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Carbon Footprint Reduction in Road Construction - A Review

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Abstract: Road construction is one of the most resource-intensive sectors within civil infrastructure, generating significant carbon emissions through energy-intensive materials, heavy machinery, transport logistics, and maintenance activities. With global emphasis on climate change mitigation and sustainable development, reducing the carbon footprint of road construction has become a critical research priority. This review synthesizes contemporary advancements, sustainable material alternatives, eco-efficient technologies, and life-cycle-based assessment (LCA) frameworks that aim to decarbonize road infrastructure. Key strategies include replacing conventional materials with industrial by-products (fly ash, GGBFS, PMA), utilizing natural fibers (bamboo, coconut, human hair), incorporating recycled aggregates, adopting warm mix asphalt, and integrating digital tools such as BIM–LCA for real-time emission quantification. The review identifies major emission hotspots, evaluates technological interventions, and outlines policy, design, and material innovations for low-carbon road construction. Research gaps highlight the need for integrated LCA models, long-term durability studies of sustainable materials, and large-scale field validation, particularly in developing countries such as India. The findings support the development of cost-effective, durable, and low-carbon pavement systems that align with global carbon neutrality goals.
Keywords: Carbon footprint, road construction, rigid pavement, recycled materials, industrial by-products, LCA, greenhouse gas emissions, sustainable infrastructure, warm mix asphalt, digital construction.

I. INTRODUCTION

The rapid growth of transportation infrastructure has significantly increased global greenhouse gas (GHG) emissions, with road construction emerging as a major contributor due to its dependency on energy-intensive materials, heavy equipment, and fossil-fuel-driven processes. Cement production alone accounts for approximately 8% of global CO_2 emissions, while asphalt production and construction machinery further add to the carbon intensity of road projects. As nations pursue sustainable development and carbon neutrality targets under frameworks such as the Paris Agreement (2015), it has become imperative to transition towards low-carbon construction practices. Road construction involves multiple carbon-intensive phases, including material extraction, manufacturing, transportation, construction operations, maintenance, and end-of-life disposal. Each phase produces quantifiable emissions that can be analyzed through Life Cycle Assessment (LCA) methodologies defined in ISO 14040/14044. Recent studies reveal that material production contributes the highest share of emissions, particularly from cement, steel reinforcement, bitumen, aggregates, and their transportation. To address these concerns, global research has focused on identifying sustainable materials—industrial by-products like fly ash, GGBFS, silica fume; natural fibers such as bamboo, coconut, and human hair; and recycled aggregates from demolition waste. Simultaneously, technological interventions such as warm mix asphalt (WMA), digital tools like Building Information Modelling (BIM) integrated with LCA, and optimized construction methods are being adopted.

This review compiles and evaluates the extensive body of literature on carbon footprint reduction strategies in road construction, highlighting their environmental, economic, and performance implications. It further identifies research gaps that must be addressed to accelerate the adoption of low-carbon pavements in India and other developing economies.

II. LITERATURE REVIEW

The construction and transportation sectors are increasingly recognized as major contributors to global greenhouse gas (GHG) emissions, and road construction, in particular, plays a significant role due to the extensive use of energy-intensive materials, heavy machinery, and fossil fuel consumption during construction activities.

With the escalating concerns regarding climate change and environmental sustainability, researchers, engineers, and policymakers have emphasized the urgent need to adopt sustainable construction practices that minimize the carbon footprint of infrastructure projects. This literature review aims to provide a comprehensive understanding of the current state of knowledge regarding carbon emission sources in road construction, the application of sustainable materials, innovative construction technologies, and life-cycle assessment (LCA) approaches to quantify environmental impacts. The review synthesizes findings from global studies while highlighting research trends, technological advancements, and gaps that require further investigation. Specifically, the chapter focuses on alternative reinforcement materials, such as natural fibers including bamboo, coconut, and human hair, as well as industrial by-products such as fly ash and ground granulated blast furnace slag (GGBFS), which have shown promise in reducing cement consumption and enhancing the mechanical performance of rigid pavements. Additionally, it examines how the integration of these sustainable materials contributes to durability, crack resistance, and long-term performance while aligning with global efforts to reduce carbon emissions and achieve environmentally responsible infrastructure development.

