Cost and Carbon Evaluation of Sustainable Highway Pavement Materials

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ABSTRACT

This study assessed the life cycle cost and carbon footprint of highway pavement systems using sustainable construction materials. It compared conventional pavement with alternatives such as reclaimed asphalt pavement, warm mix asphalt, recycled concrete aggregate, and fly ash/slag-modified pavement. The assessment considered material production, transportation, construction, maintenance, rehabilitation, and end-of-life stages. Results showed that sustainable pavement systems reduced overall construction cost, lowered carbon emissions, conserved natural resources, and improved long-term environmental performance. The study concluded that life cycle-based evaluation is essential for selecting cost-effective and low-carbon pavement materials for sustainable highway infrastructure development.

Keywords: *Life Cycle Cost, Carbon Footprint, Sustainable Materials, Highway Pavement.*

I. INTRODUCTION

Highway pavement systems play a vital role in transportation infrastructure because they support mobility, trade, public access, regional connectivity, and economic development. However, the construction, maintenance, rehabilitation, and disposal of pavement structures require large quantities of natural resources, energy, fuel, aggregates, bitumen, cement, water, and construction equipment, which create significant economic and environmental burdens throughout the life cycle of a road project. In traditional pavement planning, the main focus was generally placed on initial construction cost, structural strength, traffic load capacity, and service life, while long-term maintenance expenditure and environmental impacts were often given limited attention. With increasing concerns related to climate change, rising construction costs, depletion of natural materials, carbon emissions, waste generation, and sustainable development, highway agencies and researchers have begun to evaluate pavement systems through life cycle-based approaches. Life Cycle Cost Assessment and Carbon Footprint Assessment have therefore become important tools for selecting suitable pavement materials and construction methods. Life Cycle Cost Assessment considers not only the initial construction cost but also the costs associated with maintenance, repair, rehabilitation, user delay, vehicle operation, and end-of-life activities over the entire design period of the pavement. Similarly, Carbon Footprint Assessment estimates greenhouse gas emissions generated during material extraction, manufacturing, transportation, construction, operation, maintenance, and disposal stages. When both assessments are applied together, they provide a more complete understanding of the economic efficiency and environmental sustainability of pavement alternatives. The use of sustainable construction materials in highway pavement systems has gained major importance because these materials can reduce dependence on virgin resources and lower carbon emissions. Materials such as reclaimed asphalt pavement, recycled concrete aggregate, fly ash, ground granulated blast furnace slag, waste plastic, crumb rubber, industrial by-products, warm mix asphalt, geopolymer binders, and other recycled or low-carbon materials are increasingly being studied as alternatives to conventional pavement materials. These materials can improve resource efficiency, reduce landfill waste, decrease energy consumption, and sometimes enhance pavement performance when properly designed and applied. For example, the use of reclaimed asphalt pavement can reduce the demand for fresh bitumen and aggregates, while industrial by-products such as fly ash and slag can partially replace cementitious materials and reduce carbon-intensive cement consumption. Similarly, warm mix asphalt technologies can reduce mixing and compaction temperatures, thereby lowering fuel consumption and emissions during production and construction. Despite these benefits, sustainable materials must be assessed carefully because their performance, durability, availability, transportation distance, processing requirements, and maintenance needs can influence both total life cycle cost and carbon output. A material that appears cheaper or greener at the construction stage may not remain sustainable if it leads to early pavement failure, frequent maintenance, or longer transportation distances. Therefore, an integrated evaluation is essential to compare pavement alternatives on the basis of both economic and environmental performance over their full life span. This study on life cycle cost and carbon footprint assessment of highway pavement systems using sustainable construction materials is significant because it supports decision-making for sustainable road infrastructure development. It helps engineers, planners, contractors, and policy-makers identify pavement designs that are cost-effective, durable, resource-efficient, and environmentally responsible. The study also encourages the adoption of circular economy principles in highway construction by promoting reuse, recycling, and reduction of construction waste. In the present context, where infrastructure development is expanding rapidly and environmental protection has become a global priority, sustainable pavement assessment provides a practical pathway for balancing engineering performance with ecological responsibility. By integrating life cycle cost analysis and carbon footprint estimation, highway pavement projects can be planned in a way that reduces long-term financial burden, minimizes greenhouse gas emissions, conserves natural resources, and improves the overall sustainability of transportation infrastructure. Thus, the assessment of highway pavement systems using sustainable construction materials is not only a technical requirement but also an important step toward resilient, low-carbon, and economically viable infrastructure development.

