SSRG International Journal of Civil Engineering
ISSN: 2348-8352/ https://doi.org/10.14445/23488352/IJCE-V12I10P104

Volume 12 Issue 10, 52-60, October 2025

Original Article

Integrated Assessment of Cost and Embodied Carbon in Parking Lot Pavement Design

Riza Suwondo[1], Made Suangga[2], Militia Keintjem[3], Mohammed Altaee[4]

[1,2]Department of Civil Engineering, Faculty of Engineering, Bina Nusantara University, Jakarta, Indonesia.
[3]Karbonara Research Institute, Jakarta, Indonesia.
[4]Environmental Research and Studies Centre, University of Babylon, Iraq.

[1]Corresponding Author : riza.suwondo@binus.ac.id

Received: 04 August 2025 Revised: 06 September 2025 Accepted: 05 October 2025 Published: 31 October 2025

Abstract *- The construction sector significantly contributes to global greenhouse gas emissions, with rigid pavement systems forming a substantial portion of urban infrastructure. Although structural performance has traditionally guided pavement design, there is a growing need to incorporate environmental and economic considerations, particularly embodied carbon and construction costs, into early-stage design decisions. This study aims to identify the optimum rigid pavement configuration for parking lots by evaluating the influence of concrete compressive strength and lean concrete subbase thickness on the structural thickness, embodied carbon, and cost. Twelve pavement configurations were analysed, varying in concrete grade (20–40 MPa). Subbase conditions (0, 50, and 100 mm of lean concrete), under a uniform subgrade condition (CBR 6%) and 40-year design life based on ACI 330 Traffic Spectrum C. Pavement thickness was determined using PavementDesigner.org, and a cradle-to-gate Life Cycle Assessment (LCA) was conducted in accordance with BS EN 15978 to quantify embodied carbon. Construction cost estimation followed a unit-price approach using standardised data from the Indonesian Ministry of Public Works (PUPR). The results revealed that designs using 25–30 MPa concrete without a subbase offered the best performance trade-off, achieving the lowest embodied carbon (48.2–48.3 kgCO$_2$e/m^2) and construction cost (US\$9.2–9.3/m^2), while still satisfying design reliability. In contrast, high-strength concrete (40 MPa) with a 100 mm subbase increased emissions and cost by up to 50% and 52%, respectively, with a marginal structural benefit. These findings highlight the need to avoid excessive overdesign. They show moderate-strength concrete with a minimal subbase, which offers a structurally sound, cost-effective, and environmentally friendly solution for urban parking lot pavements.*

Keywords *- Rigid Pavement, Embodied Carbon, Parking Lot Design, Life Cycle Assessment, Sustainable Construction.*

1. Introduction

Rising levels of greenhouse gas emissions have led to significant environmental effects. These include faster melting of polar ice caps and a rise in the frequency and severity of extreme weather events. The impacts of global warming threaten ecosystems, economies, and human health. As a result, cutting greenhouse gas emissions has become an urgent global priority [1-4].

The building and construction sector is one of the largest sources of global emissions, responsible for about 40% of total greenhouse gas output [5]. Within this sector, roads and other pavement infrastructures take up a large share of material use and related emissions, especially during construction.

Because of this, efforts to lower emissions from pavement construction have become a key strategy in combating climate change [6-9].

Among the various infrastructure components, parking lots make up a significant portion of the paved surfaces in modern cities. Despite their common presence, they are often ignored in sustainability efforts, which usually target larger infrastructure like highways and major roads. However, because of their extensive coverage and the use of materials that require many resources, parking lot pavements greatly add to the environmental impact of urban growth [10-13]. One important part of this impact is embodied carbon, which refers to the greenhouse gas emissions linked to all stages of a material's life cycle, including extraction, manufacturing, transportation, and construction. To effectively reduce these emissions, it is essential to adopt a lifecycle view that examines the environmental impact over the entire lifespan of the pavement system. This includes construction, maintenance, repair, and disposal at the end of life [14-17]. To achieve meaningful cuts in embodied carbon, we need a combined approach that includes using low-carbon materials, sustainable building practices, energy-efficient methods, and plans for reusing and recycling materials [18-20]. Pavement design has been studied extensively, focusing on improving structural performance while reducing economic and environmental impacts. Author looked at how concrete grade and subgrade California Bearing Ratio (CBR) affect rigid pavement performance. Their results showed that higher concrete grades increase the embodied carbon due to more cement, but have a slight impact on construction costs. On the other hand, raising the CBR values significantly lowered pavement thickness, embodied carbon, and related costs.

In a later study, Author analysed the balance between embodied carbon and construction costs for flexible and rigid pavements. They developed a decision-making framework that combined environmental and economic measures. Their findings revealed that flexible pavements with a Cement-Treated Base (CTB) had the lowest embodied carbon at 40 $kgCO_2e/m^2$, while rigid pavements with Lean Mix Concrete (LMC) showed the highest at 108 $kgCO_2e/m^2$. CTB-based flexible pavements were also the most cost-effective, highlighting the importance of choosing the right base material.

