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DOI:
10.1680/jensu.23.00089

Document Version
Accepted author manuscript

Citation for published version (APA):
Suwondo, R., Keintjem, M., Suangga, M., & Cunningham, L. (2024). Sustainable design of two-way slab on beam systems: A comparative study on embodied carbon and cost. *Proceedings of the Institution of Civil Engineers: Engineering Sustainability*, 1-9. https://doi.org/10.1680/jensu.23.00089

Published in:
Proceedings of the Institution of Civil Engineers: Engineering Sustainability

Sustainable Design of Two-Way Slab on Beam Systems:

A Study on Embodied Carbon and Cost

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Abstract

In an era characterised by a growing imperative for environmental sustainability, the construction industry finds itself at a crossroads where innovation and well-informed decision-making are paramount. This study explored the intricate interplay between structural performance, economic viability, and environmental impact in the realm of reinforced concrete slabs, with a specific focus on two-way slab-on-beam structures. This study examined the relationship between slab thickness, concrete grade, reinforcement ratios, embodied carbon emissions, and total construction costs. The findings paint a vivid, if not unexpected, picture: thinner slabs are associated with lower embodied carbon emissions and construction costs. However, there is a caveat: thinner slabs may find their place in projects with less demanding structural requirements, whereas thicker slabs, while offering superior structural performance, incur higher costs and environmental impacts. The choice of slab thickness, as this research indicates, is far from a one-size-fits-all decision and necessitates meticulous evaluation of project-specific demands. The data-driven insights presented in this study have the potential to improve construction practices. This research serves as a foundational reference point for the construction industry's journey towards sustainability, where structures are not merely functional, but also environmentally and economically sustainable.

Keywords

Building structures and design, Built environment, Concrete structures, Sustainability, UN SDG 13: Climate action

1. Introduction

The extensive utilisation of reinforced concrete in the construction industry remains pervasive, despite mounting concerns surrounding its ecological sustainability. The production of cement, a fundamental component of concrete, contributes to approximately 8-10% of global carbon emissions from human activities (Monteiro, Miller and Horvath, 2017; Cao *et al.*, 2021). This conspicuous environmental repercussion highlights the pressing need to confront issues pertaining to sustainability within the construction industry, particularly amid the ongoing climate crisis (Goodchild, Webster and Elliott, 2009; Nurruddin *et al.*, 2018; Hammad, Amr and Shaaban, 2023).

Embodied carbon emissions encompass a comprehensive quantification of the environmental impacts that transpire throughout various construction phases. These phases include raw material extraction, manufacturing, transportation, the construction process itself, ongoing upkeep and maintenance, and the final phases of decommissioning and end-of-life disposal (G. P. Hammond and Jones, 2008; RIBA, 2017; Gibbon *et al.*, 2022). In this context, two-way reinforced concrete slabs on beams have gained popularity as preferred structural floor systems, particularly in seismically active regions (Sitanggang and Tarigan, 2011; Tunc, Azizi and Tanfener, 2023). The efficiency of two-way slabs on beams is particularly evident when compared with other types of slab systems (Tunc, Proje and Azizi, 2020). Their widespread adoption in moment-resisting frames, which constitute the most common and effective seismic design systems, underlines their importance in seismic regions. Moreover, these slabs play a pivotal role as diaphragms, facilitating the efficient transfer of horizontal loads to the lateral resisting system and thereby enhancing the overall seismic performance of structures in seismic regions.

Numerous research endeavours have focused on the mitigation of embodied carbon in reinforced concrete slabs, and an extensive body of work has investigated methods to optimise costs and embodied energy. Sahab et al. (2005) conducted a comprehensive study on cost optimisation in flat slabs, considering three critical variables: column layout, slab thickness, and reinforcement design. Their research underscored the pivotal role of optimising column layout, which could yield substantial cost savings. Additionally, their work emphasised the feasibility of increasing reinforcement ratios to reduce slab thickness, particularly in designs governed by deflection criteria, resulting in an overall cost reduction.

Goodchild et al. (2009) developed a set of design charts for slabs and other reinforced concrete frame elements, offering insights into the minimum cost considerations for various spans. The charts were generated using a series of parametric designs. In their research, they meticulously controlled deflections according to the Eurocode 2 guidelines (CEN, 2004), thereby establishing adjusted span-to-depth ratios. Notably, their findings indicated that increasing the reinforcement to further reduce the allowable slab thickness could contribute to overall cost reduction. Ferreiro-Cabello et al. (2016) embarked on a study involving flat slabs with varying thickness for different column grids. Their research highlighted the significance of reducing spans as a means of minimising embodied carbon. Moreover, their work demonstrated that designs with the lowest embodied carbon approached the minimum feasible slab thickness, indicating a delicate trade-off between slab depth and reinforcement content.

