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Comparative Analysis of Carbon Emissions Between Precast Concrete and Cast-In-Place Methods

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Abstract: The construction sector significantly contributes to global carbon emissions, underscoring the need for strategies that balance development with sustainability. Precast concrete offers a potential alternative to reduce carbon emissions while improving cost efficiency and implementation time. This study aims to analyze the extent to which carbon emission reductions and cost efficiencies can be achieved by comparing precast and cast-in-place concrete construction methods. The analysis is based on a case study of the Klungkung District Attorney's Office, Bali Province. It compares the environmental impacts, particularly carbon emissions, and construction costs of the two methods. The study considers total CO_2 emissions, material efficiency, transportation, energy consumption, and equipment use, employing a quantitative descriptive approach that integrates both primary and secondary data. The results show that the precast method produces 24% lower carbon emissions than the cast-in-place method, with total emissions amounting to 134 tons of CO_2. This reduction is attributed to lower material losses and the efficiency of the fabrication process.

Keywords: carbon emissions, cast-in-place concrete, material efficiency, precast concrete, sustainable construction.

INTRODUCTION

Global climate change is a major challenge with far-reaching impacts on human health, the environment, and the economy. The increase in global temperatures is largely driven by greenhouse gas emissions from five main sectors: energy, industry, construction, transportation, and AFOLU (*agriculture, forestry, and other land use*) (Lamb et al., 2021). In 2023, atmospheric CO_2 concentrations reached a record high of 420 ppm—an increase of 2.8 ppm from the previous year—marking the fourth-largest annual rise since 1950 (WMO, 2025).

The construction sector is a significant contributor to global carbon emissions, particularly through cement production and the combustion of fossil fuels (Monahan & Powell, 2011). The production, transportation, and installation of building components generate substantial carbon emissions during construction activities (Ramesh et al., 2010). Therefore, transitioning to sustainable construction methods is a key priority to support climate change mitigation and low-carbon development (Liu et al., 2020; Milberg & Tommelein, 2020; Wang & Liu, 2024; Zheng et al., 2023; Zhu et al., 2023).

Sustainable infrastructure development plays a strategic role in driving economic growth while minimizing the environmental impact of the construction sector. In line with Sustainable Development Goals (SDGs) 9 and 13, the application of environmentally friendly technologies and innovations, such as *precast* construction systems, contributes to increased resource efficiency, reduced carbon emissions, and the acceleration of low-carbon development. Integrating sustainability principles also enhances the competitiveness of the national construction industry and supports climate change mitigation efforts (Li & Zheng, 2020; J. Lim & Kim, 2020; Mohebbi et al., 2023; Yang et al., 2013).

The *precast* construction system is considered more efficient and environmentally friendly than conventional methods. By shifting most construction processes to a controlled factory environment, this method can reduce waste, save energy, and lower carbon emissions by up to 20.11% per volume of concrete (Ding et al., 2020). Additionally, *precast* methods can reduce material consumption by up to 55% for concrete and 40% for steel, while also accelerating project completion times.

Indonesia has committed to achieving carbon neutrality by 2060, as declared at COP26 in 2021 (IEA, 2022), with an interim goal of a 29% emission reduction by 2030 (Ministry of Energy and Mineral Resources, 2021). In support of this target, the Bali Provincial Government has introduced the "Bali Net Zero Emission" program to achieve carbon neutrality by 2045. This initiative, grounded in Bali Governor Regulation No. 45 of 2019 on Clean Energy, represents a significant milestone in the province's journey toward sustainable development.

However, the large-scale implementation of *precast* concrete often faces challenges due to significant increases in construction costs, which can hinder companies' ability to reduce carbon emissions through this method.