Expanding beyond localised case studies, Santero et al. [21] suggested specific actions to lower the embodied carbon of pavement systems in different situations. These included increasing supplementary cementitious material content (e.g., fly ash), enhancing reflectivity with white aggregates, and improving rehabilitation methods. Many of these approaches achieved at least 10% reductions in GHG emissions, often at costs aligned with global carbon pricing benchmarks. Meanwhile, Rengelov et al. [22] in their review of 27 projects across the U.S., highlighted mixture overdesign, especially excessive cement content, as a critical contributor to carbon emissions. Their findings support data-driven interventions, such as standard mix optimisation and lifecycle carbon reporting, as effective tools for reducing the environmental impact of the construction sector.

Complementing these findings, Abey and Kolathayar [23] reviewed lifecycle energy and carbon emissions from various pavement systems and emphasised the role of recycled and alternative materials (e.g., fly ash, recycled aggregates) in reducing embodied impacts. Similarly, Bernardin et al. [24] provided a systems-level view by integrating both construction-related embodied carbon and vehicle emissions during operation, showing that design decisions such as implementing dedicated freight lanes can have long-term sustainability benefits. Their findings highlight the importance of linking infrastructure design with operational energy savings.

Further contributing to methodological advancement, Singh et al. [25] developed a comprehensive Life Cycle Assessment (LCA) approach to compare Pervious Concrete Pavement (PCP) and Portland Cement Concrete Pavement (PCCP). Their results showed that PCP systems with aggregate bases could reduce embodied energy and GHG emissions by 3% and 2.7%, respectively, compared to PCCP systems. Although the capital costs for PCP were slightly higher with ready-mix concrete (1.21%), they were significantly lower (4.13%) when constructed with in-situ mixing, highlighting the importance of context-specific construction practices in determining overall sustainability.

Although considerable research has been dedicated to evaluating the environmental impacts of pavement infrastructure, existing studies have predominantly concentrated on high-volume roads, such as highways and arterial routes. In contrast, parking lot pavements, despite their extensive use in urban areas, remain underrepresented in sustainability-focused research. Although previous studies have addressed embodied carbon, life cycle energy, and construction costs for general pavement systems, there is a lack of integrated analyses that combine both environmental and economic assessments tailored specifically to rigid parking lot pavements.

To address this gap, this study explores the optimisation of rigid pavement design configurations for parking lots by varying the concrete compressive strengths and lean concrete subbase thicknesses. A cradle-to-gate Life Cycle Assessment (LCA) approach was employed to quantify the embodied carbon, while standardised cost estimation methods based on Indonesian construction data were used to evaluate construction costs. The overarching objective is to identify the most cost-effective and environmentally efficient rigid pavement solutions, thereby supporting informed and sustainable decision-making in urban infrastructure development.

2. Methodology

This study aimed to find the best rigid pavement setup for parking lots by looking at the embodied carbon and construction costs of different design options. The methodology includes four main stages: (1) Defining design Scenarios, (2) Designing The Structure of Rigid Pavements, (3) assessing Embodied Carbon, and (4) Estimating Construction Costs.

2.1. Design Scenarios

This study looked at different rigid pavement designs for parking lots, focusing on changes in material strength and subbase makeup. The design scenarios were created by changing two main factors: concrete compressive strength and subbase thickness, while keeping the subgrade condition the same. This method enabled a comparison of the embodied carbon and construction costs for a variety of practical design options. Four concrete grades were considered in the analysis: 20, 25, 30, 35, and 40 MPa. These grades represent commonly used mixes in pavement construction and show different levels of material strength and cement content. These factors directly affect both the structural performance and environmental impact of the pavement. To examine the role of subbase support, three subbase configurations were evaluated: (i) no subbase layer, (ii) a 50 mm-thick subbase, and (iii) a 100 mm-thick subbase.

The subbase layer is made from Lean Mix Concrete (LMC), a low-strength mixture often used to provide uniform support, reduce deflections, and improve load transfer under the rigid pavement slab. By varying the subbase thickness, this study looked at the balance between material input, structural strength, and the environmental and economic impact.

A uniform subgrade condition with a California Bearing Ratio (CBR) of 6% was adopted across all design configurations to represent typical medium-strength soils commonly encountered in urban parking lots. This standardisation ensures a consistent baseline that allows for a controlled comparison of how variations in concrete compressive strength and subbase thickness influence pavement performance, cost, and embodied carbon. By isolating these variables, the analysis maintained scientific validity and avoided confounding effects from geotechnical variability. Although site-specific subgrade differences may exist in practice, the use of a constant CBR in this study supports methodological clarity and aligns with previous literature on pavement design optimisation.

2.2. Rigid Pavement Design

The structural design of rigid pavement in this study is conducted per the guidelines outlined in ACI PRC-330-21[26], specifically adopting the Traffic Spectrum C, which is suitable for light to medium truck traffic commonly encountered in commercial and public parking lot facilities. The design was performed for a service life of 40 years, ensuring long-term structural adequacy under repeated loading.

The design traffic is characterised by an Average Annual Daily Truck Traffic (AADTT) of 500 trucks per day, representing a moderately trafficked parking area intended for commercial use. A design reliability level of 95% was adopted, with the allowable performance criterion set such that no more than 5% of the pavement slabs were expected to exhibit cracking at the end of the design life. These parameters match the industry standards for parking lot design. They aim to balance structural performance, cost, and sustainability.