Eleftheriadis et al. (2018) employed a BIM-based genetic algorithm to optimise flat slabs, wherein they systematically varied the dimensions and reinforcement of slabs and columns, along with the column layout. Their investigation led to the conclusion that designs with the least embodied carbon leaned towards shorter column spacings and thinner slabs. This study also observed that increasing the slab thickness to reduce the reinforcement ratio could effectively diminish the overall embodied carbon content. Bechmann and Weidner (2021) compared a standard multi-storey concrete building with optimised concrete and a hybrid timber solution, each with 29 floors. The optimised concrete building included a specific concrete mix, specifically adjusted structural systems, and material manufacturing. The hybrid timber building was designed with a foundation, underground levels, and a stiffening core made of concrete, while the slabs of all upper floors featured 200-millimeter timber panels with 100-millimeter concrete topping slabs. The results of this study revealed the potential for substantial reductions in carbon emissions, with the selection of hybrid timber over conventional concrete design leading to carbon emission reductions of up to 78 %. Additionally, it was observed that a concrete optimisation approach could considerably reduce carbon emissions by 47 %.

The evaluation of construction sustainability necessitates a comprehensive examination of its environmental impact throughout the various stages of its life cycle, as standardised by BS EN 15978 (2011). According to this norm, stages A1 to A3, collectively referred to as 'cradle-to-gate', encompass the Product stage. This phase encompasses activities such as raw material procurement, material transportation, and manufacturing (Gibbon *et al.*, 2022). Notably, the London Energy Transformation Initiative (2020) underscores a substantial proportion of embodied carbon, often accounting for up to 50% of the entire life-cycle carbon footprint, as shown in Figure 1. This is in stark contrast to the relatively small contribution of the construction phase, which is typically approximately 5% of the total. Researchers including Sansom and Pope (2012), Wen et al. (2015), and Gan et al. (2017) also explored embodied carbon across the life cycle in various case studies, consistently finding that transportation and construction activities collectively account for a contribution within the range of 1% to 15%. Thus, it is reasonable to employ cradle-to-gate embodied carbon as a performance indicator. This option facilitates a focused examination of the environmental implications associated with variations in the concrete grade and slab thickness while maintaining a constant construction method.

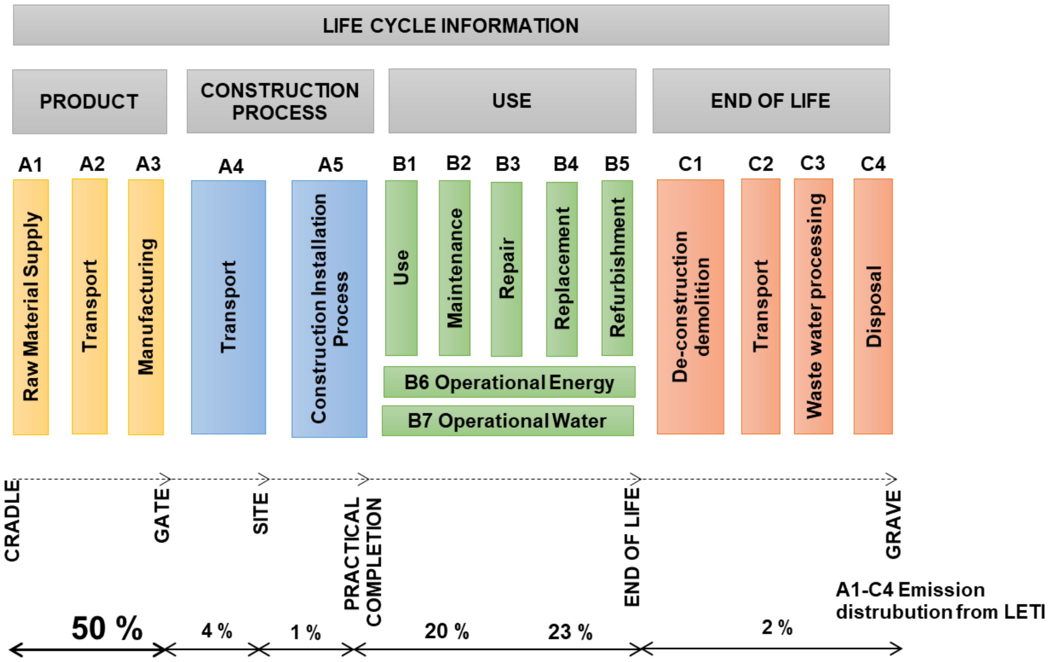

Figure 1 Life cycle stages, based on BS 15978 (BSI, 2011)

The present study investigates the environmental implications and financial costs associated with the construction of two-way slab-on-beam structures, contingent on the concrete grade and slab thickness. Economic expenditure and embodied carbon emissions are two key metrics under scrutiny. The fundamental unit of analysis, or the product of focus, is a square metre of the modelled structure. This product is a composite of two primary construction materials, reinforcing steel and concrete, both of which undergo permanent integration into a structural assembly.