Two influential studies provide important benchmarks yet leave gaps that this research seeks to address. Jaillon, Dong, and Poon (2016) conducted a life cycle assessment (LCA) comparing *precast* and *cast-in-situ* concrete in a residential building in Hong Kong and found that *precast* facades reduce carbon emissions by about 6.3% over the cradle-to-construction phase, illustrating environmental benefit albeit modest in scale. Dong et al. (2020) further estimated that *precast* methods can cut emissions by up to 20.11% per concrete volume compared to *cast-in-place*, attributed to factory control, reduced waste, and efficient material use. While these works convincingly demonstrate emissions reductions under controlled comparisons, they typically focus on narrow case studies or component-level analysis and often underplay cost implications, regional material constraints, and implementation barriers in developing contexts. Moreover, few studies rigorously optimize trade-offs between carbon reduction and cost escalation in large-scale concrete construction.

This study aims to identify optimal strategies for reducing carbon emissions in concrete construction as a contribution to promoting more sustainable construction practices in Indonesia. The benefit is to provide decision-makers and practitioners with evidence-based, implementable guidance to accelerate low-carbon construction in support of Indonesia's carbon neutrality targets.

MATERIALS AND METHOD

The research was conducted at the Klungkung District Attorney's Office in Klungkung Regency, Bali Province. The building occupied a land area of 652.96 m^2, with a total building area of 1,655.46 m^2.

The study began by collecting CO_2 emission data generated during the production and construction phases of both precast and cast-in-place concrete. CO_2 emission values were selected from multiple database sources to improve the accuracy of the estimates. The analysis involved reviewing published studies and data inventories from relevant institutions to assess emissions from key materials such as concrete, steel, and vehicle fuels. This process also included converting energy consumption data, such as diesel fuel and electricity, into CO_2 emission estimates based on the use of heavy equipment and machinery at the construction site.

Table 1. Sources and Emissions of CO_2 Generated at Each Stage of Construction

Emission Sources	**Description**	**CO_2 Emission**	**Reference**	**Applied Method**
Material	Production of Ready-mix Concrete	340.9 kg CO_2/m^3	(Kim et al., 2016)	Precast, Cast-in-Place
	Production of steel bar	4,002.04 kg CO_2/ton	(Lee et al., 2012)	Precast, Cast-in-Place
Transportation (Vehicle)	Heavy Duty Trucks (Rigid <=7.5t)	0.32 kg CO_2/km	Fuel consumption factors 102 (g/km) (Papadimitriou et al., 2013)	Cast-in-Place
	Heavy Duty Trucks (Rigid 12-14t)	0.46 kg CO_2/km	Fuel consumption factors 148 (g/km) (Papadimitriou et al., 2013)	Precast, Cast-in-Place
	Heavy Duty Trucks (Rigid 14-20t)	0.54 kg CO_2/km	Fuel consumption factors 173 (g/km) (Papadimitriou et al., 2013)	Precast, Cast-in-Place
	Heavy Duty Trucks (Rigid 20-26t)	0.66 kg CO_2/km	Fuel consumption factors 209 (g/km) (Papadimitriou et al., 2013)	Precast
	Kapal Ro-Ro (Roll-On/Roll-Off)	0.02 kg CO_2/ton-km	(Mckinnon & Piecyk, 2010)	Precast, Cast-in-Place
Concrete and Rebar Prefabrication Activities for concrete and rebar (factory use)	Fuel (Diesel)	10.16 kg CO_2/ gallon (2.68 kg CO_2/liter)	U.S. Energy Information Administration Estimates (EIA, 2023)	Precast
	Electricity factor	0.84 kg CO_2/kWh	(Febijanto, 2016)	Precast
On-site placement activities	Onsite placement activities (fuel, pumping, vibration)	9 kg CO_2/m^3	(Ghayeb et al., 2020) (Flower & Sanjayan, 2007)	Cast-in-Place
Equipment on-site installation	Mobile crane 50t	41.5 kg CO_2/hour	(T.-K. Lim et al., 2016)	Precast

The basic principle of calculating embodied carbon is to multiply the quantity of each material or product by the appropriate carbon factor for each relevant life cycle module. The formula is as follows:

$$Embodied\ Carbon = Quantity \times Carbon\ Factor \qquad (1)$$

The data collection process was conducted systematically through two main sources: primary data and secondary data. Once the data was collected, the study focused on three main criteria to compare precast and cast-in-place concrete construction.

