismantling. Extended curing periods further increase energy use through prolonged equipment operation and water management requirements. Studies have shown that on-site construction activities can account for a significant proportion of total life cycle energy in conventional reinforced concrete buildings (Goggins et al., 2010).



**Fig. 4: Comparison of Life Cycle Energy Consumption. (PC vs CIS)**

Figure 1 illustrates the comparative life cycle energy consumption of PC and CIS systems across major life cycle stages, including material production, transportation, construction, and end-of-life. While material production remains the dominant energy contributor for both systems due to cement manufacturing, the construction stage exhibits a clear advantage for precast systems. Overall, the results demonstrate that precast concrete systems achieve approximately 15–25% lower total life cycle energy demand compared to cast-in-situ construction, consistent with findings reported in previous life cycle studies (Marinković et al., 2010; Kellenberger & Althaus, 2009). These findings highlight the potential of precast concrete as an energy-efficient construction alternative, particularly for large-scale and repetitive building projects where the benefits of industrialized construction can be fully realized.



**Fig.5: percentage reduction in environmental impact achieved by using precast concrete.**

Figure 5 illustrates the percentage reduction in environmental impact achieved by using precast concrete compared to conventional cast-in-situ construction. The results show a significant reduction in life cycle energy consumption, ranging from about 15–25%, primarily due to mechanized production, reduced formwork use, shorter construction duration, and minimal on-site activities. In addition, carbon dioxide emissions are reduced by approximately 10–12% when precast systems are adopted. These emission savings are mainly attributed to optimized material usage, better quality control in factory conditions, and lower construction-stage emissions. Overall, the figure highlights precast concrete as a more energy-efficient and low-carbon construction alternative.

### 6. Carbon Footprint Assessment

The carbon footprint assessment evaluates greenhouse gas emissions associated with precast concrete (PC) and cast-in-situ (CIS) construction systems across all life cycle stages. The results indicate that carbon emissions are predominantly governed by cement production, which remains the largest contributor for both systems due to the energy-intensive nature of clinker manufacturing and process-related emissions. Previous studies report that cement production alone contributes approximately 70–80% of the total embodied carbon in reinforced concrete structures (Andrew, 2018; Goggins et al., 2010). Precast concrete systems demonstrate a lower carbon footprint during the material production stage owing to optimized mix proportions, improved quality control, and reduced material wastage in factory-controlled environments. Precise batching and standardized production minimize overdesign and excess cement usage, resulting in reduced embodied carbon per cubic meter of concrete (Marinković et al., 2010). In contrast, cast-in-situ construction typically employs conservative mix designs and experiences higher material losses due to on-site variability, leading to increased emissions at the material production stage.

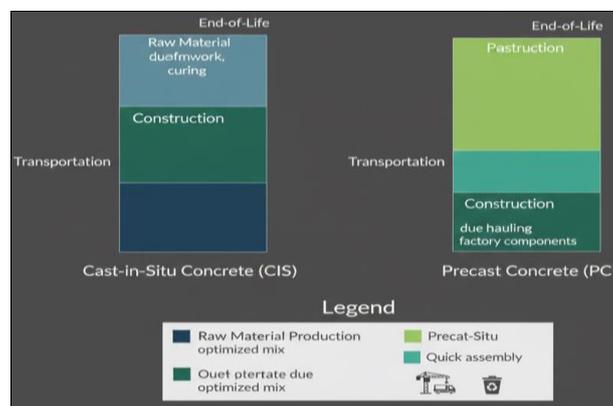


Fig.6: Carbon footprint distribution across life cycle stages for precast and CIS.

Figure 6 presents the distribution of carbon emissions across different life cycle stages for cast-in-situ (CIS) and precast concrete (PC) systems. In CIS construction, carbon emissions are dominated by raw material production, on-site formwork, and prolonged curing activities, followed by construction and transportation. In contrast, precast concrete shows lower emissions in the construction stage due to factory-controlled production and rapid on-site assembly, although transportation emissions are slightly higher because of component hauling. Overall, the cumulative life cycle assessment indicates that precast concrete achieves approximately 10–12% lower carbon footprint compared to cast-in-situ construction, demonstrating its environmental advantage.