2. Methodology

Two-way concrete slabs were designed on beams configured as 3 × 3 bays. These designs incorporate the parametric variation of both slab thickness and concrete grade, with a particular focus on assessing the resulting fluctuations in the embodied carbon per unit floor area. These simulations are based on the contextual parameter characteristics of an office building. The distribution of the columns within the structural framework adheres to a grid pattern with dimensions of 8m × 8m, as shown in Figure 2. This particular layout was consistent with the common column arrangements encountered in practical construction scenarios. Gravity loads were considered according to the guidelines provided by Indonesian Standard SNI 1727:2020 (BSN, 2020). The dead load, which includes the self-weight of the structure, a superimposed dead load of 2 kN/m^2, and a live load of 2.4 kN/m^2 were considered throughout. The ultimate limit state combination which adopts a factor of 1.2 for the dead load and 1.6 for the live load, was used in the structural analysis. The well-established commercial finite element software package ETABS (CSI, 2023) was employed to conduct structural analysis.

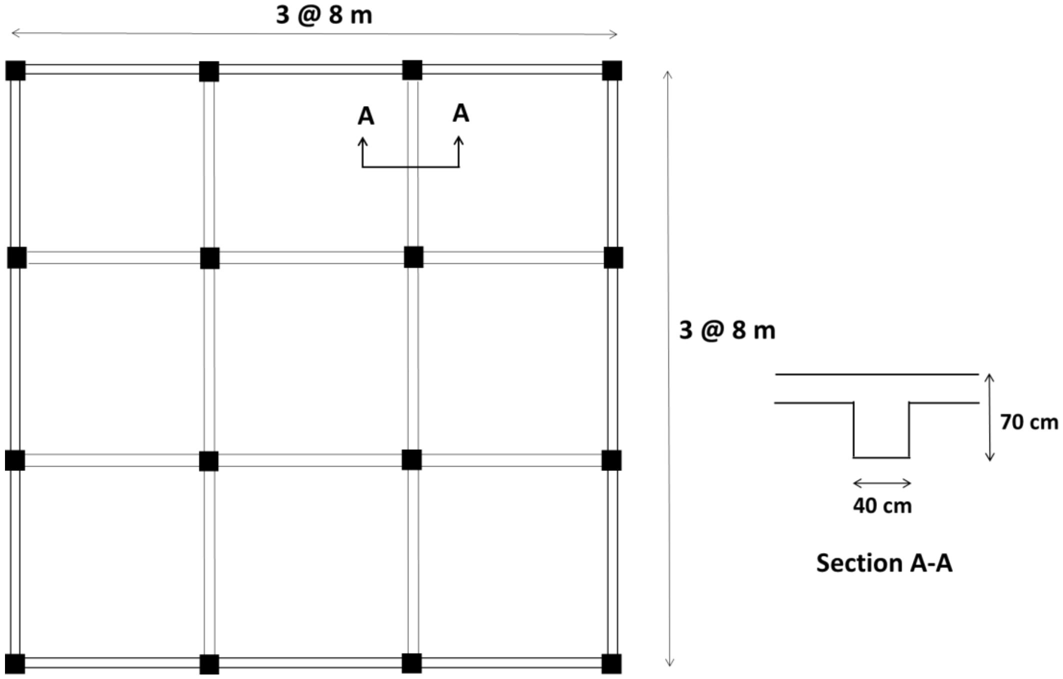

Figure 2 Representative building frame layout

In accordance with Indonesian Standard SNI 2847:2019 (BSN, 2019), the minimum allowable slab thickness, h_{min}, obtained by applying Equation 1, was adopted as the baseline for this study.

$$h_{min} = \frac{l_n\left(0.8+\frac{fy}{400}\right)}{36+9\beta} \tag{1}$$

where l_n is the length of the clear span measured face-to-face on the supports, f_y is the yield strength of the reinforcement, and β is the ratio of long to short dimensions. By adopting this minimum thickness requirement, it is reasonable to assume that slab deformation, often a critical consideration in structural analysis, can be disregarded. This simplification allows for a more streamlined assessment of the key variables under investigation.

