Sustainable Design of Raft Foundations: Analyzing Embodied Carbon and Cost Impacts

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ABSTRACT

The construction industry is a significant contributor to global carbon emissions, necessitating the adoption of sustainable design practices. This study investigates the embodied carbon and cost implications of raft foundations, focusing on the effects of different concrete grades, K300, K400, and K500, and slab thicknesses. A comprehensive methodology, guided by BS EN 15978, was employed to assess the carbon emissions across the product, construction, and end-of-life stages. Additionally, a cost analysis was conducted, reflecting typical construction expenses relevant to the Indonesian context. The findings revealed that increasing the concrete grade consistently leads to higher embodied carbon and costs, with K300 demonstrating the lowest values across all thicknesses. Moreover, thicker slabs exacerbate both the environmental and financial impacts, highlighting the trade-offs inherent in material selection and design choices. The study concludes that a strategic balance between structural requirements, cost efficiency, and environmental sustainability can be achieved by utilizing lower-grade concrete, where high strength is not essential. These insights contribute to the discourse on sustainable construction practices, advocating for informed decision-making in raft foundation design to minimize the carbon footprint while maintaining economic viability.

Keywords-raft foundation; embodied carbon; built environment; sustainability; UN SDG 13: Climate action

I. INTRODUCTION

The world is currently experiencing an unprecedented series of extreme climatic events, such as storms, floods, droughts, and wildfires, which are occurring with an increasing frequency and intensity. These phenomena are primarily driven by the accumulation of Greenhouse Gases (GHGs) emitted due to the human activities, leading to significant disruptions in the Earth's climate system [1-3]. Efforts to combat the climate change have intensified globally and nationally, particularly since the adoption of the landmark Paris Assessment in 2015 [4-6]. This international accord represents a near-universal commitment to reducing GHG emissions and promoting sustainable development. The Paris Agreement emphasizes the critical need to control emissions and sets a collective target to limit global warming to well below 2°C above pre-industrial levels, with a more ambitious aim of restricting the temperature increase to 1.5°C [7].

The building and construction industry is a major contributor to global emissions, responsible for nearly 40% of the energy-related GHG emissions worldwide [8]. This underscores the critical need to adopt sustainable practices in this sector to reduce its environmental impacts. A comprehensive approach to carbon reduction in construction requires a clear understanding of the two main categories of carbon emissions associated with buildings: embodied and operational carbon [9-10]. Embodied carbon refers to the emissions produced throughout a building's lifecycle, including the production and transportation of construction materials, construction processes, maintenance, and demolition [11]. These emissions are essentially "locked in" once the building is completed. On the other hand, operational carbon is linked to the energy used during the building's daily operations, such as heating, cooling, lighting, and water usage. While efforts in recent decades have been focused on reducing operational carbon through improved energy efficiency, embodied carbon is now gaining recognition as a critical area for action, especially as operational emissions decline due to advancements in the renewable energy and energy-efficient technologies.

Recent projections indicate that embodied carbon contributes to approximately 49% of the total carbon emissions from buildings [12]. Since these emissions are "locked in" once construction is completed, addressing embodied carbon is crucial for achieving substantial reductions in the building sector's overall carbon footprint. In recent years, efforts to reduce embodied carbon have focused primarily on superstructures, driven by advancements in the material technology and design optimization [13-17]. However, substructures, particularly foundations, have received relatively less attention, despite their significant contribution to a building's total carbon emissions. Foundations are a major source of embodied carbon due to the large volume of materials required and the energy-intensive processes involved in their construction [18].

Recent research has highlighted the significant role of foundations to the embodied carbon in construction and has explored strategies to reduce this impact. For instance, authors in [19] calculated the carbon emissions from a cast-in-situ pile foundation and a prestressed concrete pipe pile foundation under the same bearing capacity. The findings revealed that the cast-in-situ pile foundation releases 1.4 times more carbon than the prestressed concrete pipe pile foundation, while in the rectifications of battered piles, the prestressed concrete pipe pile foundation has significantly lowered carbon emissions, to as much as one third of other solutions. Additionally, in [20], an innovative multilevel modeling tool was designed to help designers discover strategies for minimizing the embodied carbon of reinforced concrete piles. The study found that modifying design parameters, such as the steel-to-concrete ratio, concrete grade, and pile slenderness ratio, can significantly reduce the embodied carbon in the final pile design. Similarly, authors in [21] investigated an innovative approach to reducing the embodied carbon of reinforced concrete shallow foundations using thin shell foundation typologies. The results demonstrated that thin shell foundations can reduce embodied carbon by approximately 50% for smaller column loads on weaker soils, while for high applied loads, thin-shell foundations significantly outperform conventional prismatic footings, reducing the environmental impact by nearly two-thirds. Furthermore, in [22], the embodied GHG emissions associated with four foundation design options were evaluated for a modular residential building in East Midlands, UK. The study found that helical piles and reinforced concrete slabs supported by expanded polystyrene were the most sustainable options, demonstrating lower emissions than those of the conventional strip and pad foundations.