Andiyani et al. (2025) conducted a case study to quantify the carbon footprint associated with rigid pavement road construction, highlighting the significant environmental impact of concrete-based road infrastructure. The study systematically mapped the construction process to identify major sources of CO2 emissions, employing data collected through site observations and stakeholder interviews. The total carbon emissions were calculated to be 176.45 tons CO2e, with the majority (168.87 tons, 95.7%) arising from material production, followed by 4.02 tons (2.3%) from construction activities and 3.56 tons (2.0%) from material transportation. Notably, the single reinforcement woven work sequence in concrete pavement was identified as the largest contributor, producing 80.05 tons of CO2. The authors emphasize that these findings underscore the need for further research focused on implementing low-carbon materials and ultra-low-emission construction equipment to mitigate the environmental impact of rigid pavement projects. This study provides crucial insights into the life cycle carbon emissions of rigid pavements and demonstrates the importance of integrating sustainable materials and construction practices to achieve carbon reduction in roadway infrastructure.

Verma et. al. (2025) investigated the observation and identification of carbon footprints associated with highway construction materials in India, highlighting the environmental challenges posed by rapid urbanization and increasing construction activities. The study emphasizes that construction practices, including the use of materials, machinery, and fossil fuels, significantly contribute to greenhouse gas (GHG) emissions, thereby exacerbating global warming and environmental degradation. To promote sustainable construction, the research explores the use of alternative materials, such as RBI grade-81—a patented natural soil stabilizer—which enhances the California Bearing Ratio (CBR) of subgrade soils and allows for reduced pavement thickness in flexible pavements, consequently lowering lifecycle GHG emissions. The study situates these findings within the broader context of environmental preservation, emphasizing the need to limit the consumption of natural resources, including aggregates and bitumen. By reviewing carbon footprint concepts and assessing CO2 emissions and energy consumption for bituminous and concrete road pavements, the research highlights the imperative for transportation agencies to adopt greener practices, optimize construction methods, and implement policies that reduce the environmental impact of road infrastructure. Overall, the study underscores the significance of integrating sustainable materials and design strategies to achieve low-carbon, environmentally responsible highway construction in India.

Lou et al. (2025) presented an innovative approach to quantifying carbon footprints in road construction through the integration of Building Information Modelling (BIM) and life cycle assessment (LCA) techniques, focusing specifically on earthwork operations. Recognizing that heavy-duty machinery accounts for a significant portion of energy consumption and greenhouse gas emissions during construction, the study developed a BIM-based methodology to accurately calculate CO2 emissions from earthwork machines, a component that has been historically underrepresented due to its operational complexity. The research analyzed a 3 km bicycle lane project in Trondheim, Norway, considering excavation, transport, and compaction tasks, while accounting for multiple operating modes of excavators (idling, moving, working), different transport vehicles (wheel dozer, tractor scraper, articulated dump truck), and two types of compaction machines (sheepsfoot and vibratory rollers). The study found that a total of 75.5 tons of CO2 emissions were generated by on-site machinery, with transport activities contributing the largest share (56%), particularly during soil relocation. Additionally, emissions from non-productive machine states, such as idling and moving, were noted as significant (2.9 t CO2), highlighting the importance of workflow optimization and efficient planning. The research underscores the strategic value of early-stage planning in reducing fuel consumption, improving operational efficiency, and mitigating environmental impacts, providing a practical framework for integrating digital construction tools with sustainability assessment. This study contributes to the advancement of low-carbon construction practices by demonstrating how BIM can enhance accuracy in carbon footprint evaluation and support sustainable infrastructure decision-making.