First, material waste is assessed differently between precast and cast-in-place methods. This difference forms the basis for a comprehensive analysis of the case study, particularly in terms of material use efficiency. Second, transportation distance is analyzed to evaluate the logistical impact of both construction methods. This includes an assessment of transportation efficiency, which directly affects carbon emissions from material delivery activities. Third, the comparison considers energy consumption and equipment usage during the construction phase for both methods. This evaluation aims to quantify CO_2 emissions at each construction stage, thereby providing a deeper understanding of energy efficiency and the environmental impact of each approach.

The scenarios are developed to compare carbon emissions and costs between the use of precast and cast-in-place concrete. The scenarios address material waste, transportation (in terms of delivery distance and equipment usage), and the use of machinery during fabrication and installation. Table 2 presents an overview of the scenarios used as a guide for this case study. Each scenario is designed to highlight specific differences between the construction methods, providing a structured framework for environmental impact analysis.

Table 2. CO_2 Emission Comparison Scenarios

Emission Sources	Variation	Scenario Classification	Description of Scenario
Material	*Loss*	Precast	Concrete 3%, rebar 3%
		Cast-in-Place	Concrete 10%, rebar 5%
Transport (under normal conditions)	Distance	Precast	Ready mix concrete factory, supplier of reinforcing steel, and precast molds to the precast concrete factory location Precast concrete factory to project site
		Cast-in-Place	Ready mix concrete factory, supplier of reinforcing steel, formwork and scaffolding to project locations
Fabrication and Installation	Use of Equipment	Precast	Use of equipment in off-site prefabrication and installation of precast elements on site
		Cast-in-Place	Use of equipment for the fabrication and installation of cast-in-place concrete on site

RESULTS AND DISCUSSION

Material Loss

Table 3. Concrete and Reinforcement Volume and CO_2 Emission Calculation

Material	Volume		CO_2 Emissions Unit	CO_2 Emission kg CO_2	
	Precast	**Cast- in-Place**		**Precast (loss 3%)**	**Cast-in-Place (Concrete loss 10%, rebar loss 5%)**
Concrete (m^3)	358	452	340.9 kg CO_2/m^3 (Kim et al., 2016)	118,351	138,762
Rebar (ton)	72	102	4,002.04 kg CO_2/ton (Lee et al., 2012)	278,784	387,800
			Total CO_2 Emission	**397,135**	**526,562**

The results of the analysis show a difference in the total carbon dioxide (CO_2) emissions produced between the precast and cast-in-place construction methods. This difference reflects not only the variation in material volume but also the efficiency of material utilization and the level of waste generated during the construction process.

Based on the CO_2 emission calculations in this case study, the precast method results in lower emissions compared to the cast-in-place method. Total emissions for the precast method amount to 397,135 kg CO_2, while the cast-in-place method results in 526,562 kg CO_2. This represents a difference of 129,427 kg CO_2, or 25%, with the precast method generating lower emissions. The 25% reduction in emissions can be attributed to the material efficiency achieved through the precast process. In this method, fabrication is carried out in a controlled factory environment, allowing for the minimization of material waste.

Based on the analysis, it can be concluded that the precast construction method offers advantages over the cast-in-place method in terms of reducing carbon emissions associated with the use of primary materials, namely concrete and reinforcing steel. The efficient use of materials and lower levels of waste in the precast method directly contribute to a reduction in total carbon emissions.