These studies presented various strategies for reducing the embodied carbon of foundations, including the use of alternative foundation types, advanced modeling tools, and material substitutions. However, there remains a clear research gap regarding the impact of specific design parameters, such as the concrete grade and slab thickness, on both the embodied carbon and cost of raft foundations.

II. METHODOLOGY

This study examines the embodied carbon and cost implications of raft foundations in a multistory building, specifically analyzing the effects of the concrete grade and slab thickness. The building is a six-story structure with a uniform floor height of 4 m. The layout and design details of the building are presented in Figure 1. All structural member dimensions, including beams, columns, and slabs, were designed compliant with the requirements outlined in the Indonesian Standard SNI 2847:2019 [23].

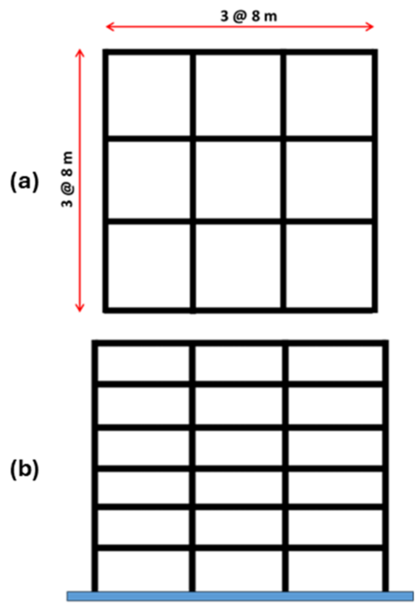

Fig. 1. The layout and design parameters of the building: (a) building plan, (b) building elevation.

The building was designed to withstand both gravitational and seismic loads. Gravity loads include a live load of 3 kN/m² and a dead load of 2 kN/m², reflecting typical usage scenarios for multistory buildings. In addition to gravitational forces, the design accounts for seismic forces in accordance with the Indonesian Standard SNI 1726:2019 [24]. The seismic design parameters were defined as follows: Peak Ground Acceleration (PGA) of 0.0603 g, 0.2-second spectral acceleration (S_S) of 0.1159 g, and 1-second spectral acceleration (S1) of 0.0799 g.

The structural analysis of the building was conducted using the commercial finite element software ETABS, a robust platform for simulating the complex interactions between structural elements and external forces. In the present study, the interaction between the raft foundation and the underlying soil was explicitly modelled to capture the Soil-Structure Interaction (SSI) effects, which are crucial for accurately evaluating the foundation behaviour under applied loads. To incorporate SSI, the foundation was modeled using spring area elements, which represent the response of the underlying soil. The spring constants were derived from the modulus of the subgrade reaction (*Ks*), a parameter that characterizes soil stiffness in response to applied loads. The modulus of the subgrade reaction was determined based on the conceptual relationship between ground pressure and deflection, as shown by:

$$Ks = \frac{Allowable\ bearing\ pressure}{Allowable\ settlement\ of\ foundation} \quad (1)$$

This approach provides a reliable estimate of soil stiffness, which is crucial for accurately modeling the interaction between the raft foundation and soil. The specific soil parameters are summarized in Table I, detailing the values adopted for *Ks* and other relevant soil characteristics.

TABLE I. SOIL PARAMETERS

Soil parameters	Values
Density (γ)	1.87 g/cm^3
Cohesion (s)	12 kPa
Friction angle (φ)	20º
Modulus of elasticity (E)	84.6 MPa
Poisson's ratio (μ)	0.35

A. Raft Reinforcement Design

The reinforcement design of the raft foundation was based on the flexural requirements in accordance with the guidelines provided by SNI 2847:2019 [20]. A BjTS 420A steel reinforcement with a yield strength of 420 MPa was adopted, as specified by SNI 2052:2017 [25]. This reinforcement specification was chosen for its strength and compliance with the local standards to ensure structural safety and performance. The flexural strength of the raft slab (φM_n) was determined using:

$$\varphi M_n = \varphi A_s f_y \left(d - \frac{a}{2}\right) \quad (2)$$

where:

- φ = 0.9 for flexure
- A_s = area of tension reinforcement
- f_y = yield strength of the rebar
- d = distance from the compression fiber to the tension reinforcement
- a = depth of the equivalent rectangular stress block, which is calculated by:

  $$a = \beta_1 c \quad (3)$$

where β_1 is a factor relating the depth of the equivalent rectangular compressive stress block to the depth of the neutral axis equal to 0.85, and c is the distance from the extreme compression fibre to the neutral axis.