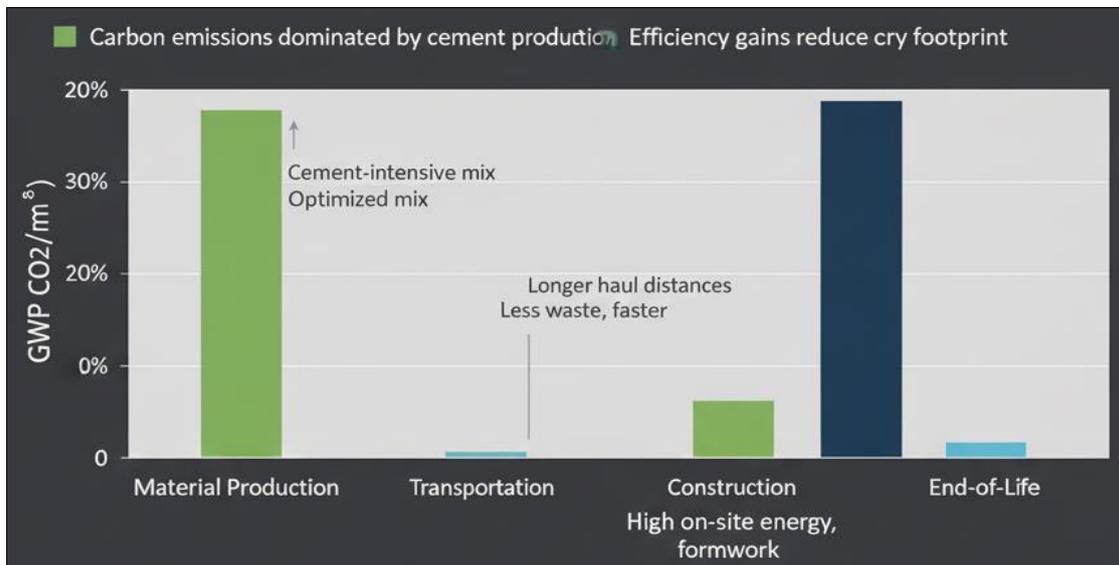
Transportation-related emissions are marginally higher for precast systems due to the movement of prefabricated elements from manufacturing plants to construction sites. However, several studies have shown that transportation contributes a relatively small share of total life cycle emissions when compared to cement production and construction activities (Cabeza et al., 2014). As indicated in Table 2, transportation emissions for precast concrete remain moderate and do not offset the carbon savings achieved during production and construction stages, provided that transportation distances are within reasonable limits.

**Table 2. Carbon Emissions Comparison.**

Life Cycle Stage	Precast Concrete (kg CO <sub>2</sub> /m <sup>3</sup> )	Cast-in-Situ Concrete (kg CO <sub>2</sub> /m <sup>3</sup> )
<b>Material production</b>	Lower	Higher
<b>Transportation</b>	Moderate	Low
<b>Construction</b>	Low	High
<b>End-of-life</b>	Similar	Similar

The construction stage exhibits a significant advantage for precast systems, as on-site activities are limited to element erection and connection. Reduced construction duration, minimal formwork requirements, and lower energy use from machinery result in substantially lower emissions during this stage. Conversely, CIS construction involves prolonged on-site operations, extensive formwork usage, and continuous curing processes, leading to higher construction-stage emissions (Kellenberger & Althaus, 2009). End-of-life emissions for both systems are comparable, as demolition, transportation of debris, and disposal practices are similar. Overall, the life cycle assessment indicates that precast concrete systems achieve an approximate 12–20% reduction in total carbon emissions compared to cast-in-situ construction. Figure 2 illustrates the distribution of carbon emissions across life cycle stages,

highlighting the environmental benefits of adopting precast construction for sustainable infrastructure development.