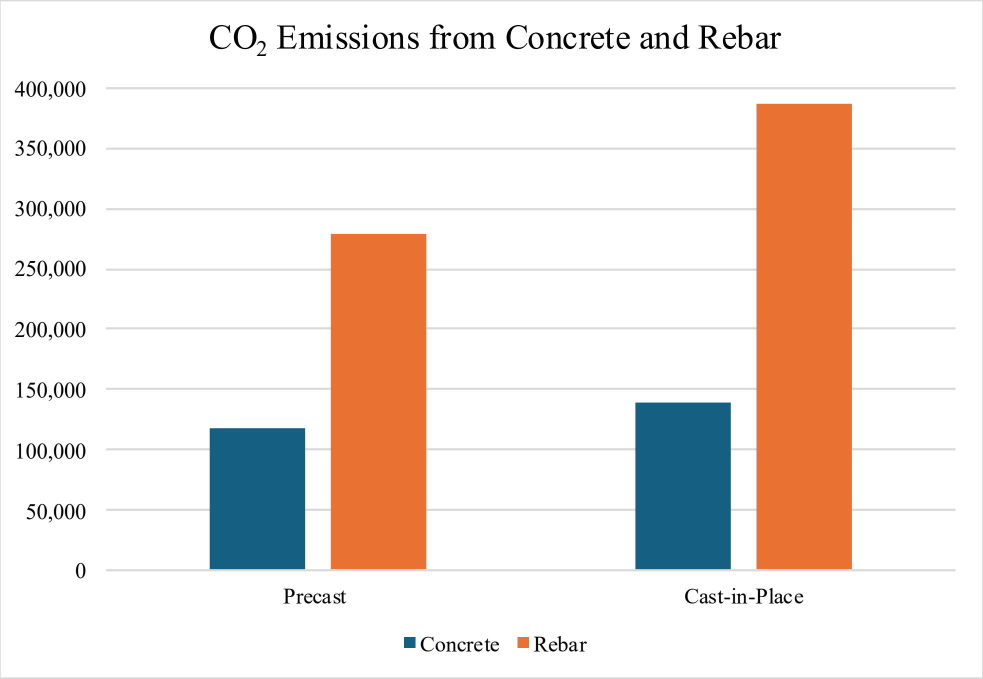

Figure 1. Comparison of CO_2 Emissions from Concrete and Rebar

Transportation

In this study, an analysis was conducted based on a transportation distance scenario reflecting actual site conditions. CO_2 emissions were estimated using real transportation distances to evaluate the environmental impact of the precast method compared to the cast-in-place method. This approach aims to assess the contribution of transportation distance to carbon emissions and to provide environmental considerations for selecting concrete construction methods.

In the precast system, the logistics flow is divided into two main stages: (1) the transportation of materials such as ready-mix concrete, reinforcing steel, and precast molds to the precast factory; and (2) the distribution of the precast elements, once cast, to the project site. Each stage involves different distances and uses various types of vehicles with varying capacities and fuel consumption rates.

In contrast, the cast-in-place method has a simpler logistics flow, as all materials—including ready-mix concrete, reinforcing steel, formwork, and scaffolding—are delivered directly from suppliers to the construction site. Although this system may appear more straightforward, it does not necessarily produce lower emissions, as larger shipment volumes are often required to accommodate higher levels of material loss.

Table 4. Precast CO_2 Emissions for Transportation by Distance

Vehicle	Material	Material Amount	Vehicle Capacity	CO_2 Emissions /vehicle	Vehicle Q'ty	Distance to site (km)	CO_2 Emission (kg CO_2)
Heavy Duty Trucks (Rigid 12-14t)	Ready Mix Concrete	358 m^3	6 m^3/ vehicle	0.46 kg CO_2/km (Papadimitriou et al., 2013)	60	21	586
Heavy Duty Trucks (Rigid 14-20t)	Rebar	72 ton	20 ton	0.54 kg CO_2/km (Papadimitriou et al., 2013)	4	427	928
Kapal Ro-Ro (Roll-On/Roll-Off)	Rebar	72 ton	733 ton	0.02 kg CO_2/km (Mckinnon & Piecyk, 2010)	1	4.5	5
Heavy Duty Trucks (Rigid 14-20t)	Precast mold	16 ton	20 ton	0.54 kg CO_2/km (Papadimitriou et al., 2013)	1	430	234
Ro-Ro Ship (Roll-On/Roll-Off)	Precast mold	16 ton	733 ton	0.02 kg CO_2/ton-km (Mckinnon & Piecyk, 2010)	1	4.5	1
Heavy Duty Trucks (Rigid 20-26t)	Precast Elements	903 ton	25 ton	0.66 kg CO_2/km (Papadimitriou et al., 2013)	37	16	389
					Total CO_2 Emission		**2,142**