Wang et al. (2024) presented a comprehensive review of building lifecycle carbon emissions (CEBL) and corresponding reduction approaches, synthesizing findings from over 300 recent publications and discussing more than 100 key studies. The review systematically examined CO2 emissions across all phases of a building's lifecycle, including material production, transportation, construction, operation, demolition, and material recycling. While much of the existing literature emphasizes operational energy efficiency, the study identified critical gaps in quantifying emissions from transportation, on-site construction equipment, and the specific characteristics of non-residential buildings. Additionally, the review highlighted the pressing need for improved construction waste management, particularly in developing countries where landfilling remains prevalent. For carbon reduction, the authors discussed strategies such as leveraging carbon dioxide sinks, implementing integrated energy systems, integrating building-integrated photovoltaics (BIPV), and enacting effective policy interventions. By addressing both data and theoretical limitations in current research, the study advocates for more integrated, context-specific approaches to building lifecycle carbon assessment, thereby supporting the development of a sustainable built environment. This work provides valuable insights for engineers, architects, and policymakers seeking to minimize lifecycle carbon emissions and advance low-carbon strategies in the construction sector.

Lendra et al. (2024) conducted a comprehensive literature review to examine the environmental impacts of road construction and explore strategies for promoting green technologies in Indonesia. The study highlights that traditional road construction methods, particularly those using asphalt and cement, are highly energy-intensive and contribute significantly to greenhouse gas emissions. Utilizing the PRISMA method, the authors reviewed literature published between 2004 and 2024 from both national and international sources to identify best practices for reducing emissions throughout the construction process. Key strategies identified include the use of recycled materials, warm mix asphalt (WMA) technology, permeable pavement systems, green roofs, and energy-efficient construction equipment. The study emphasizes that sustainable design practices, combined with life cycle assessment (LCA), are essential for mitigating environmental impacts. Despite progress in implementing green technologies, challenges such as limited funding, inadequate technological adoption, and poor coordination persist in Indonesia. The authors recommend enhancing commitment and financial support, building technical capacity, improving coordination among stakeholders, and enforcing stricter regulations to advance sustainable road construction. The study further suggests that future research should focus on developing innovative green materials, optimizing construction equipment efficiency, and implementing advanced pavement design techniques to reduce carbon emissions and promote sustainable infrastructure development.

Suryakant Maurya and Ushendra Kumar (2024) The study highlighted the pressing need for sustainable practices in rigid pavement construction, stressing both the environmental and economic advantages of utilizing waste materials. It emphasized that incorporating industrial by-products such as fly ash, slag, and silica fume, along with recycled aggregates from demolished concrete and even plastic waste, can enhance mechanical strength, durability, and crack resistance while simultaneously conserving resources and minimizing landfill disposal. The study consolidated findings from recent research, demonstrating that such waste-inclusive pavements can achieve enhanced compressive strength and long-term performance, alongside potential cost savings in both construction and maintenance. Despite these advantages, the authors noted regulatory challenges, including the need for standardized testing protocols and quality assurance measures to ensure safety and reliability. They recommended further research on the long-term behavior of pavements containing waste materials and the development of guidelines and rigorous testing standards to ensure uniform quality. Overall, the review provides a comprehensive perspective on the dual benefits of sustainable waste utilization in rigid pavement construction, offering guidance for future research and practical applications in sustainable infrastructure development.

Kumar and Zhang (2024) explored carbon emission reduction (CER) in the construction industry, emphasizing the critical influence of procurement, project delivery methods (PDM), and emerging technologies such as artificial intelligence (AI) in fostering low-carbon practices. Using a qualitative approach, the study employed semi-structured interviews with industry professionals alongside engagement with generative AI tools to analyze patterns and identify effective strategies for CER. Findings revealed that early contractor involvement and integrated PDM are pivotal for achieving carbon reduction goals, with project owners playing a central role in steering projects toward sustainability. The study also highlighted key barriers to CER, including cost limitations, material availability, and human resource capacity. To address these challenges, the authors proposed the adoption of innovative low-carbon materials, financial incentives, educational initiatives, and regulatory standards. Additionally, the research explored the transformative potential of AI in optimizing construction practices, from material selection to operational planning, suggesting a pathway for technological integration to enhance environmental performance.