Once the slab thickness was established, the reinforcement was determined based on the flexure in accordance with the guidelines provided by SNI 2847:2019 (BSN, 2019). The flexural strength of the slab ϕM_n was determined using Equation 2.

$$\phi M_n = 0.9 A_s f_y \left(d - \frac{a}{2}\right) \tag{2}$$

where A_s is the area of tension reinforcement, f_y is the yield strength of the rebar, d is the distance from the compression fibre to the tension reinforcement, and a is the depth of the equivalent rectangular stress block, which is determined using Equation 3.

$$a = \beta_1 c \tag{3}$$

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

This study encompasses a deliberate examination of concrete grades, specifically focusing on three distinct grades: K250, K350, and K500, equivalent to European grade strengths C20/25, C28/35, and C40/50, respectively. The selection of these grades serves to represent a range of concrete strength levels, enabling a comprehensive evaluation of their impact on both structural performance and embodied carbon. BjTS 420A with a yield strength of 420 MPa was adopted for the steel reinforcement in accordance with SNI 2052:2017 (BSN, 2017).

The estimation of embodied carbon in the reinforced concrete slabs was conducted in accordance with the 'cradle-to-gate' framework, which encompasses stages A1 to A3 as outlined in BS EN 15978 (BS 15978: 2011, 2011). The values used for this assessment were derived from an inventory of carbon and energy using circular ecology (G. Hammond and Jones, 2008). The following data were adopted in this study as representative values for environmental impact assessment.

- Reinforcing steel: 1.99 kg CO_2e/kg (world average steel)
- Concrete grade K250: 267 kg CO_2e/m^3 (assumed 285 kg cementitious binder per m^3)
- Concrete grade K350: 301 kg CO_2e/m^3 (assumed 325 kg cementitious binder per m^3)
- Concrete grade K500: 380 kg CO_2e/m^3 (assumed 420 kg cementitious binder per m^3)

The total embodied carbon for each reinforced concrete slab was determined by combining the contributions of the reinforcing steel and concrete. To reinforce the steel, the total mass required for each slab was first calculated. This mass was then multiplied by an embodied carbon factor of 1.99 kg CO2e/kg, which reflects the global average steel production processes. This step provided the total embodied carbon attributed to the steel reinforcement used in each slab. The volume required for each slab thickness and concrete grade was computed for concrete. This volume was then multiplied by a specific embodied carbon factor for each grade. Finally, the total embodied carbon for each slab design was obtained by summing the contributions from both reinforcing steel and concrete.

To illustrate, if a slab required 10 m^3 of K350 concrete, the total embodied carbon for the concrete was calculated by multiplying the volume of concrete by its associated embodied carbon value. In this example, the total embodied carbon for concrete was 3010 $kgCO_2e$. The individual contributions from the reinforcing steel and concrete were summed to determine the total embodied carbon for the entire slab. For instance, if the total embodied carbon for reinforcing steel is 1990 $kgCO_2e$ and for concrete is 3010 $kgCO_2e$, then the total embodied carbon for the slab would be 5000 $kgCO_2e$.

In terms of cost, the analysis considers typical construction costs relevant to Indonesia, as shown in Table 1. These cost factors are paramount in assessing the economic implications of the designed slabs and their variations in concrete grade and slab thickness. Aligning the study with local construction cost data ensures that the findings are not only environmentally relevant but also economically practical within the context of the study area.

Table 1 Unit cost of materials (Ministry of public works and housing, 2022)

Material	Cost Rp	Cost in US $
Reinforcing steel (kg)	10,000	0.63
Concrete grade K250 (m^3)	850,000	53.47
Concrete grade K350 (m^3)	940,000	59.13
Concrete grade K500 (m^3)	1,050,000	66.05

3. Results and discussions

This paper presents a comprehensive evaluation of the required reinforcement for two-way slab-on-beam components, considering different concrete grades (K250, K350, and K500) and varying slab thicknesses. The corresponding required reinforcement, expressed in kilograms per cubic meter (kg/m³), was analysed for each concrete grade and thickness, offering a comprehensive overview of the structural considerations.

The results shown in Figure 3 reveal that the concrete grade does not exert a significant influence on the amount of required reinforcement. This indicates that the primary factor influencing the required reinforcement is slab thickness. Regardless of whether the concrete grade was K250, K350, or K500, the variations in the required reinforcement remained relatively consistent for a given slab thickness.

It can be observed that across all concrete grades, an increase in slab thickness is associated with a general decrease in the required reinforcement. However, the results indicate an interesting trend for slab thicknesses of 180 mm and 220 mm, wherein the required reinforcement increases rather than decreases with increasing slab thickness. This phenomenon can be attributed to the minimum reinforcement requirement stipulated by SNI 2847-2019, which prescribes a minimum steel reinforcement ratio of 0.18%. Consequently, for thicker slabs within the specified range, where structural demands may not necessitate higher reinforcement, the minimum reinforcement requirement becomes the governing factor. This reveals the importance of optimising the slab thickness to satisfy structural requirements while minimising the use of reinforcement materials.