The flexural strength of concrete (modulus of rupture (MR)) is a key input for pavement thickness designs. In this study, MR was calculated empirically based on the concrete compressive strength (f'_c) using the following equation [27]:

$$MR = 0.75\sqrt{f_c'} \tag{1}$$

Where MR is expressed in megapascals (MPa), and f'_c is the 28-day compressive strength of the concrete in MPa. The tensile performance of concrete, which determines the slab's resistance to flexural cracking under wheel loadings, can be conservatively estimated using this relationship.

The American Concrete Pavement Association (ACPA), the National Ready Mixed Concrete Association (NRMCA), and the Portland Cement Association (PCA) collaborated to create PavementDesigner.org, a well-known web-based tool for designing pavement thickness. This platform employs a cumulative fatigue damage analysis method, considering user-defined input parameters, including:

- Traffic loading
- Concrete flexural strength
- The subgrade support is represented by the modulus of subgrade reaction (k-values), which varies based on the subbase condition.
- Design reliability: 95%
- Allowable slab cracking: 5% at the end of design life

These input parameters allow PavementDesigner.org to simulate realistic loading and deterioration scenarios and compute the required pavement thickness to achieve the targeted design reliability and performance criteria for different design scenarios.

2.3. Embodied Carbon Assessment

This study used a cradle-to-gate Life Cycle Assessment (LCA) framework based on BS EN 15978:2011[28], which standardises the environmental assessment of construction products, to assess the environmental performance of each rigid pavement configuration. Modules A1–A3, which cover the phases from raw material extraction and transportation to manufacturing facilities and material production processes, were the only ones included in the analysis. In order to concentrate on material-related impacts—which are usually the most important in terms of embodied carbon—this boundary was selected.

Prior studies have substantiated the significance of evaluating the cradle-to-gate stage. According to the London Energy Transformation Initiative (LETI) [29], construction activities (Module A5) typically contribute only about 5% of the total lifecycle embodied carbon in typical buildings. In comparison, Modules A1–A3 can account for up to 50% of this total. Comparable results from other case studies show that site construction and transportation together usually contribute between 1% and 15% [31]. In order to compare the environmental performance of various materials and design configurations, the cradle-to-gate stage offers a targeted and significant indicator. Based on the amounts of the materials and the corresponding carbon emission factors, the total Embodied Carbon (EC) for each pavement configuration was determined in this study. The following equation was applied.

$$EC = \sum Q_i CF_i \quad (2)$$

Where CF_i is the corresponding carbon factor ($kgCO_2e/m^3$) for material i and Q_i is the amount (mass) of material i used in the pavement design (m^3). The Carbon Factors (CF) used in the calculations are listed in Table 1 and obtained from reliable and standardised sources, including the Inventory of Carbon and Energy (ICE v3.0) and Circular Ecology's carbon database [32].

Table 1. Carbon factor value

Material	Carbon factor
Lean concrete	213 $kgCO_2e/m^3$
Concrete grade fc' 20 MPa	284 $kgCO_2e/m^3$
Concrete grade fc' 25 MPa	301 $kgCO_2e/m^3$
Concrete grade fc' 30 MPa	355 $kgCO_2e/m^3$
Concrete grade fc' 35 MPa	380 CO_2e/m^3

2.4. Construction Cost Estimation

The economic performance of each rigid pavement configuration was evaluated through a construction cost analysis, which estimated the total initial cost associated with material procurement and placement. The analysis adopts a unit-cost-based approach, consistent with prevailing industry practices in Indonesia. The total construction cost per square meter of pavement was calculated by summing the costs of all material components, primarily concrete for the pavement slab and lean concrete for the subbase layer (if present). The cost calculation follows the following equation:

$$Cost = \sum Q_i P_i \quad (3)$$

Where Pi is the unit price of material i. Unit prices (Pi) are obtained from the standard regional construction cost database issued by the Indonesian Ministry of Public Works [36], ensuring that the cost estimates align with the actual market conditions and government-regulated pricing structures. Table 2 lists the unit prices used in this study.

Table 2. Unit costs of materials (1 US$ = 16,000 IDR)

Material	Unit price (US$)
Lean concrete	45.5
Concrete grade fc' 20 MPa	51.5
Concrete grade fc' 25 MPa	57.6
Concrete grade fc' 30 MPa	63.6
Concrete grade fc' 35 MPa	69.7

The resulting construction cost values are expressed in Indonesian Rupiah per square meter (US$/m²) and are used in conjunction with the embodied carbon results to evaluate the trade-offs between environmental and economic performance. This dual-criteria assessment supports the identification of pavement configurations that are both cost-efficient and environmentally sustainable for parking lot applications.

3. Results and Discussion

Figure 1 shows the relationship between the concrete compressive strength and required pavement thickness for three subbase configurations: no subbase, 50 mm Lean Mix Concrete (LMC), and 100 mm LMC. As expected, the results showed that pavement systems without a subbase consistently required the greatest slab thickness for all concrete strengths.