II. RESEARCH BACKGROUND

Li and Bao (2026) examined the challenges of carbon management in tunnel engineering, emphasizing that carbon emission intensity was highly sensitive to design schemes, which complicated mitigation efforts during the design phase. They reviewed existing literature on design-oriented carbon emission management, noting that although progress had been made, the research remained fragmented and lacked a comprehensive overview. The study employed a systematic literature review following PRISMA guidelines, analyzing 60 core publications to identify prevailing trends and research gaps. It was reported that current studies focused primarily on assessment methods, low-carbon design elements, optimization of carbon emissions in design schemes, and emission reduction strategies. However, four major limitations were highlighted: the absence of uncertainty analysis in assessment methods, insufficient exploration of coupling mechanisms among low-carbon design elements, lack of dynamic lifecycle optimization, and limited adaptability of emerging technologies. To address these issues, the authors proposed a novel framework for tunnel carbon management based on “intelligent perception–regulation optimization–negative carbon conversion.”

Wan et al. (2026) addressed the growing emphasis on designing low-carbon emission railways and noted that previous studies had not sufficiently evaluated carbon emissions across the entire alignment search space, limiting the identification of low-emission areas. They proposed a carbon emission pre-evaluation model, in which the study area was discretized into voxels through geographic information system (GIS) analysis, and structural properties were recorded for each voxel. Carbon emissions were then quantified for standard structural segments and allocated to the corresponding voxels. The model was subsequently integrated with an earlier alignment environmental suitability model that accounted for topologic and geologic factors. Using a multi-criteria decision-making approach, specifically the CRITIC-VIKOR method, a three-dimensional environmental suitability classification map (3D-ESCM) was derived. This 3D-ESCM was combined with a customized three-dimensional distance transform (3D-DT) algorithm to optimize alignment. The methodology was ultimately applied successfully to a realistic case study, demonstrating its effectiveness in low-carbon railway planning.

Duan et al. (2025) investigated the dual challenge of construction waste accumulation and the shortage of conventional construction materials by examining the recycling potential of construction and demolition waste (CDW) in pavement base applications. The study employed waste concrete and waste bricks as recycled aggregates, while cement, lime, and fly ash were used as stabilizing agents to evaluate the feasibility of recycled aggregate-based road materials. It was reported that the physical and macro-mechanical properties of the materials were systematically analyzed, and the effects of stabilizer dosage (ESR), recycled aggregate dosage (RASR), and brick-concrete ratio (BCR) on road performance were assessed. The findings indicated that stabilized recycled aggregates were suitable for road subgrade applications, with factor significance ranked as BCR > RASR > ESR. The optimal mixture was identified at 30–45% recycled aggregate content and a 1:2 BCR. Life cycle assessment further revealed notable carbon emission reductions, confirming the substantial environmental benefits of recycled aggregates in pavement construction.

Zhang et al. (2024) examined the growing concern of greenhouse gas emissions across sectors such as industry, agriculture, and transportation, with particular emphasis on carbon dioxide emissions arising from fossil fuel combustion and the use of secondary energy sources. The study highlighted that the construction phase of road engineering required substantial energy consumption and played a significant role in greenhouse gas emissions and environmental pollution within the transportation sector. It was reported that the authors provided a comprehensive summary of the theoretical foundations, calculation methods, and selection criteria for carbon emission factors in asphalt pavement construction. By evaluating the current environmental impacts associated with asphalt pavement construction, the study further outlined the principles and approaches for quantitatively estimating future carbon emissions. The findings emphasized that reducing carbon emissions in road construction was of considerable importance, thereby underscoring the need for more effective mitigation strategies and sustainable practices in pavement engineering and transportation infrastructure development.