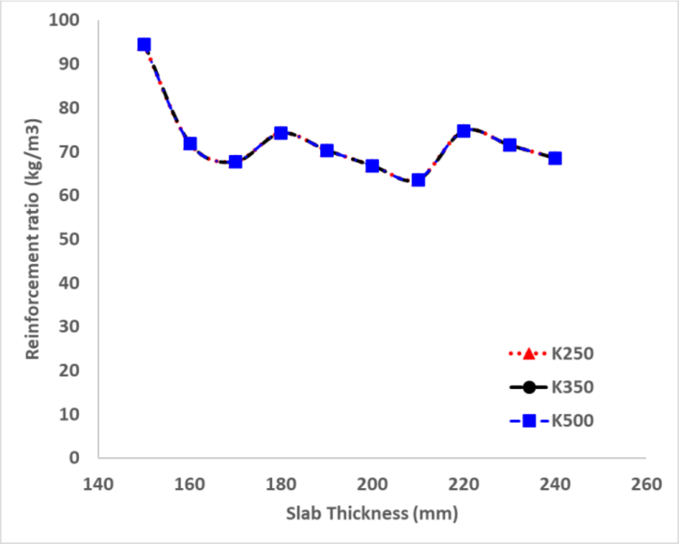

Figure 3 Reinforcing steel per cubic meter of concrete slab

The design of reinforced-concrete slabs typically focuses on flexure, addressing the bending moments induced by uniform loads. However, it is crucial to recognise that point loads can introduce punching shear, influencing slab design by necessitating consideration of concrete compressive strength. Concrete grades vary in their ability to resist punching shear, thereby affecting the required reinforcement. Additionally, variations in live and dead load factors, as per the Indonesian Standard SNI 1727:2020, are pivotal in ultimate limit state design, affecting safety and cost. Higher load factors increase structural demands, potentially requiring more reinforcement, whereas lower factors might reduce requirements but must be balanced for safety. Understanding these load variations is imperative for optimising structural design for safety and cost-effectiveness in construction projects.

A comprehensive assessment of the embodied carbon in two-way slabs-on-beams was performed by considering different concrete grades (fc') and slab thicknesses. The total carbon emissions per square metre (kg/m²) of the concrete slab are shown in Figure 4. The results of the embodied carbon analysis offered valuable insights into the environmental implications of different concrete grades and slab thicknesses for these types of slabs.

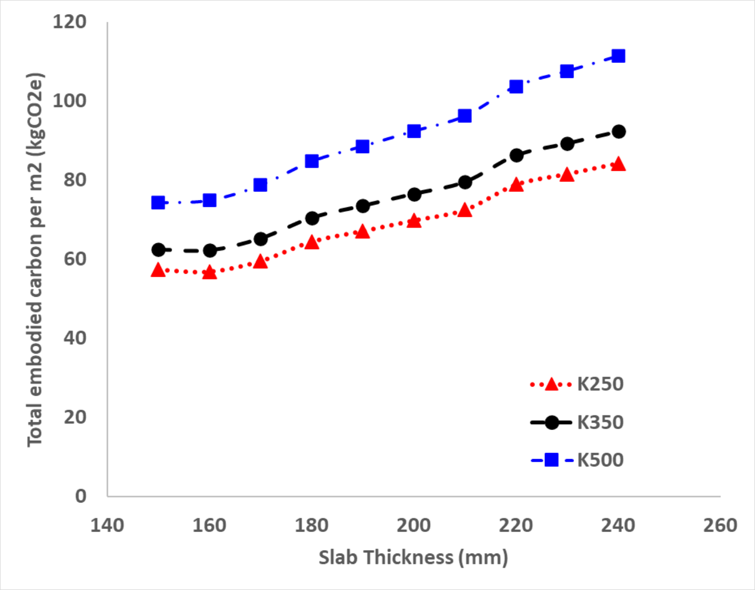

Figure 4 Total embodied carbon of reinforced concrete slab per square meter

The results revealed the profound impact of the concrete grade (K250, K350, and K500) on the embodied carbon per square meter of the concrete slab. Across all slab thicknesses, there was a discernible pattern: as the concrete grade increased, the embodied carbon also increased. This trend is consistent and aligns with expectations given the higher cement content and associated carbon emissions in the production of high-strength concrete. It is noteworthy that the difference in embodied carbon between K250, K350, and K500 was more pronounced for thicker slabs, demonstrating the significance of concrete grade selection when aiming to reduce the carbon footprint of a structure. For a given slab thickness, higher concrete grades tend to result in higher carbon emissions per square meter than those of lower-grade concrete. This effect is primarily owing to the increased cement content and associated carbon emissions during the production of high-strength concrete.