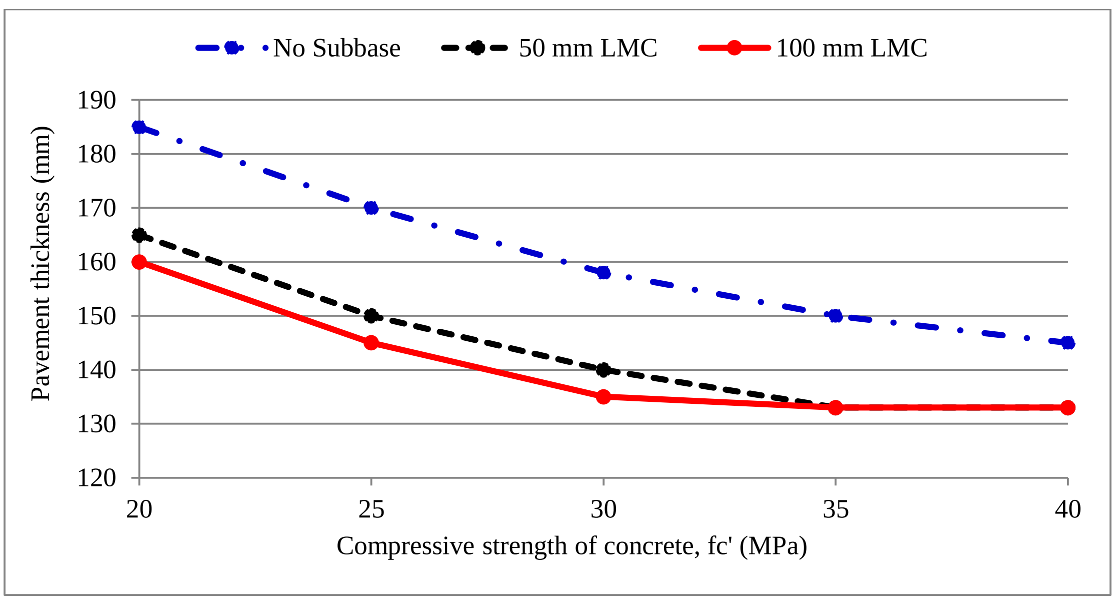

Fig. 1 Effect of concrete compressive strength and subbase thickness on required pavement thickness

This outcome is attributed to the lower effective subgrade modulus in the absence of a subbase, which increases the tensile stress experienced by the slab under loading, thus necessitating a thicker section to meet the structural performance criteria. The addition of a lean concrete subbase significantly enhanced the support stiffness, thereby reducing the required slab thickness. For example, at a compressive strength of 25 MPa, the required thickness decreases from approximately 170 mm (no subbase) to 160 mm with a 50 mm LMC layer and to 145 mm with a 100 mm LMC subbase. This trend demonstrates the structural efficiency provided by the subbase, which distributes the load more effectively and minimizes the flexural stresses at the bottom of the slab.

Increasing the compressive strength of concrete also resulted in a systematic reduction in pavement thickness under all subbase conditions. This is because the higher flexural strength (modulus of rupture) is associated with higher compressive strength, which can withstand higher tensile stresses, allowing for thinner slab sections while still satisfying the fatigue and reliability requirements. Notably, the reduction in thickness appears more pronounced between lower strength classes (e.g., from 20 to 25 MPa) and gradually diminishes as the concrete grade increases, indicating diminishing returns at higher strength levels. This suggests that beyond a certain point, further increases in concrete strength may offer limited benefits in terms of thickness reduction and may not be cost-effective when considering material and environmental impacts.

Figure 2 presents the embodied carbon values for each pavement configuration, considering the variations in the concrete compressive strength and sub-base thickness. The results confirmed a clear influence of both design parameters on the total embodied carbon per square meter of pavement. The use of a lean concrete subbase significantly increased the embodied carbon, with the 100 mm LMC consistently yielding the highest emissions across all strength levels. For instance, at 30 MPa, the embodied carbon increases from 48.2 $kgCO_2e/m^2$ (no subbase) to 52.8 $kgCO_2e/m^2$ (50 mm LMC) and 61.9 $kgCO_2e/m^2$ (100 mm LMC). This trend is expected because the lean concrete subbase contributes additional cement content, which is one of the most carbon-intensive materials used in pavement construction.