Table 5. Cast-in-Place CO_2 Emissions for Transportation by Distance

Vehicle	Material	Material Amount	Vehicle Capacity	CO_2 Emissions /vehicle	Vehicle Q'ty	Distance to site (km)	CO_2 Emission (kg CO_2)
Heavy Duty Trucks (Rigid 12-14t)	Ready Mix Concrete	452 m^3	6 m^3 /vehicle	0.46 kg CO_2/km (Papadimitriou et al., 2013)	76	35	1,236
Heavy Duty Trucks (Rigid 14-20t)	Rebar	102 ton	20 ton	0.54 kg CO_2/km (Papadimitriou et al., 2013)	6	443	1,444
Ro-Ro Ship (Roll-On/Roll-Off)	Rebar	102 ton	733 ton	0.02 kg CO_2/ton-km (Mckinnon & Piecyk, 2010)	1	5	7
Heavy Duty Trucks (Rigid <=7.5t)	Formwork	46 ton	20 ton	0.54 kg CO_2/km (Papadimitriou et al., 2013)	3	30	49
Heavy Duty Trucks (Rigid <=7.5t)	Scaffolding	23 ton	7.5 ton	0.32 kg CO_2/km (Papadimitriou et al., 2013)	4	30	38
					Total CO_2 Emission		**2,775**

Based on the calculated results of carbon dioxide (CO_2) emissions from material transportation activities, there are notable differences between the precast and cast-in-place construction methods. In the precast system, the total emissions generated from all transportation activities amount to 2,142 kg CO_2, whereas in the cast-in-place system, total emissions reach 2,775 kg CO_2. This difference indicates that the cast-in-place method has a transportation-related carbon intensity approximately 30% higher than the precast method. The disparity is attributed to differences in vehicle types, the number of trips, and the distribution distances for materials.