This study provides valuable empirical insights into the interplay between contracting methods, stakeholder engagement, and advanced technologies in decarbonizing the construction sector, emphasizing that strategic procurement and policy-driven approaches are essential for sustainable infrastructure development.

Franesqui, Yepes, and Valencia-Díaz (2024) investigated innovative strategies to improve the sustainability of asphalt pavements, with particular attention to low-energy production techniques, waste recycling, and the use of local geomaterials in volcanic environments. The study emphasized warm mix asphalt (WMA) technologies, which lower manufacturing temperatures compared to traditional hot mix asphalt, resulting in reduced energy consumption and emissions. Additionally, the research explored the incorporation of recycled materials, including rubber powder from used tires and residual aggregates from highly vesiculated volcanic rocks, to enhance mechanical properties while addressing waste disposal challenges. Laboratory tests on rubberized warm mix asphalt (RWMA) demonstrated compliance with current specifications and showed improved performance, including greater resistance to moisture and plastic deformation, as well as higher stiffness modulus for enhanced durability. Eco-efficiency analysis indicated that RWMA production reduces energy consumption and emissions by approximately 9%, with over 95% of waste materials effectively reused. The study concluded that combining low-energy asphalt techniques with local recycled materials can significantly enhance the sustainability and eco-efficiency of asphalt pavements, offering a practical solution to reduce environmental impact while maintaining engineering performance standards.

Jakhar and Meena (2023) reviewed study focused on the use of recycled materials in pavement construction, emphasizing their contribution to sustainability without compromising structural performance. It highlighted the urgent need for eco-friendly construction practices in response to increasing urbanization and resource depletion. Various recycled materials—such as recycled concrete aggregates (RCA), coarse recycled aggregates (CRA), rubberized materials, fibers, reclaimed asphalt pavement (RAP), jarosite, fly ash, and ground-granulated blast-furnace slag (GGBS)—were examined for their mechanical and durability characteristics. Findings revealed that these materials can achieve or even surpass conventional performance standards in terms of compressive strength, tensile strength, and elasticity. Durability tests showed that pavements incorporating recycled components often exhibit equal or improved resistance to environmental stressors like moisture, temperature variations, and chemical attack. Furthermore, the adoption of recycled materials offers significant environmental advantages, including reduced carbon emissions and minimized waste generation. The review concluded by stressing the importance of optimizing mix proportions, refining treatment techniques, and formulating standardized design and implementation guidelines to ensure sustainable and consistent use of recycled materials in pavement construction.Overall, the study concluded that incorporating recycled materials provides a practical pathway toward sustainable infrastructure, balancing ecological benefits with structural performance, and guiding future research, engineering practices, and policy development.

Zheng et al. (2023) investigated the evaluation of carbon emissions in roadway construction at contaminated sites, employing a life cycle assessment (LCA) approach to quantify environmental impacts across multiple construction scenarios. The study addresses the growing global concern over greenhouse gas emissions and emphasizes the need to reduce carbon outputs in transportation infrastructure, particularly when construction intersects with polluted soils. Three soil remediation methods were analyzed: off-site cement kiln co-processing, on-site ex-situ thermal desorption, and on-site ex-situ solidification/stabilization, with each scenario assessing the associated carbon emissions throughout the construction lifecycle. The baseline scenario involved off-site remediation and the transport of clean soil, while the other scenarios incorporated the reuse of remediated soils as roadway subgrade materials. Results indicated that total carbon emission reductions ranged from 1168.48 to 2379.62 tons per basic unit, corresponding to decreases of 19.31% to 39.33% relative to the baseline. Furthermore, the study highlighted that substituting conventional materials such as sand and ordinary Portland cement (OPC) with solid waste in roadway construction contributed to a reduction of 498.98 tons of CO2. The findings demonstrate that both optimized soil remediation strategies and the reuse of solid waste are crucial interventions for minimizing carbon emissions in roadway projects. This research contributes to sustainable infrastructure planning by illustrating how LCA can guide environmentally responsible construction practices, particularly in complex contexts such as contaminated sites.