The influence of slab thickness on embodied carbon per square meter was evident when examining the data. Irrespective of the concrete grade (K250, K350, or K500), there is a universal trend: an increase in slab thickness results in an increase in embodied carbon. This correlation is expected because thicker slabs require a larger volume of concrete, which contributes to a higher embodied carbon. Although thicker slabs may require less reinforcement, the role of concrete in the overall embodied carbon footprint should not be underestimated.

In the context of reducing embodied carbon in concrete, the recent study undertaken by ARUP and Innovate UK (2023) provides an embodied carbon classification scheme, which categorises concrete from A to G based on low to high carbon emissions, as shown in Figure 5. It is worth noting that the concrete used in the present study is within the F classification, signifying a relatively high embodied carbon. As previously discussed, higher concrete grades (e.g. K500) are generally associated with higher carbon emissions owing to their elevated cement content, which inherently contributes to a higher carbon footprint. However, it is essential to recognise that this is not the only determinant. The optimum design thickness is instrumental in influencing embodied carbon, as indicated by the findings of the present study.

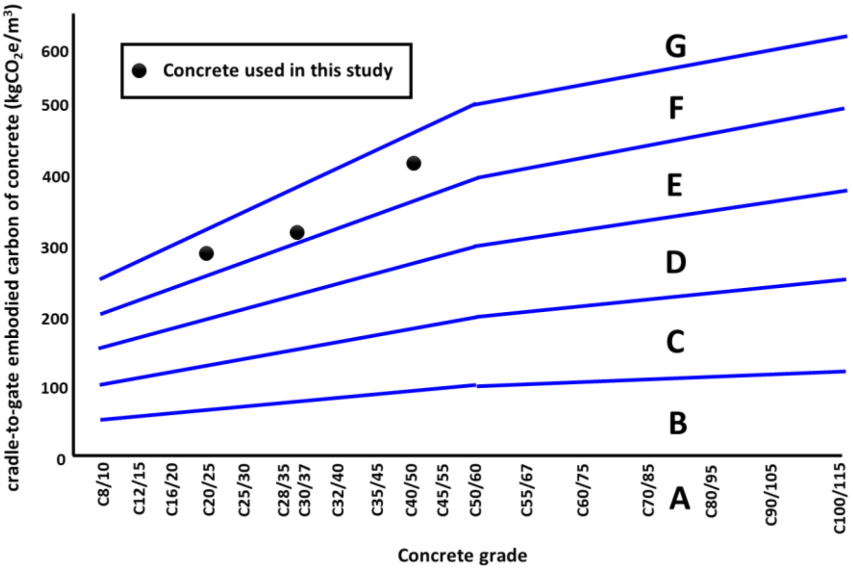

Figure 5 Embodied carbon classification scheme (based on ARUP and Innovate UK, 2023)

The present study reveals a nuanced reality: while selecting lower-carbon concrete or concrete with a higher rating (e.g. moving from F to a lower category) can effectively reduce the embodied carbon, there is a caveat to this approach. Simply choosing lower-carbon concrete does not guarantee a reduced carbon footprint. As shown in Figure 6, a concrete slab with a lower carbon classification may produce higher embodied carbon if the optimum design parameters are not in place. For instance, concrete of K250 grade classified as F, with a design thickness of 150 mm, can potentially result in lower embodied carbon compared with concrete of K250 grade classified as E, with a design thickness of 240 mm.