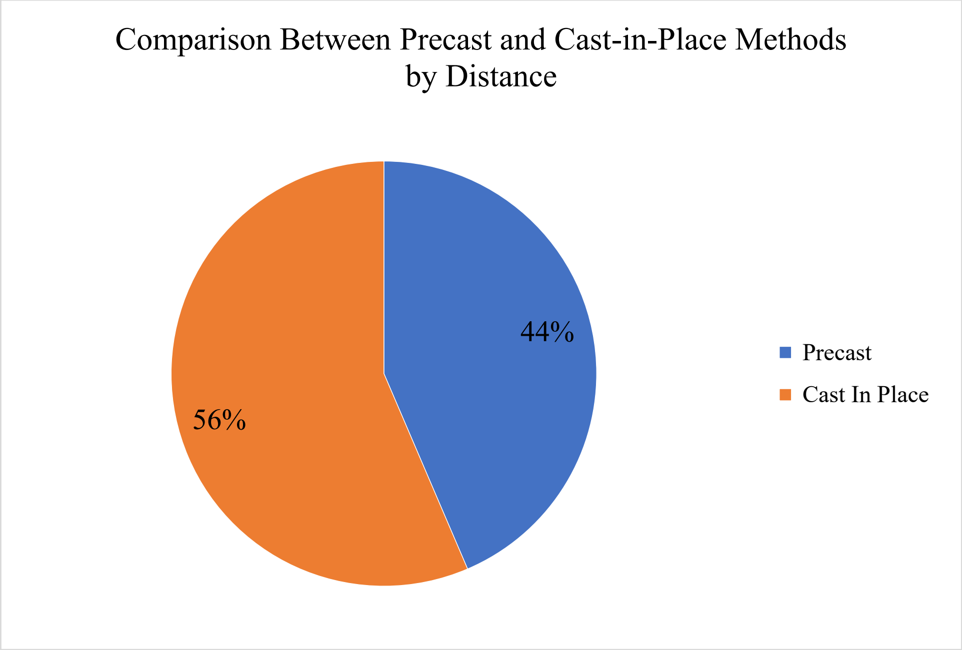

Figure 2. Comparison Between Precast and Cast-in-Place Methods by Distance

This study adopts a realistic logistics scenario to demonstrate that although the precast method involves a more complex transportation process, its potential for reducing material volume and minimizing material loss can offset, and even surpass, the emissions associated with the cast-in-place method. Therefore, evaluating the logistics system should be an integral part of the overall emissions assessment when analyzing the sustainability of construction methods—particularly since transportation is one of the major contributors to carbon emissions throughout a construction project's life cycle. Based on this analysis, it can be concluded that the precast method offers advantages in terms of transportation efficiency and is more environmentally friendly in the context of carbon emissions, especially when the project site is located relatively close to the precast plant and material suppliers.

Fabrication and Installation

Table 6. CO_2 Emissions for Fabrication and Installation of Precast

Activity	Evaluation	ECF (*Embodied Carbon Factor*)	CO_2 Emission (kg CO_2)	References/ Assumptions
Off-site prefabrication	903 ton (3% *loss for precast*)	[b] 8.94 kg CO_2/ton	8,068	Based on the total use of equipment utilities in the factory
Installation on site (mobile crane)	[a] 240 hour	41.5 kg CO_2/hour (*mobile crane* 50t)	9,960	2 months precast installation

Activity	Evaluation	ECF (*Embodied Carbon Factor*)	CO_2 Emission (kg CO_2)	References/ Assumptions
		Total CO_2 Emission	**18,028**	

[a] (4 hour/day x 30 day x 2 month) x 1 unit mobile crane = 240 hours

[b] (1) + (2) = 8.94 kg CO_2/ton

(1) Diesel: (0.5 liter (Ma et al., 2016)) x (2.68 kg CO_2/liter (EIA, 2023)) = 1.34 kg CO_2/ton

(2) Electricity: (9 kWh (Ma et al., 2016)) x (0.84 kg CO_2/ kWh (Febijanto, 2016)) = 7.6 kg CO_2/ton

Table 7. CO_2 Emissions for Fabrication and Installation of Cast-in-Place

Activity	Evaluation	ECF (Embodied Carbon Factor)	CO_2 Emission (kg CO_2)	References/ Assumptions
Fabrication on project site	1,074 ton (10% loss of concrete and 5% loss of rebar)	9 kg CO_2/m^3 (20.7 kg CO_2/ton) (Flower & Sanjayan, 2007; Ghayeb et al., 2020)	22,228	Including fuel, pump, vibrator
		Total CO_2 Emission	**22,228**	

Based on the calculation results derived from the assumed data scenario, the precast method produces 19% lower CO_2 emissions compared to the cast-in-place method. Several factors contribute to this difference. First, the disparity in the amount of material used in fabrication between the two methods, where the cast-in-place method exhibits a higher level of material loss in the base scenario. Second, the location of the fabrication process also influences energy consumption. In the precast method, energy is utilized in a controlled off-site environment, whereas the cast-in-place method is carried out directly on-site at the project location. Third, CO_2 emissions are also correlated with the overall construction duration and the sequence of activities. In the case studies analyzed, construction schedules and activity management may vary depending on field conditions. Generally, the cast-in-place method tends to have higher energy consumption due to longer fabrication and implementation times, although there are limitations regarding the accuracy of the estimates used.