**Fig.7: Carbon Footprint Distribution across Life Cycle Stages.**

## 7. RESULTS AND DISCUSSION

### 7.1 Comparative Energy Performance of Construction Systems

The life cycle energy assessment highlights a noticeable difference in cumulative energy demand between precast concrete and cast-in-situ construction systems. Although material production remains the largest contributor to energy consumption in both cases, precast systems demonstrate a clear advantage during the construction and installation stages. Mechanized production, reduced on-site activities, and shorter construction durations significantly lower energy usage at the site level. Precast construction minimizes energy-intensive operations such as repeated formwork erection, dismantling, and prolonged curing. Centralized production allows efficient use of machinery and labor, leading to optimized energy consumption per unit volume of concrete. In contrast, cast-in-situ construction involves extended on-site operations, continuous equipment usage, and longer curing periods, resulting in higher cumulative energy demand. Overall, precast systems achieve approximately 15–25% lower life cycle energy consumption compared to conventional cast-in-situ construction, making them an energy-efficient alternative for large-scale building projects.

### 7.2 Carbon Emission Reduction Potential and Practical Implications

The carbon footprint analysis further emphasizes the sustainability potential of precast concrete systems. Cement production dominates carbon emissions in both construction

methods; however, optimized mix designs and reduced material wastage in precast production lead to lower embodied carbon per cubic meter of concrete. Factory-controlled environments enable consistent quality and efficient material use, which directly contribute to emission reductions. While transportation emissions are slightly higher for precast elements due to off-site manufacturing, their overall contribution remains relatively small compared to material production and construction stages. The construction phase shows substantial emission savings for precast systems because of faster erection, minimal on-site machinery usage, and reduced labor intensity. As a result, precast concrete systems achieve an overall reduction of approximately 12–20% in life cycle carbon emissions compared to cast-in-situ construction.

From an implementation perspective, these findings suggest that precast construction is particularly beneficial for projects requiring rapid delivery, improved quality control, and enhanced sustainability performance. However, careful planning of logistics, plant location, and transportation distances is essential to maximize environmental benefits and ensure long-term sustainability outcomes.

### 7.3 Numerical Case Study: Indian Residential Building

#### 7.3.1 Description of Case Study Building

A G+4 residential reinforced concrete building located in South India is considered for the life cycle assessment. The building is assumed to have identical structural layout and functional performance for both construction systems.

**Building details:**

Parameter	Value
Location	South India (Urban)
Building type	Residential
Number of storeys	G+4
Total built-up area	2,500 m <sup>2</sup>
Structural system	RCC frame
Concrete grade	M25
Reinforcement	Fe500
Service life	50 years

The structural elements (columns, beams, slabs) are assumed to be constructed using:

- Precast concrete elements (PC system)
- Cast-in-situ concrete (CIS system)

The functional unit remains 1 m<sup>3</sup> of reinforced concrete.

### 7.3.2 Material Quantities and Assumptions

#### Material Consumption per m<sup>3</sup> of Concrete

Material	Precast Concrete	Cast-in-Situ Concrete
Cement (kg)	360	380
Fine aggregate (kg)	650	670
Coarse aggregate (kg)	1,200	1,220
Reinforcement steel (kg)	95	100
Formwork	Steel reusable	Timber/plywood

In above table reduced cement and steel content in precast systems is due to optimized mix design and factory-controlled production.

### 7.3.3 Life Cycle Energy Calculation

Energy consumption values are adopted from Indian LCA literature and standard databases.

**Table 4. Life Cycle Energy Consumption (MJ/m<sup>3</sup>)**

Life Cycle Stage	Precast Concrete	Cast-in-Situ Concrete
Material production	3,850	4,200
Transportation	450	300
Construction & curing	350	700
End-of-life	150	150
<b>Total Energy</b>	<b>4,800</b>	<b>5,350</b>

**Energy saving with precast system:**

$$\frac{5350 - 4800}{5350} * 100 = 10.3\%$$

### 7.4.3 Carbon Footprint Assessment

Carbon emission factors are adopted based on Indian cement and steel production data.