In addition to the flexural requirements, the raft foundation was designed to resist punching shear forces around the columns, a critical consideration for ensuring the slab's performance under concentrated loads. The punching shear capacity of the slab was evaluated based on the provisions of SNI 2847:2019 [23], which offer guidelines for evaluating the slab's resistance to localized shear stresses.

The punching shear strength (ϕV_c) was calculated by:

$$\phi V_c = \phi 0.33\sqrt{f_c'} b_0 d \quad (4)$$

where:

- f_c'= concrete design compressive strength
- d = effective depth of the slab
- b_o = perimeter of the critical section located *d/2* from the column face.

B. Embodied Carbon Analysis

The evaluation of construction sustainability requires a comprehensive assessment of its environmental impact across various phases of the life cycle, as defined by the BS EN 15978 standard [26]. This standard categorizes the life cycle into four key stages: product, construction process, use, and end-of-life. This study specifically focuses on analyzing embodied carbon during the product stage (A1-A3), the transportation stage (A4), and the construction process stage (A5), as these stages represent the primary contributors to the environmental footprint of construction projects.

The embodied carbon content during the product stage ($EC_{A1\text{-}A3}$) was determined by:

$$EC_{A1-A3} = \sum Q_i \cdot CF_{A1-A3} \quad (5)$$

where $Q_i$represents the material quantity and CF_{A1-A3} are the carbon factors associated with the material.

Table II provides the carbon factors for the materials used in this study, sourced from the Inventory of Carbon and Energy (ICE) [27].

TABLE II. CARBON FACTORS IN THE PRODUCT STAGE ASSOSIATED WITH VARIOUS MATERIALS

Materials	Carbon Factor ($CF_{A1\text{-}A3}$)
Reinforced steel	1.99 kg CO_2e/ kg
Concrete grade K300	284 kg CO_2e/m^3
Concrete grade K400	330 kg CO_2e/m^3
Concrete grade K500	380 kg CO_2e/m^3

The embodied carbon during the transportation stage (EC_{A4}) was evaluated by:

$$EC_{A4} = Q_i \cdot CF_{A4} \quad (6)$$

where $CF_{A4}$is the carbon factor for transportation, calculated by:

$$CF_{A4} = TD \cdot TEF \quad (7)$$

where TD is the transport distance (assumed to be 100 km) and TEF is the transport emission factor, taken as 0.10749 gCO_2e/km [28].

The embodied carbon during the construction process stage (EC_{A5}) was assessed using two components: emissions due to on-site waste (EC_{A5w}) and emissions from construction activities (EC_{A5a}). Emissions due to waste generated onsite (EC_{A5w}) were calculated by:

$$EC_{A5w} = \sum Q_i \cdot CF_{A5w} \tag{8}$$

The emission factor $A5w$ due to on-site waste (CF_{A5w}), can be calculated by:

$$CF_{A5w} = WF_i \cdot (CF_{A1-A3} + CF_{A4}) \tag{9}$$

where WF_irepresents the waste factor, which quantifies on-site material waste as a percentage of the material quantities used in the final asset. The waste factor is derived by converting the waste rate (WR_i):

$$WF_i = \frac{1}{1-WR_i} - 1 \tag{10}$$

The recommended value for the waste rate (WR_i) for both concrete and reinforcing steel is 5% [25].

The emissions associated with energy usage during the construction activities (EC_{A5a}), including equipment operation, are determined by:

$$EC_{A5a} = CAEF \cdot \frac{PC}{100{,}000} \tag{11}$$

where $CAEF$ is the construction activity emission factor, taken as 700 $kgCO_2e$/£100,000, and PC is the total project cost.

The embodied carbon calculations presented facilitate a comprehensive evaluation of the emissions associated with the material production, transportation, and construction processes. This holistic approach provides an insight into the overall environmental impact of the raft foundation, accounting for both material waste and construction activities.

C. *Cost Analysis*

The cost analysis in this study incorporates typical construction costs relevant to the Indonesian context, offering a comprehensive assessment of the economic implications of the raft foundation design. The analysis includes the costs of labor, equipment, and materials associated with the construction of the raft foundation, as outlined in Table III. These cost data reflect the current market rates in Indonesia [26] and are critical for accurately estimating the total financial requirements of the foundation construction.