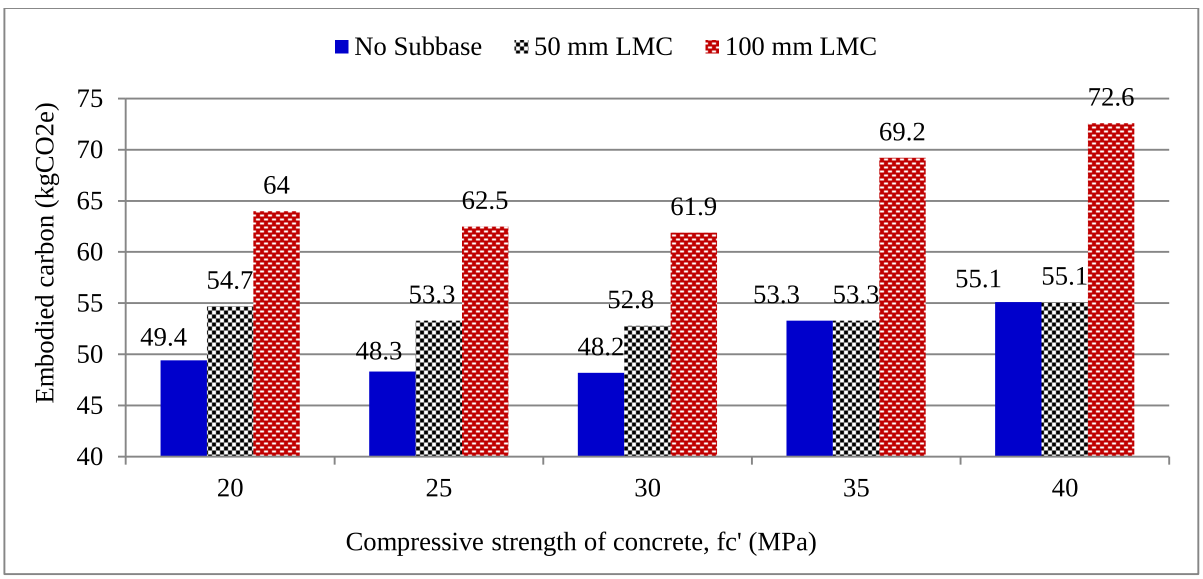

Fig. 2 Embodied carbon of pavement configurations across varying concrete strengths and subbase thicknesses

Across all subbase configurations, increasing the concrete strength from 20 to 40 MPa resulted in a nonlinear increase in the embodied carbon. Although the required slab thickness decreases with higher strength (as shown in Figure 1), the gain in material efficiency is eventually offset by the increasing cement content in high-strength mixes. The lowest embodied carbon was achieved at 25 MPa and 30 MPa, particularly for the configuration without a subbase, which showed values of 48.3 $kgCO_2e/m^2$ and 48.2 $kgCO_2e/m^2$, respectively. These represent the optimum range, offering a favourable balance between structural efficiency and material emissions. In contrast, the use of 40 MPa concrete with a 100 mm LMC subbase produced the highest embodied carbon at 72.6 $kgCO_2e/m^2$, which was over 50% higher than the optimum configuration. These findings emphasise the environmental cost of overdesign and highlight the need to avoid unnecessarily high-strength concrete or thick subbase layers unless structurally justified.

Figure 3 shows the estimated total construction cost per square meter (US$/m²) for various pavement configurations, considering different concrete compressive strengths and subbase thicknesses. The results clearly demonstrate the combined effect of the material grade and layer composition on the construction cost. Similar to the embodied carbon trend observed in Figure 2, incorporating a lean concrete subbase significantly increased the total construction cost. For each compressive strength level, the 100 mm LMC subbase consistently produced the highest cost, followed by the 50 mm LMC, whereas the configuration with no subbase was the most economical. For instance, at 30 MPa, the construction cost increased from US$ 9.2/m² (no subbase) to US$ 10.3/m² (50 mm LMC) and US$ 12.3/m² (100 mm LMC). This cost escalation is directly attributed to the additional volume of cementitious material in the subbase layer and the associated construction activities.

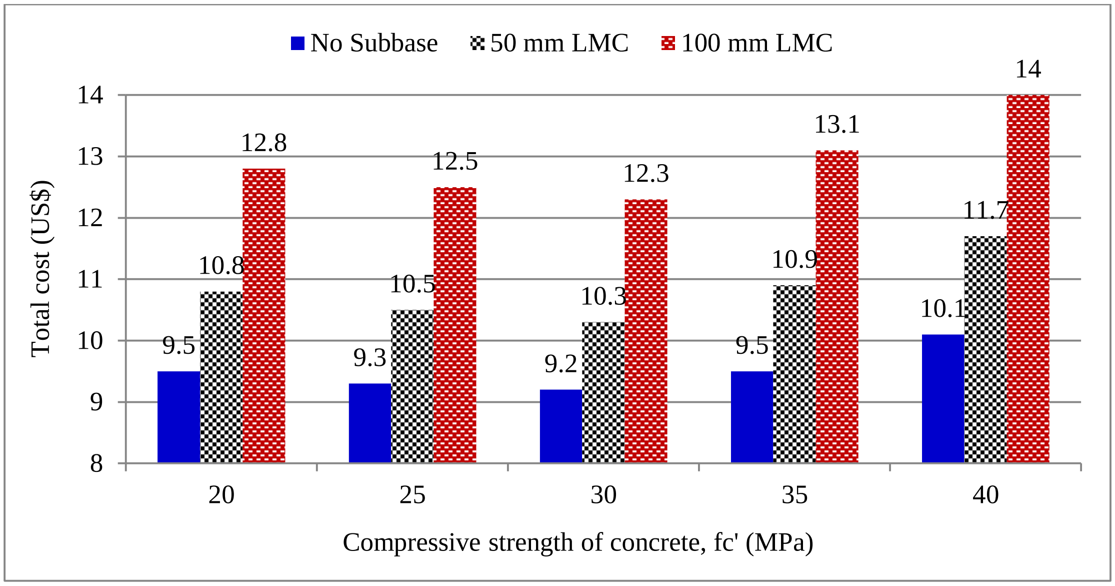

Fig. 3 Construction cost of pavement configurations across varying concrete strengths and subbase thicknesses

Furthermore, the effect of concrete compressive strength on cost followed a nonlinear pattern. Although higher-strength concretes enable reduced slab thickness, they incur higher material unit prices owing to their greater cement content. Consequently, the total cost began to increase more noticeably beyond 30 MPa, particularly when combined with thicker subbase layers. The highest cost was observed at 40 MPa with a 100 mm LMC subbase, reaching US$ 14.0/m², representing a 52% increase compared with the lowest-cost configuration. Notably, concrete strengths of 25 MPa and 30 MPa without a subbase consistently offer the most cost-efficient solutions, with values of US$ 9.3/m² and US$ 9.2/m², respectively. These configurations are not only economically favourable but also align with the lowest embodied carbon values identified in Section 3.2. This synergy reinforces the viability of these intermediate-strength concrete options as optimal design choices for balancing sustainability and cost efficiency in parking lot pavement construction.