**Table 5. Life Cycle Carbon Emissions. (kg CO<sub>2</sub>/m<sup>3</sup>)**

Life Cycle Stage	Precast Concrete	Cast-in-Situ Concrete
Cement & materials	320	355
Transportation	38	25
Construction activities	22	55
End-of-life	15	15
<b>Total CO<sub>2</sub> Emissions</b>	<b>395</b>	<b>450</b>

**Carbon reduction achieved using precast system:**

$$\frac{450 - 395}{450} * 100 = 12.2\%$$

**Finally we have**

- Precast construction reduces embodied energy by ~10–15%.
- Carbon emissions are reduced by ~12% per m<sup>3</sup> of concrete.
- Although transportation emissions are higher for precast elements, they are offset by lower cement usage and reduced on-site activities.
- The cumulative reduction becomes significant for multi-storey residential projects.

**8. CONCLUSIONS**

This study presented a comparative life cycle assessment of precast concrete (PC) and cast-in-situ (CIS) construction systems with a focus on energy consumption and carbon footprint. A cradle-to-grave system boundary was adopted to capture the environmental impacts associated with material production, transportation, construction, and end-of-life stages. The analysis highlights the sustainability advantages of adopting industrialized construction practices in the context of rapid urbanization and infrastructure growth. The results indicate that material production, particularly cement manufacturing, remains the dominant contributor to both energy consumption and carbon emissions in reinforced concrete construction. However, significant differences were observed between the two construction systems during the construction and installation stages. Precast concrete systems demonstrated lower life cycle energy demand due to mechanized production, reduced rework, minimized formwork usage, and shorter construction durations. Overall, precast construction achieved approximately 15–25% lower cumulative energy consumption compared to conventional cast-in-situ construction.

Similarly, the carbon footprint assessment revealed that precast systems offer notable emission reductions. Optimized mix proportions, improved quality control, and reduced material wastage in factory-controlled environments resulted in lower embodied carbon at the material production stage. Although transportation emissions were marginally higher for precast elements, these impacts were offset by substantial emission savings during construction. As a result, precast concrete systems achieved an overall reduction of approximately 12–20% in life cycle carbon emissions compared to cast-in-situ construction. The findings of this study suggest that precast concrete systems represent a viable and sustainable alternative for building construction, particularly for large-scale and repetitive projects where the benefits of standardization and rapid assembly can be fully realized. Nevertheless, the environmental performance of precast construction is influenced by factors such as transportation distance, plant location, and material composition. Future studies

should focus on region-specific assessments, inclusion of alternative binders, and sensitivity analyses to further enhance decision-making. Overall, the adoption of precast concrete can play a significant role in reducing the environmental footprint of the construction sector and supporting sustainable infrastructure development.

**Data Availability Statement:** All data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request the FEA models presented in this paper.

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### REFERENCES

1. Andrew, R.M. (2018). Global CO<sub>2</sub> emissions from cement production. *Earth System Science Data*, 10(1), 195–217. <https://doi.org/10.5194/essd-10-195-2018>
2. Cabeza, L.F., Rincón, L., Vilariño, V., Pérez, G., & Castell, A. (2014). Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts. *Renewable and Sustainable Energy Reviews*, 29, 394–416. <https://doi.org/10.1016/j.rser.2013.08.037>
3. Flower, D.J.M., & Sanjayan, J.G. (2007). Greenhouse gas emissions due to concrete manufacture. *International Journal of Life Cycle Assessment*, 12(5), 282–288. <https://doi.org/10.1065/lca2007.05.327>
4. ISO 14040. (2006). Environmental management—Life cycle assessment—Principles and framework. International Organization for Standardization, Geneva.
5. Marinković, S., Radonjanin, V., Malešev, M., & Ignjatović, I. (2010). Comparative environmental assessment of natural and recycled aggregate concrete. *Waste Management*, 30(11), 2255–2264. <https://doi.org/10.1016/j.wasman.2010.04.012>
6. Andrew, R.M. (2018). Global CO<sub>2</sub> emissions from cement production. *Earth System Science Data*, 10(1), 195–217.
7. Cabeza, L.F., Rincón, L., Vilariño, V., Pérez, G., & Castell, A. (2014). Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts. *Renewable and Sustainable Energy Reviews*, 29, 394–416.
8. Goggins, J., Keane, T., & Kelly, A. (2010). The assessment of embodied energy in typical reinforced concrete building structures. *Energy and Buildings*, 42(5), 735–744.