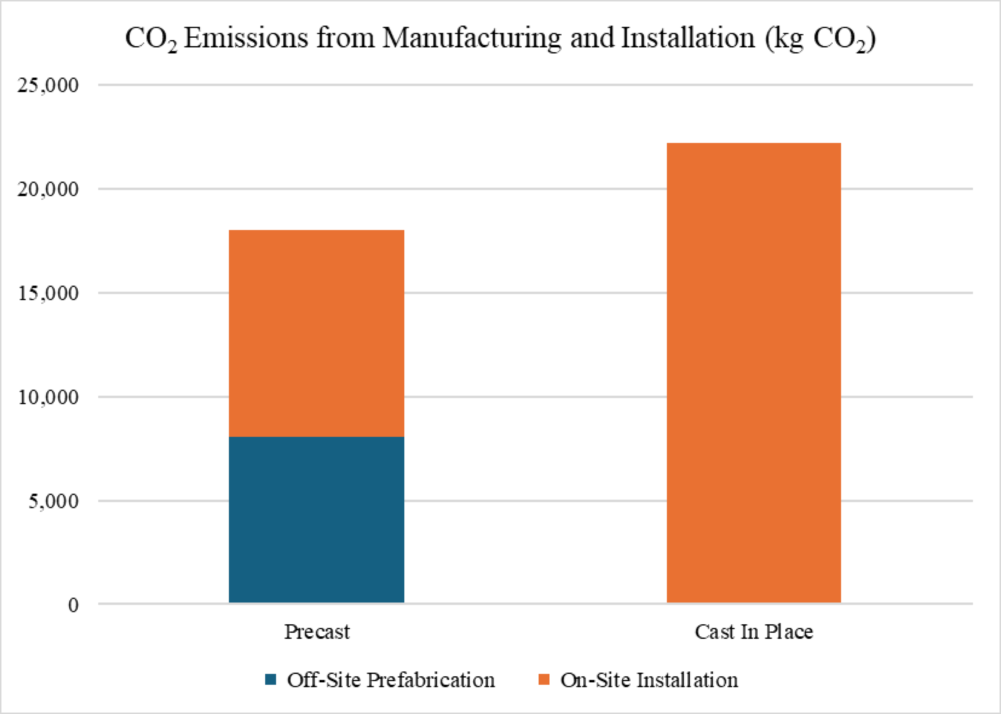

Figure 3. Comparison of CO_2 Emissions from Manufacturing and Installation

Comparison of Total Amount and Carbon Emission Ratio

The total CO_2 emissions in this case study are compared and illustrated in Figure 4. The evaluation was conducted based on several criteria, namely material loss, transportation distance, fabrication method (off-site or on-site), and installation processes.

Table 8. Recapitulation of CO_2 Emission Calculation Evaluation (kg CO_2)

Activity	Description	Precast (kg CO_2)	Cast-in-Place (kg CO_2)
Material	Concrete	118,351	138,762
	Rebar	278,784	387,800
Transportation	Heavy Duty Trucks (Rigid <=7.5t)	-	87
	Heavy Duty Trucks (Rigid 12-14t)	586	1,236
	Heavy Duty Trucks (Rigid 14-20t)	1,161	1,444
	Heavy Duty Trucks (Rigid 20-26t)	389	-
	Ro-Ro Ship (Roll-On/Roll-Off)	6	7
Fabrication and Installation	Off-Site Prefabrication	8,068	-
	On-Site Installation	9,960	22,228
	Total CO_2 Emission	**417,305**	**551,565**