Samad et al. (2024) examined the urgent issue of greenhouse gas (GHG) emissions in relation to climate change and emphasized the growing environmental concerns associated with expanding highway infrastructure in India. The study applied the life cycle assessment (LCA) approach to evaluate GHG emissions during the construction phase of the six-laning project of National Highway-66 in Kerala, India, using openLCA 2.0.1 software. It was reported that emissions were assessed from material production, on-site transportation, and off-site transportation activities. The findings indicated that the material production phase contributed significantly more GHG emissions than transportation-related activities. Among construction materials, Portland cement was identified as the highest emission source, followed by steel and gravel. A sensitivity analysis was further conducted by replacing conventional materials with sustainable alternatives such as fly ash and recycled coarse aggregates. The results showed that replacing 50% OPC with fly ash reduced emissions by 28.5%, while 100% recycled coarse aggregate replacement reduced emissions by 6.8%, highlighting the value of sustainable construction practices and policy support.

Zheng et al. (2023) investigated the growing global concern regarding greenhouse gas emissions and emphasized the need to reduce carbon emissions in transportation infrastructure construction and material production to mitigate climate change. The study aimed to estimate carbon emissions under three hypothetical roadway construction scenarios where roadways passed through polluted soil at contaminated sites, using the life cycle assessment (LCA) approach. It was reported that three remediation techniques—off-site cement kiln co-processing, on-site ex-situ thermal desorption, and on-site ex-situ solidification/stabilization—were evaluated. The baseline scenario involved off-site remediation with imported clean soil for roadway subgrade, while the other two scenarios reused treated contaminated soil as subgrade material. The LCA results demonstrated that total carbon emissions were reduced by 1168.48 to 2379.62 tons per basic unit, equivalent to 19.31% to 39.33% compared to the baseline. The study further revealed that reusing solid waste in place of sand and ordinary Portland cement significantly lowered emissions, highlighting sustainable remediation and material reuse as effective carbon reduction strategies.

Siva Rama Krishna and Naga Satish Kumar (2022) examined the significant role of transport infrastructure in shaping the social and economic development of nations and emphasized that pavement maintenance selection should be based on sustainability and long-term performance requirements. The study presented a case analysis of bituminous concrete pavement, in which pavement design, life cycle cost analysis, and greenhouse gas emissions were evaluated through a life cycle approach. Two maintenance alternatives, namely bituminous concrete overlay and ultra-thin cement concrete overlay (white topping), were compared. It was reported that bituminous concrete overlay was not considered a preferable option, whereas concrete overlay demonstrated better global performance. The findings indicated that ultra-thin white topping concrete overlay incorporating sustainable materials was a superior maintenance strategy. Although greenhouse gas emissions were found to be slightly higher in some cases, the life cycle cost analysis based on the net present value method and long-term pavement performance supported its adoption. The study concluded that this overlay option was more sustainable from economic and environmental perspectives.

Ongpeng and Ginga (2021) investigated the environmental sustainability of reconstructing earth-retaining walls (ERWs) for roads and highways in post-disaster scenarios, emphasizing their importance in restoring transportation access and supporting economic resilience. The study employed a cradle-to-gate life cycle assessment (LCA) to compare ERWs constructed with concrete containing natural aggregates (NAs) and recycled aggregates (RAs) derived from construction and demolition waste (CDW). Three ERW types—gravity walls, cantilever walls, and mechanically stabilized earth (MSE) walls—were evaluated. The findings indicated that MSE walls generated substantially lower environmental impacts, showing 50–70% less impact than the other ERW types. It was further reported that the use of RAs in concrete production reduced environmental impacts by up to 15% compared to NAs, despite a 10% increase in cement content to offset strength loss. The study also suggested optimal transport distances and recommended further research on economic feasibility and sustainable supply chains during reconstruction.