The results of this study provide a comprehensive evaluation of rigid pavement design alternatives for parking lots by integrating structural, environmental, and economic criteria. The analysis clearly demonstrated that both the subbase thickness and concrete compressive strength significantly influenced the pavement thickness, embodied carbon, and construction cost. From a structural perspective, increasing the concrete strength and incorporating a lean concrete subbase effectively reduced the slab thickness owing to improved flexural performance and better subgrade support. However, these structural benefits must be weighed against their environmental and economic impact. The embodied carbon analysis revealed that thicker subbase layers and higher-strength concrete, particularly beyond 30 MPa, substantially increased the total emissions. A similar trend was observed in the construction cost results, where higher-strength concrete and sub-base use resulted in up to 52% higher costs than the most economical configurations.

The integration of the findings indicates that designs using 25 MPa and 30 MPa concrete without a subbase layer represent the most optimum solutions. These configurations achieved the lowest embodied carbon values (48.3 and 48.2 kgCO_2e/m², respectively) and the lowest construction costs (US$ 9.3/m² and US$ 9.2/m², respectively), while still meeting the structural performance requirements for a 40-year design life under moderate truck loading. The marginal difference between 25 and 30 MPa in both environmental and economic metrics suggests that either grade can be justified, depending on local material availability, cost fluctuations, and durability preferences. Conversely, the use of high-strength concrete (40 MPa) combined with a 100 mm

LMC subbase offers minimal additional structural benefit but results in the highest environmental impact (72.6 $kgCO_2e/m^2$) and cost (US$ 14.0/m²), making it an inefficient choice unless dictated by site-specific performance constraints.

In addition to the initial embodied carbon and construction cost, long-term performance is a critical factor in pavement design. The use of higher concrete grades, such as 30 MPa and 35 MPa, generally enhances the mechanical performance and resistance to fatigue cracking, which can extend the service life and reduce maintenance needs. However, as observed in this study, 25 MPa concrete achieves a favourable balance between adequate structural performance and sustainability indicators.

Moreover, the inclusion of lean concrete subbases significantly improved the load distribution and mitigated the effects of subgrade deformation, particularly over the 40-year design life considered in this study. This is consistent with the performance data from rigid pavements in temperate and tropical regions, which show that even minor subbase layers can substantially reduce long-term cracking and corner break distress. Therefore, the proposed configurations not only reduce embodied carbon and construction costs but are also expected to perform reliably with minimal interventions over time, making them well-suited for sustainable urban parking infrastructure.

In summary, the findings support the adoption of moderate-strength concrete (25–30 MPa) and minimal subbase use as sustainable and cost-effective strategies for rigid pavement design in parking-lot applications. Compared to studies conducted in other regions, the findings of the study show alignment and important distinctions. For instance, Singh et al. [25] highlighted in their comparative life cycle assessment of pervious and Portland cement pavements in India that concrete strength and base layer type significantly affect both environmental and economic outcomes, similar to the trends observed in this study. Meanwhile, in the United States, Rengelov et al. [22] found that optimizing mix designs by avoiding overdesign in concrete composition was the most effective strategy for reducing embodied carbon, particularly due to the dominant impact of cement on total emissions—echoing the present study's observation on the relationship between compressive strength and embodied carbon. However, regional cost variations and material availability play a crucial role; for example, in some high-income countries, the cost difference between pavement types may be less pronounced owing to subsidies or mature recycling systems, whereas in Indonesia, cost efficiency remains a more dominant factor. These comparisons reinforce the applicability of the cradle-to-gate embodied carbon approach in various contexts, highlighting the need for region-specific design strategies that balance performance, cost, and sustainability.

In addition to structural design and material strength considerations, the integration of low-carbon materials is increasingly recognised as a critical pathway for decarbonising pavement infrastructure. Recent studies have demonstrated the potential of alternative binders, such as geopolymer binders [33-35] and recycled aggregate mixes [36-38], present additional avenues for reducing embodied carbon beyond structural design optimisation. The integration of such materials could extend the reduction potential achieved in this study.

4. Conclusion

This study investigated the optimum design of a rigid pavement for parking lot applications by evaluating a series of configurations that varied in terms of the concrete compressive strength and lean concrete subbase thickness. The assessment integrated structural performance, embodied carbon, and construction cost using a cradle-to-gate life cycle perspective and standardised cost estimation based on Indonesian data.

The results confirmed that increasing the concrete strength and incorporating a lean concrete subbase effectively reduced the required slab thickness owing to the improved flexural capacity and subgrade stiffness. However, these benefits are accompanied by significant increases in embodied carbon and construction costs. Notably, the use of a 100 mm subbase and 40 MPa concrete resulted in the highest environmental impact (72.6 $kgCO_2e/m^2$) and construction cost (US$ 14.0/m²), indicating an inefficient use of materials under typical parking lot conditions.