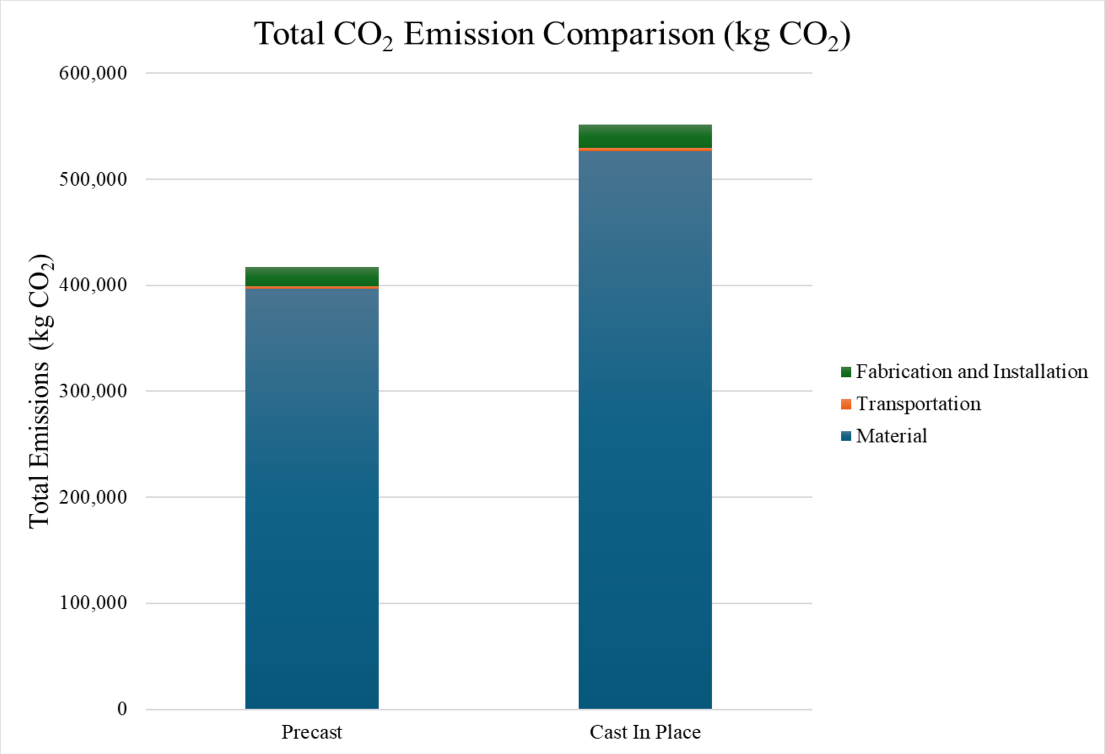

Figure 4. Total Comparison of CO_2 Emissions from Precast and Cast-in-Place

Based on the results of the case study conducted using a comparative scenario, the total CO_2 emissions generated by the cast-in-place concrete method were found to be significantly higher than those from the precast method. Specifically, the cast-in-place system emitted approximately 134 tons, which represents a 32% increase compared to the emissions from the precast system. This finding indicates that the precast concrete method offers a substantial reduction in carbon emissions—by about 24%—highlighting its potential as a more environmentally sustainable alternative in construction practices.

Figure 4 presents a quantitative comparison in the form of a bar graph, illustrating the contribution of each activity to the total CO_2 emissions. The main factors contributing to this significant difference are the high emissions resulting from material loss and on-site installation activities. Unlike the precast method, which involves centralized component fabrication in an off-site controlled environment (off-site prefabrication), the cast-in-place method is executed entirely on-site. As the cast-in-place method lacks a prefabrication process, all construction activities occur in the field, leading to higher emissions from on-site installation.

Meanwhile, the difference in emissions from the transportation aspect is relatively minor. However, this does not imply that transportation and installation contributions to CO_2 emissions can be overlooked. Every stage of the construction process has the potential to cause environmental harm but can be optimized to support emission reduction efforts. Therefore, the primary focus should be on identifying and implementing science-based strategies that minimize environmental impacts at each stage of construction. Adopting the right approach can contribute significantly to achieving more sustainable and environmentally friendly development goals.

CONCLUSION

The analysis showed that the precast concrete method offered clear environmental benefits compared to the cast-in-place approach, with the latter producing 32% higher emissions, equivalent to about 134 tons of CO_2. By reducing material losses and minimizing on-site installation activities, the precast method lowered overall emissions by 24%, demonstrating its potential as a more sustainable construction alternative. Since these findings stem from project-specific data, future research should expand the scope through broader life cycle assessments across diverse building types and regional contexts to better capture variations in materials, energy sources, and implementation challenges.

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