Roukounakis et al. (2020) investigated the growing environmental concerns associated with rising global transport demand and emphasized the importance of greenhouse gas (GHG) emissions in transport network planning and operational management. The study described the development of a novel methodology for estimating the carbon footprint of the major motorway Egnatia Odos in Northern Greece. It was reported that total GHG emissions for the base year 2014 were calculated from all corporate activities, including stationary and mobile combustion, fugitive emissions, purchased electricity, personnel travel, waste disposal, and contractor-related emissions. The study further incorporated end-user vehicle emissions using annual traffic data and emission factors derived from the TREMOVE model for various vehicle and fuel categories. An electronic platform was also developed to facilitate future carbon footprint calculations by highway personnel. The findings revealed that the total carbon footprint of Egnatia Odos S.A. in 2014 was estimated at 770 ktCO2e, with 91% of emissions attributed to end-user vehicle operations.

Karlsson et al. (2020) investigated the significant contribution of the construction sector to global CO_2 emissions, noting that it accounted for nearly one quarter of total emissions worldwide. The study assessed the potential for reducing the climate impact of road construction through a participatory integrated assessment involving key supply chain stakeholders, supported by energy and material flow mapping, literature review, and scenario analysis. It was reported that road construction CO_2 emissions could technically be reduced by half using currently available technologies and practices, more than three quarters by 2030, and nearly to net zero by 2045. The findings suggested that achieving near-term reductions depended heavily on sustainably produced second-generation biofuels, while also emphasizing the importance of alternative strategies such as optimized material use, improved mass handling, increased recycling of steel, asphalt, and aggregates, and greater adoption of alternative concrete binders. The study further highlighted the need for aligned policies, procurement reforms, electrification, carbon capture, and broader industrial transformation for deep decarbonization.