Conversely, the most environmentally and economically optimal designs were achieved using moderate-strength concrete (25–30 MPa) without a subbase layer. These configurations yielded the lowest embodied carbon (48.2–48.3 $kgCO_2e/m^2$) and construction cost (US$9.2–9.3/m²), while still satisfying the design requirements of ACI 330 Traffic Spectrum C for a 40-year design life at 95% reliability. These findings highlight the importance of avoiding overdesign and emphasise the role of material selection and structural efficiency in achieving sustainability goals.

In conclusion, rigid pavement designs that combine moderate concrete strength with minimal subbase use provide the best balance of structural adequacy, environmental impact, and cost efficiency. These findings provide practical guidance for engineers and urban planners seeking to balance sustainability and cost efficiency in parking lot pavement design. Although this study focused on cradle-to-gate assessment and medium-strength subgrades, future research should explore full lifecycle performance, maintenance considerations, and the use of alternative low-carbon materials. These insights support more sustainable decision-making in urban pavement design and contribute to broader efforts to reduce embodied carbon in the construction sector.

Acknowledgements

The authors express their sincere gratitude to the Karbonara Research Institute for the invaluable support and resources provided throughout this study. Special thanks are extended to the Civil Engineering Department of BINUS University for their continuous guidance and access to the necessary facilities and equipment. The authors acknowledge the use of AI-powered language models, particularly ChatGPT, in assisting with the drafting of this manuscript, while affirming that the research methodology, analysis, and conclusions remain entirely the work of the authors.

Funding Statement

Bina Nusantara University supported this study.

Author Contribution

RS prepared the manuscript, MS reviewed it, MK performed the analysis, and MA reviewed it.

Data availability

Data analysis https://zenodo.org/records/16600693

References

[1] Muhammad Shafique, and Xiaowei Lu, "Environmental Life Cycle Assessment of Battery Electric Vehicles from the Current and Future Energy Mix Perspective," *Journal of Environmental Management*, vol. 303, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[2] Larry E. Erickson, and Gary Brase, *Reducing Greenhouse Gas Emissions and Improving Air Quality: Two Interrelated Global Challenges*, 1st ed., CRC Press, pp. 1-178, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[3] Nonna Martinov-Bennie, "Greenhouse Gas Emissions Reporting and Assurance: Reflections on the Current State," *Sustainability Accounting, Management and Policy Journal*, vol. 3, no. 2, pp. 244-251, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[4] Michał P. Drewniok et al., "Mapping Material Use and Embodied Carbon in UK Construction," *Resources, Conservation and Recycling*, vol. 197, pp. 1-10, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[5] UNEP, "*2023 Global Status Report for Buildings and Construction*," Global Alliance for Buildings and Construction, Report, pp. 1-18, 2023. [Publisher Link]

[6] Nwe Ni Myint, and Muhammad Shafique, "Embodied Carbon Emissions of Buildings: Taking a Step towards Net Zero Buildings," *Case Studies in Construction Materials*, vol. 20, pp. 1-20, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[7] Elena Pérez-Bernabeu et al., "Horizontal Cooperation in Road Transportation: A Case Illustrating Savings in Distances and Greenhouse Gas Emissions," *International Transactions in Operational Research*, vol. 22, no. 3, pp. 585-606, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[8] Valentina Radić et al., "Regional and Global Projections of Twenty-First Century Glacier Mass Changes in Response to Climate Scenarios from Global Climate Models," *Climate Dynamics*, vol. 42, pp. 37-58, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[9] Bin Ouyang et al., "Methodology of Urban Transport Carbon Emission Calculation Applicable for China: Guangzhou as a Case Study," *Proceedings of 4th International Conference on Logistics, Informatics and Service Science*, pp. 447-456, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[10] Giulia Del Serrone, Paolo Peluso, and Laura Moretti, "Photovoltaic Road Pavements as a Strategy for Low-Carbon Urban Infrastructures," *Heliyon*, vol. 9, no. 9, pp. 1-15, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[11] Kuldip Kumar et al., "In-Situ Infiltration Performance of Different Permeable Pavements in a Employee Used Parking Lot – A Four-Year Study," *Journal of Environmental Management*, vol. 167, pp. 8-14, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[12] Tiziano Dalla Mora et al., "Mitigation Urban Heat Island by Using Porous and Permeable Block Pavement," *Energy and Buildings*, vol. 346, pp. 1-31, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[13] Xiaodan Chen, and Hao Wang, "Life-Cycle Assessment and Multi-Criteria Performance Evaluation of Pervious Concrete Pavement with Fly Ash," *Resources, Conservation and Recycling*, vol. 177, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[14] Jaime Styer et al., "Innovations in Pavement Design and Engineering: A 2023 Sustainability Review," *Heliyon*, vol. 10, no. 13, pp. 1-24, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[15] Qingcheng Meng et al., "Assessing the Environmental Impact of Building Life Cycle: A Carbon Reduction Strategy through Innovative Design, Intelligent Construction, and Secondary Utilization," *Developments in the Built Environment*, vol. 16, pp. 1-14, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[16] Ellen Marsh, John Orr, and Tim Ibell, "Quantification of Uncertainty in Product Stage Embodied Carbon Calculations for Buildings," *Energy and Buildings*, vol. 251, pp. 1-28, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[17] Lizhen Huang et al., "Carbon Emission of Global Construction Sector," *Renewable and Sustainable Energy Reviews*, vol. 81, pp. 1906-1916, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[18] Sajan KC, and Dipendra Gautam, "Progress in Sustainable Structural Engineering: A Review," *Innovative Infrastructure Solutions*, vol. 6, pp. 1-85, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[19] Zhi Cao et al., "*Decarbonizing Concrete: Deep Decarbonization Pathways for the Cement and Concrete Cycle in the United States, India, and China*," Industrial Sustainability Analysis lab-Climate works foundation, Technical Report, 2021. [Google Scholar]