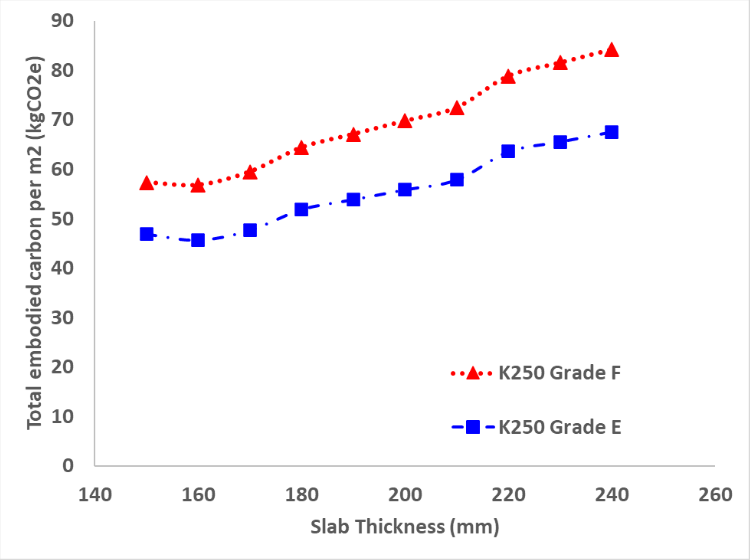

Figure 6 The embodied carbon of K250 Grade F vs Grade E

This emphasises the critical importance of adopting a holistic approach that considers both the concrete mix design specifications and slab thickness in tandem. By optimising design parameters, including concrete grade and slab thickness, embodied carbon emissions in construction projects can be effectively reduced. These efforts are directly aligned with the goals of UN SDG 13 for climate action as they contribute to mitigating the significant role of the construction industry in global carbon emissions. This study underlines the necessity of evaluating multiple factors comprehensively, rather than relying on a one-size-fits-all solution, to achieve sustainable construction outcomes and support the objectives outlined in SDG 13.

In pursuit of balanced structural, environmental, and financial objectives, the present study next examines the cost implications of two-way slab-on-beam structures. Figure 7 shows the total cost per square meter for concrete slabs in these types of structures. The results show that the concrete grade (K250, K350, and K500) has a considerable impact on the cost per square meter of the concrete slab. Across all slab thicknesses, a discernible pattern emerges showing the cost per square meter increasing with concrete grade. This trend is consistent with expectations because higher concrete grades generally require higher cement contents and other additives , which are typically more expensive. The cost difference between K250, K350, and K500 becomes more pronounced for thicker slabs, highlighting the significance of concrete grade selection when aiming to optimise project costs. It can also be observed that for each concrete grade (K250, K350, or K500), there is a consistent trend: an increase in slab thickness corresponds to an increase in the cost per square meter. This correlation is anticipated because thicker slabs necessitate a greater volume of materials, contributing to higher costs.

The local cost data used in this study reflect broader economic trends in Indonesia's construction industry, highlighting material costs, labour rates, and resource availability. As sustainability gains importance, this data can inform policymaking by demonstrating the cost-effectiveness of sustainable practices, such as optimised slab thickness and lower-grade concrete. Aligning economic trends with sustainability goals can encourage regulations and incentives to promote environmentally friendly construction, leading to a more sustainable and resilient built environment in Indonesia.

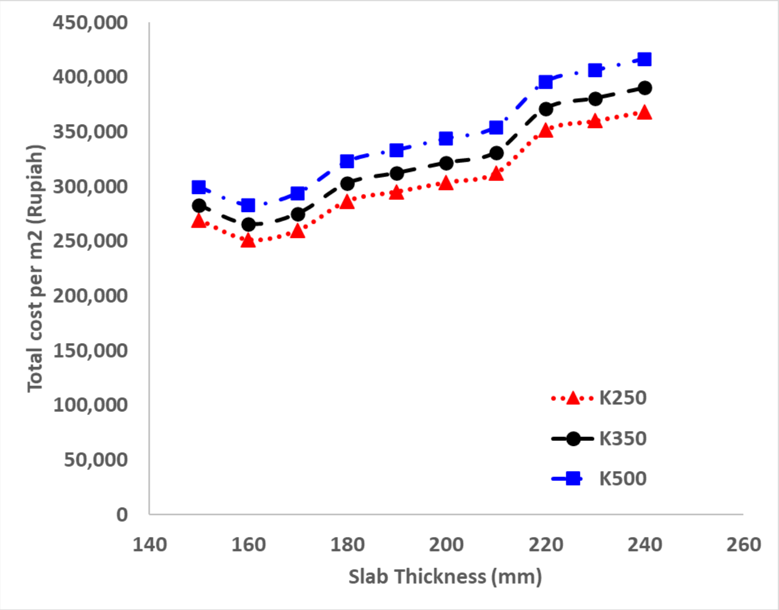

Figure 7 Total cost of reinforced concrete slab per square meter

The data collectively emphasises the importance of a balanced and integrated approach to design. Thinner slabs tend to result in lower embodied carbon emissions and construction costs. However, this seemingly favourable outcome must be interpreted in a broader context. Thinner slabs may find application in projects with less stringent structural demands, but their appropriateness diminishes in settings that require enhanced structural performance. In contrast, thicker slabs, while offering superior structural robustness, are associated with elevated costs and heightened environmental impact. Therefore, the selection of slab thickness must be aligned with the specific goals and performance requirements of a project. This balance highlights the critical role of informed design decisions that consider the structural, environmental, and economic objectives.

Additionally, higher strength concrete, such as K500, has higher embodied carbon and cost compared to lower grades, such as K250 and K350, owing to the increased cement content. This aspect must be considered carefully in the context of sustainable construction practices. Lower-grade concrete, such as K250 and K350, may offer better ductility, which is crucial for energy dissipation during seismic events. Ductility allows the structure to deform without failing, whilst absorbing or dissipating energy from an earthquake. Therefore, in seismically active regions, the choice of concrete grade must consider not only the compressive strength but also the ability of the material to perform under seismically induced stress. Balancing these properties is essential for the design of structures that are both strong and resilient.