TABLE III. UNIT COST OF MATERIALS

Materials	Unit rate (Rupiah)
Reinforcing steel	19,548
Concrete grade K300	1,993,000
Concrete grade K400	2,138,000
Concrete grade K500	2,353,000

The total cost is calculated by summing the contributions of labor, equipment, and materials, offering a detailed financial overview of the raft foundation's construction. This approach offers valuable insights into the design's cost, enabling a balanced evaluation of its economic and environmental performance.

III. RESULTS AND DISCUSSION

The analysis in this study considers three concrete grades—K300, K400, and K500—to evaluate their impact on both the environmental and economic performance. Additionally, various slab thicknesses were examined to assess their influence on the embodied carbon and cost of the foundation.

Figure 2 presents the embodied carbon analysis per m^2 of the raft foundation, categorized by material, concrete and steel reinforcement, for varying slab thicknesses, 900, 1000, 1100, and 1200 mm, and concrete grades, K300, K400, and K500.

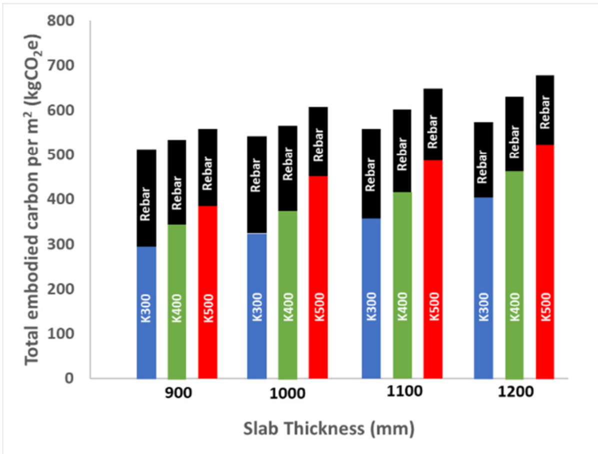

Fig. 2. Total embodied carbon per m^2 of the raft foundation (kg CO_2e) by material type for varying slab thicknesses and concrete grades.

The results indicate that having increased the concrete grade from K300 to K500 consistently raised the total embodied carbon across all slab thicknesses, primarily due to the higher cement content and the energy-intensive materials required for higher-grade concrete. This is in accordance with [14], where the embodied carbon of the concrete slabs was investigated and it was reported that higher concrete grades are associated with increased embodied carbon. Similarly, increasing the slab thickness amplified the embodied carbon regardless of the concrete grade, as thicker slabs necessitate more material. As the concrete grade increased, a noticeable reduction in the embodied carbon contribution from steel reinforcement was observed. This reduction is attributed to the higher strength of the higher-grade concrete, which decreases the required amount of steel reinforcement while maintaining structural performance

Concrete consistently emerged as the dominant contributor to the total embodied carbon across all scenarios. This underscores the need to optimize concrete mix designs to mitigate environmental impacts. Strategies, such as using lower-grade concrete when structurally feasible or incorporating supplementary cementitious materials, like fly ash or slag, could significantly reduce emissions. Notably, the combination of higher-grade concrete and increased slab thickness resulted in the highest embodied carbon values, highlighting the compounded environmental costs of using high-grade materials and thicker slabs, even when structurally necessary.

Figure 3 portrays the impact of the total embodied carbon footprint during the life cycle stages. It reveals that the product stage (A1-A3) is the predominant contributor to the total embodied carbon, accounting for approximately 89-91% of the total emissions across all scenarios. This stage encompasses the extraction and processing of raw materials, which are high energy-intensive and the primary source of the carbon emissions associated with the raft foundation construction. In contrast, the transportation (A4) and construction (A5) stages contribute relatively small shares, typically ranging between 10-12% of the total emissions. These findings underscore the need to focus carbon reduction efforts on material selection and production processes, as these have the most significant impact on the foundation's overall environmental footprint.

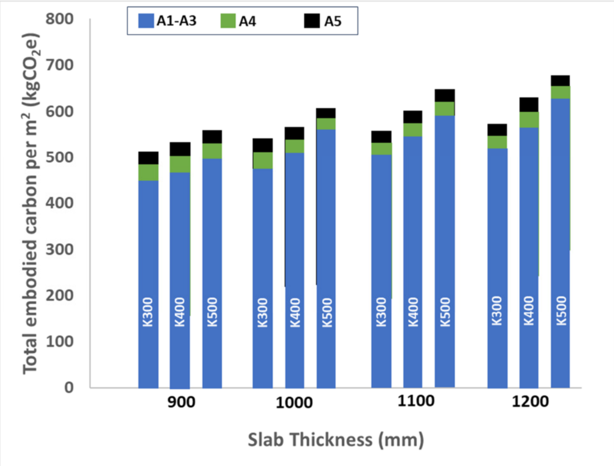

Fig. 3. Total embodied carbon per m^2 of the life cycle stages (A1-A5) of raft foundation (kg CO_2e) for varying slab thicknesses and concrete grades.