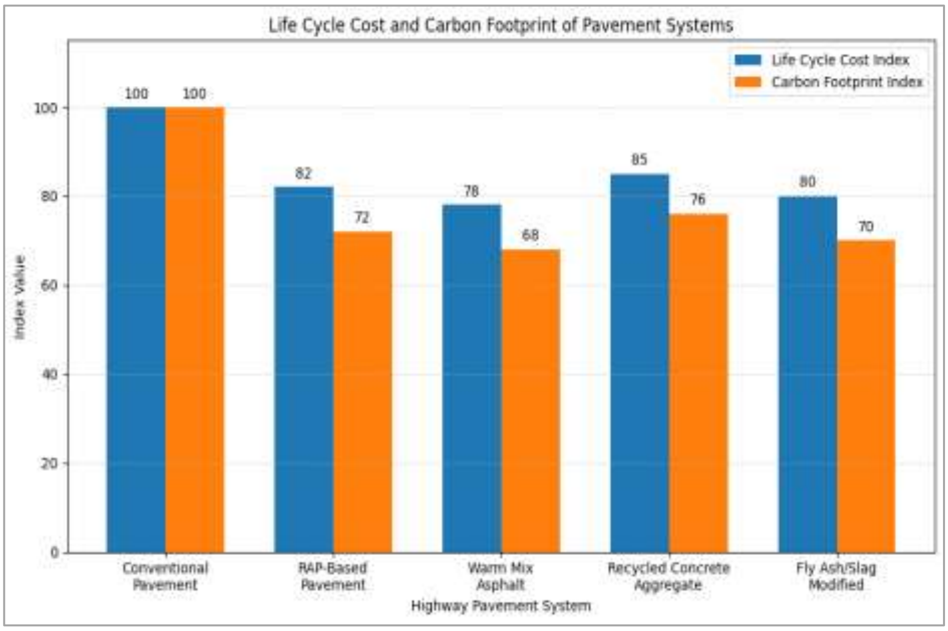
III. METHODOLOGY

The methodology of this study was based on a comparative life cycle assessment of conventional and sustainable highway pavement systems. First, different pavement alternatives were selected, including conventional asphalt pavement, reclaimed asphalt pavement, warm mix asphalt, recycled concrete aggregate pavement, and fly ash/slag-modified pavement. Relevant data were collected regarding material quantity, transportation distance, fuel consumption, construction energy, maintenance requirements, service life, and end-of-life disposal or recycling practices. After data collection, the study boundary was defined from material extraction to construction, maintenance, rehabilitation, and final disposal. This helped in evaluating the complete economic and environmental impact of each pavement system rather than considering only the initial construction stage. For life cycle cost assessment, all major cost components were calculated, including material cost, transportation cost, construction cost, maintenance cost, rehabilitation cost, and disposal cost. These costs were compared over a fixed analysis period to identify the most economical pavement option. For carbon footprint assessment, emission factors were applied to each activity, such as aggregate production, bitumen use, cement replacement, material transport, equipment operation, and asphalt mixing temperature. The total carbon emission of each pavement alternative was then estimated in terms of CO_2 equivalent. Finally, the obtained cost and carbon values were compared using tables and bar graphs. The results were interpreted to identify pavement systems that provided lower long-term cost, reduced greenhouse gas emissions, better resource efficiency, and improved sustainability performance. This methodology helped in selecting cost-effective and environmentally responsible pavement materials for highway construction.

IV. RESULT

The result of the study showed that highway pavement systems constructed with sustainable materials performed better in terms of long-term economy and environmental sustainability than conventional pavement systems. Although conventional pavement materials had lower familiarity and easier availability, their overall life cycle cost increased due to repeated maintenance, high consumption of virgin aggregates, bitumen, cement, and greater energy demand during production and construction. In comparison, sustainable pavement alternatives using reclaimed asphalt pavement, recycled concrete aggregate, fly ash, slag, crumb rubber, waste plastic, and warm mix asphalt reduced the dependency on natural resources and lowered greenhouse gas emissions throughout the pavement life cycle. The life cycle cost assessment indicated that sustainable pavement systems could reduce total project cost by decreasing material procurement cost, reducing waste disposal expenses, and improving resource utilization. The use of recycled and industrial by-product materials helped in lowering the cost of raw material extraction and transportation. In addition, pavements incorporating durable sustainable materials required comparatively less frequent rehabilitation, which reduced maintenance expenditure over the service period. The carbon footprint assessment also showed a clear reduction in CO_2 emissions because sustainable materials reduced energy-intensive production processes and minimized the use of high-carbon conventional binders.

Bar Graph



The bar graph compares life cycle cost index and carbon footprint index of different highway pavement systems. The conventional pavement shows the highest value, with both cost and carbon footprint indexed at 100, which indicates greater dependence on virgin materials, higher energy consumption, and more emissions during construction and maintenance. In comparison, all sustainable pavement systems show reduced values. Warm Mix Asphalt performs best, with a life cycle cost index of 78 and carbon footprint index of 68, showing that lower production temperature can reduce fuel use, construction cost, and CO_2 emissions. Fly Ash/Slag Modified Pavement also performs well, with cost and carbon indices of 80 and 70, because industrial by-products reduce the need for cementitious and conventional materials. RAP-based pavement records 82 cost index and 72 carbon index, proving that recycled asphalt can save materials and reduce emissions. Overall, the graph clearly shows that sustainable pavement systems are more economical and environmentally friendly than conventional pavement.

V. CONCLUSION

The study concluded that sustainable highway pavement systems provided better long-term economic and environmental performance than conventional pavement systems. The life cycle cost assessment showed that materials such as reclaimed asphalt pavement, warm mix asphalt, recycled concrete aggregate, fly ash, and slag could reduce overall project expenses by lowering the demand for virgin materials, reducing transportation needs, minimizing waste disposal, and decreasing maintenance frequency. Although some sustainable materials may require careful processing and quality control, their long-term benefits were found to be more significant than their initial limitations. The carbon footprint assessment also confirmed that sustainable construction materials helped in reducing greenhouse gas emissions throughout the pavement life cycle. Warm mix asphalt and fly ash/slag-modified pavement showed strong potential because they reduced energy consumption, fuel use, and carbon-intensive material production. The comparative graph clearly indicated that sustainable alternatives had lower cost and emission indices than conventional pavement. Overall, the use of sustainable construction materials in highway pavement systems supports cost-effective, durable, and low-carbon infrastructure development. Therefore, life cycle cost and carbon footprint assessment should be included in pavement design and material selection to promote environmentally responsible and economically viable road construction.

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