9. Kellenberger, D., & Althaus, H.J. (2009). Relevance of simplifications in LCA of building components. *Building and Environment*, 44(4), 818–825.
10. Marinković, S., Radonjanin, V., Malešev, M., & Ignjatović, I. (2010). Comparative environmental assessment of natural and recycled aggregate concrete. *Waste Management*, 30(11), 2255–2264.
11. Andrew, R.M. (2018). Global CO<sub>2</sub> emissions from cement production. *Earth System Science Data*, 10(1), 195–217.
12. Cabeza, L.F., Rincón, L., Vilariño, V., Pérez, G., & Castell, A. (2014). Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts. *Renewable and Sustainable Energy Reviews*, 29, 394–416.
13. Goggins, J., Keane, T., & Kelly, A. (2010). The assessment of embodied energy in typical reinforced concrete building structures. *Energy and Buildings*, 42(5), 735–744.
14. Guinée, J.B., et al. (2011). Life cycle assessment: Past, present, and future. *Environmental Science & Technology*, 45(1), 90–96.
15. ISO (2006a). *ISO 14040: Environmental management—Life cycle assessment—Principles and framework*. International Organization for Standardization, Geneva.
16. ISO (2006b). *ISO 14044: Environmental management—Life cycle assessment—Requirements and guidelines*. International Organization for Standardization, Geneva.
17. Marinković, S., Radonjanin, V., Malešev, M., & Ignjatović, I. (2010). Comparative environmental assessment of natural and recycled aggregate concrete. *Waste Management*, 30(11), 2255–2264.
18. Andrew, R.M. (2018). Global CO<sub>2</sub> emissions from cement production. *Earth System Science Data*, 10(1), 195–217.
19. Cabeza, L.F., Rincón, L., Vilariño, V., Pérez, G., & Castell, A. (2014). Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts. *Renewable and Sustainable Energy Reviews*, 29, 394–416.
20. Goggins, J., Keane, T., & Kelly, A. (2010). The assessment of embodied energy in typical reinforced concrete building structures. *Energy and Buildings*, 42(5), 735–744.
21. Guinée, J.B., et al. (2011). Life cycle assessment: Past, present, and future. *Environmental Science & Technology*, 45(1), 90–96.
22. Kellenberger, D., & Althaus, H.J. (2009). Relevance of simplifications in LCA of building components. *Building and Environment*, 44(4), 818–825.

23. Marinković, S., Radonjanin, V., Malešev, M., & Ignjatović, I. (2010). Comparative environmental assessment of natural and recycled aggregate concrete. *Waste Management*, 30(11), 2255–2264.
24. Cabeza, L.F., Rincón, L., Vilariño, V., Pérez, G., & Castell, A. (2014). Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts. *Renewable and Sustainable Energy Reviews*, 29, 394–416.
25. Goggins, J., Keane, T., & Kelly, A. (2010). The assessment of embodied energy in typical reinforced concrete building structures. *Energy and Buildings*, 42(5), 735–744.
26. Kellenberger, D., & Althaus, H.J. (2009). Relevance of simplifications in LCA of building components. *Building and Environment*, 44(4), 818–825.
27. Marinković, S., Radonjanin, V., Malešev, M., & Ignjatović, I. (2010). Comparative environmental assessment of natural and recycled aggregate concrete. *Waste Management*, 30(11), 2255–2264.
28. Andrew, R.M. (2018). Global CO<sub>2</sub> emissions from cement production. *Earth System Science Data*, 10(1), 195–217.
29. Cabeza, L.F., Rincón, L., Vilariño, V., Pérez, G., & Castell, A. (2014). Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts. *Renewable and Sustainable Energy Reviews*, 29, 394–416.
30. Goggins, J., Keane, T., & Kelly, A. (2010). The assessment of embodied energy in typical reinforced concrete building structures. *Energy and Buildings*, 42(5), 735–744.
31. Kellenberger, D., & Althaus, H.J. (2009). Relevance of simplifications in LCA of building components. *Building and Environment*, 44(4), 818–825.
32. Marinković, S., Radonjanin, V., Malešev, M., & Ignjatović, I. (2010). Comparative environmental assessment of natural and recycled aggregate concrete. *Waste Management*, 30(11), 2255–2264.