To achieve balanced structural, environmental, and financial objectives, the cost implications of the raft foundation design with different concrete grades and slab thicknesses were examined. Figure 4 illustrates the total cost per m^2 of the raft foundation across different slab thicknesses and concrete grades.

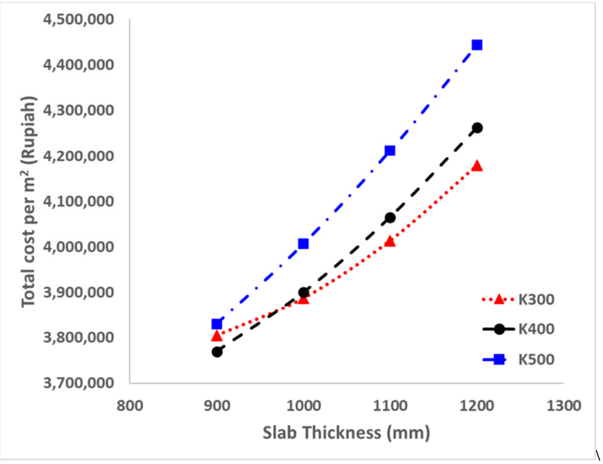

Fig. 4. Total cost of raft foundation across different slab thicknesses and concrete grades.

The results demonstrate that increasing the concrete grade consistently results in higher costs, irrespective of the slab thickness. This underscores the trade-off between the structural performance and financial outlay, as higher-grade concrete, while necessary in scenarios requiring enhanced load-bearing capacity, includes significant cost implications. These findings emphasize the importance of a careful evaluation during the design phase to ensure that the selected concrete grade aligns with both the structural demands and budgetary constraints.

As the slab thickness increases, the total cost rises, driven by the higher volumes of concrete and reinforcement required. For thinner slabs, the cost differences between different concrete grades were relatively small. However, with an increasing thickness, the gap becomes more pronounced, highlighting the compounding effect of material cost and volume on the overall expenses. Although thicker slabs enhance structural stability and performance, they incur substantial financial costs. The rate of cost increase was further pronounced for higher-grade concrete, reflecting the compounded effect of both increased material usage and the inherent cost of higher-grade materials. Therefore, optimising the slab thickness based on the required structural performance can result in significant cost savings.

IV. CONCLUSIONS

This study investigated the optimization of raft foundation design, focusing on balancing structural performance, embodied carbon, and cost efficiency. By analyzing various combinations of concrete grades, K300, K400, and K500, and slab thicknesses, 900, 1000, 1100, and 1200 mm, it provides valuable insights into the trade-offs involved in the sustainable foundation design. The key conclusions are:

- Embodied Carbon Impact: increasing the concrete grade from K300 to K500 consistently elevated the total embodied carbon across all slab thicknesses due to higher cement content in high-grade concrete. Additionally, thicker slabs resulted in higher embodied carbon, reflecting the environmental impact of increased material volume. Notably, concrete was identified as the dominant contributor to the total embodied carbon, significantly outweighing the impact of steel reinforcement.
- Life Cycle Contributions: Life cycle analysis indicated that the product stage (A1-A3) was the primary source of embodied carbon, accounting for 89-91% of emissions. In contrast, the transportation (A4) and construction (A5) stages had relatively minor contributions.
- Cost Implications: Both the concrete grade and slab thickness had significant effects on the total foundation cost. Higher-grade concrete and thicker slabs consistently increased costs, with the most substantial differences having been observed at higher slab thicknesses.
- Sustainability and Cost-Effectiveness: The combined analysis of the embodied carbon and cost revealed that higher-grade concretes, K400 and K500, were associated with both higher embodied carbon and costs, making them less favorable in terms of sustainability and cost-effectiveness. Conversely, lower-grade concrete, K300,

emerged as a more sustainable and economical choice, particularly for applications where high structural strength is not critical.

A careful consideration of these factors can lead to significant cost savings and embodied carbon reductions, contributing to a more sustainable foundation design. The findings provide valuable guidance for engineers and designers, emphasizing the critical role of material selection in reducing the environmental footprint of structural foundations while aligning with project goals.

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DATA AVAILABILITY

The data sheet can be found at: https://zenodo.org/records/13959272.

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