The findings also reveal potential opportunities for optimising both the cost and environmental impacts. Optimising slab thickness has emerged as a critical parameter, where thinner slabs, when structurally feasible, significantly reduce material usage and thus both costs and embodied carbon. Additionally, the selection of lower-grade concrete can lead to substantial reductions in embodied carbon owing to the lower cement content. These strategies collectively demonstrate that a careful and holistic design approach can effectively balance structural integrity, cost efficiency, and environmental sustainability.

Towards future design standards, these findings highlight the benefits of using lower-grade concrete with an optimised slab thickness to achieve a balance between structural integrity, environmental impact, and cost. Engineers have the opportunity to embrace an integrated design philosophy. This approach demands a deep understanding of the nuanced interplay between structural, environmental, and financial objectives. This includes exploring the potential of thin slabs in projects with less demanding structural requirements and recognising the significance of thicker slabs in high-performance applications.

It should be noted that this study adhered to the minimum slab thickness requirements outlined in the Indonesian Standard SNI 2847:2019, ensuring structural integrity and safety in buildings. However, although this standard provides a baseline for structural adequacy, there may be opportunities for optimisation beyond these minimum requirements. Future research could explore the potential of adjusting minimum thickness guidelines to reflect advancements in structural engineering, materials science, and sustainability considerations, thereby promoting more efficient and resilient building practices. Investigating the volume stability and soundness of concrete can provide valuable insights into mitigating risks and enhancing its long-term performance (Samuel, Liu and Samuel, 1993; Kabir, Hooton and Popoff, 2020). Furthermore, with a view to future trends in construction in Indonesia and elsewhere, it is likely that hybrid construction approaches such as timber-concrete composite components will increase in prevalence given the potential carbon reductions they offer compared to traditional concrete solutions. However, further research is needed to determine the optimum design of such hybrid forms, particularly within the context of seismic actions.

4. Conclusions

In an era that is increasingly attuned to environmental concerns, the construction industry is facing an urgent need for innovative and well-informed solutions. The findings of this study shed light on the relationship between structural design, environmental impact, and financial considerations in the context of two-way reinforced concrete slabs. By assessing the required reinforcement, embodied carbon emissions, and total construction cost, the data revealed the interplay between these parameters.

The research findings suggest that the choice of concrete grade has a limited impact on the required reinforcement in these structures because the variations in the required reinforcement remain relatively consistent across different concrete grades. This implies that the primary factor influencing the required reinforcement is the slab thickness, with a minimum reinforcement requirement stipulated by design standards coming into play for thicker slabs, which does not necessarily require higher reinforcement for structural performance. This highlights the importance of optimising the slab thickness to meet structural requirements while minimising the use of reinforcement materials, contributing to more sustainable construction practices.

The embodied carbon analysis indicated that slab thickness had a significant influence on the environmental footprint of these structures. Thicker slabs are associated with higher carbon emissions, primarily because of the increased volume of concrete used, making thinner slabs preferable for projects where environmental sustainability is a priority. The selection of higher concrete grades also leads to increased carbon emissions, emphasising the role of material choices in reducing the environmental impact of construction. Moreover, this study demonstrated the potential for lower carbon emissions by opting for concrete with a higher strength grade. However, it is crucial to recognise that lower-carbon concrete can inadvertently yield higher embodied carbon if an optimal design is not executed.

The financial aspects of these structures highlight the cost implications of concrete grade and slab thickness. Higher concrete grades tend to result in higher costs, primarily because of increased cement content. By contrast, thinner slabs are more cost-efficient, which can be advantageous for projects with budget constraints.

This study's comprehensive approach underscores the need for a balanced and integrated design strategy that considers structural, environmental, and economic objectives. Engineers and construction professionals have the opportunity to make informed decisions that optimise structural performance, minimise environmental impact, and control costs. This approach aligns with the goals of sustainable and well-informed construction practices, in which a harmonious balance between these factors is crucial.

Acknowledgements

This work was supported by the Directorate General of Higher Education, Research and Technology, Ministry of Education, Culture, Research and Technology as a part of the Penelitian Dasar Unggulan Perguruan Tinggi Research Grant to Binus University entitled “Konstrukti Hijau Untuk Masa Depan: Upaya Mengurangi Embodied Carbon Pada Proyek Gedung Bertingkat” with contract number 179/E5/PG.02.00/PL/2023; 1402/LL3/AL.04/2023; 149/VR. RTT/VII/2023).

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