[20] Johanna Lehne, and Felix Preston, "*Making Concrete Change Innovation in Low-carbon Cement and Concrete*," Chatham House Report, The Royal Institute of International Affairs, pp. 1-138, 2018. [Google Scholar] [Publisher Link]

[21] Nicholas Santero, Alexander Loijos, and John Ochsendorf, "Greenhouse Gas Emissions Reduction Opportunities for Concrete Pavements, *Journal of Industrial Ecology*, vol. 17, no. 6, pp. 859-868, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[22] Milena Rangelov et al., "Readily Implementable Strategies for Reducing Embodied Environmental Impacts of Concrete Pavements in the United States," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2676, no. 9, pp. 436-450, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[23] Sharon T. Abey, and Sreevalsa Kolathayar, "Embodied Energy and Carbon Emissions of Pavements: A Review," *Advances in Energy and Built Environment: Select Proceedings of TRACE 2018*, pp. 167-173, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[24] Vincent L. Bernardin, Michael Grovak, and Roberto Miquel, "Concrete versus Tailpipes: Importance of Embodied Carbon and Vehicle Emissions in Carbon Footprint of Dedicated Truck Lanes on I-70," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2270, no. 1, pp. 107-112, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[25] Avishreshth Singh, Poornachandra Vaddy, and Krishna Prapoorna Biligiri, "Quantification of Embodied Energy and Carbon Footprint of Pervious Concrete Pavements through a Methodical Lifecycle Assessment Framework," *Resources, Conservation and Recycling*, vol. 161, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[26] American Concrete Institute, *Commercial Concrete Parking Lots and Site Paving Design and Construction—Guide*, ACI Committee 330, pp. 1-5, 2021. [Publisher Link]

[27] "*Road Pavement Design Manual*," No. 03/M/BM/2024, Ministry of Public Works and Public Housing Directorate General of Highways, Technical Report, pp. 1-389, 2024. [Publisher Link]

[28] *BS EN 15978:2011: Sustainability of Construction Works. Assessment of Environmental Performance of Buildings. Calculation Method*, BSI, 2011. [Google Scholar] [Publisher Link]

[29] *LETI Embodied Carbon Primer*, Supplementary guidance to the Climate Emergency Design Guide, pp. 1-144, 2024. [Publisher Link]

[30] Michael Samson, and Roger Pope, "A Comparative Embodied Carbon Assessment of Commercial Buildings," *The Institution of Structural Engineers*, vol. 90, no. 10, pp. 38-49, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[31] Vincent J.L. Gan et al., "A Comparative Analysis of Embodied Carbon in High-Rise Buildings Regarding Different Design Parameters," *Journal of Cleaner Production*, vol. 161, pp. 663-675, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[32] Circular Ecology, "*The Inventory of Carbon and Energy (The ICE Database)*," 2020. [Google Scholar] [Publisher Link]

[33] Xiaoli Ji et al., "Advancing toward a Low-Carbon Infrastructure: Emission Reduction Potential of Geopolymer Road Maintenance," *Materials Today Sustainability*, vol. 30, pp. 1-10, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[34] K.K.D.A. Wijesekara et al., "Mechanical and Durability Analysis of Geopolymer Concrete made with Recycled Silicate Activator for Low Carbon Breakwaters," *Cleaner Waste Systems*, vol. 11, pp. 1-17, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[35] Aly Muhammed Aly Ahmed, and Islam M. Mantawy, "Additive Construction of Low Embodied Carbon Concrete: Geopolymer Concrete," *Journal of Building Engineering*, vol. 111, pp. 1-16, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[36] Huanyu Li et al., "From Waste to Worth: Biochar and Hemp Fiber Synergy for Carbon-Sequestering and Durable Recycled ggregate Concrete," *Resources, Environment and Sustainability*, vol. 22, pp. 1-13, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[37] Mingyang Ma, Meng Chen, and Tong Zhang, "Research on the Mechanical Properties and Microstructure of Low-Carbon Ultra-High Performance Concrete using Carbonated Recycled Fine Aggregate," *Construction and Building Materials*, vol. 491, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[38] Eduardo Rigo et al., "Concrete with Recycled Aggregates from Construction: Properties, Emissions and Carbon Capture Assessment," *Case Studies in Construction Materials*, vol. 23, pp. 1-21, 2025. [CrossRef] [Google Scholar] [Publisher Link]