Al-Hindawi et al. (2023) investigated the use of waste materials to enhance sustainability in rigid pavement construction, focusing on waste concrete and ground-granulated blast-furnace slag (GGBFS) as partial replacements in cement-based materials. The research included laboratory tests in which waste concrete was used as a partial replacement for natural aggregates at proportions of 0%, 10%, 20%, 30%, and 40%, with ground granulated blast furnace slag (GGBFS) incorporated as a supplementary cementitious material (SCM). The concrete specimens were evaluated for compressive, splitting tensile, and flexural strengths after 7 and 28 days of curing. Findings revealed that the Strength Activity Index (SAI) of mixes containing waste materials remained within acceptable ranges, showing only marginal reductions compared to conventional concrete. Strength improvements were observed with GGBFS addition, and the optimal mix—30% recycled aggregate combined with 55% GGBFS (R30S1.2)—delivered the best overall performance, making it suitable for main road applications. Although higher recycled aggregate contents tended to reduce strength, the incorporation of GGBFS effectively offset this drawback. Environmentally, the use of these materials reduces raw material consumption and CO_2 emissions, contributing to waste management and sustainable construction. The authors concluded that proper combinations of waste concrete and GGBFS can produce environmentally sustainable and structurally adequate concrete for rigid pavements, recommending further studies on long-term durability under traffic and environmental stresses. This research provides practical insights for civil engineers and policymakers aiming to integrate sustainable practices in infrastructure development.

Shadab Akhtar et al. (2023) study investigated the development and evaluation of sustainable pavement materials, focusing primarily on recycled concrete aggregate (RCA) as a potential eco-friendly substitute for conventional aggregates in pavement construction. The findings demonstrated that RCA exhibits favorable physical and mechanical characteristics, such as improved compaction, interlocking ability, and load-bearing capacity, making it suitable for meeting standard pavement performance requirements. Environmental analyses revealed that the use of RCA significantly reduces embodied energy, carbon emissions, and water consumption, while also minimizing construction waste through effective recycling practices. Moreover, RCA showed excellent durability and moisture resistance, ensuring reliable long-term performance under diverse environmental conditions. Compatibility assessments further confirmed its effective integration with other pavement materials, thereby minimizing the likelihood of structural deficiencies. The authors concluded that RCA is a promising sustainable material capable of achieving a balance between functional efficiency and environmental preservation. Nonetheless, they emphasized the need for continued research on its long-term durability and fatigue performance, especially under heavy traffic conditions, along with strict quality control measures and consistent material supply to ensure its practical application in real-world pavement projects.

Martinelli et al. (2023) reviewed the use of coconut fibers in cementitious composites, emphasizing their growing relevance as sustainable construction materials. The study highlighted the advantages of natural fibers, such as reducing concrete density, limiting fragmentation, and controlling crack propagation. Coconut, abundantly produced in tropical regions, generates shells that are often improperly disposed of, creating an environmental challenge. The review examined the production and properties of coconut fibers, their incorporation in cementitious composites, the use of coconut fiber textile meshes, and treatments to enhance fiber performance and durability. The authors concluded that coconut fibers demonstrate significant potential as a sustainable alternative to synthetic fibers, improving the mechanical behavior of cementitious matrices while contributing to waste valorization and environmental sustainability.

Singh et al. (2023) addressed the growing environmental concerns associated with highway construction in India by developing a specialized tool for estimating carbon emissions from construction materials. Recognizing the increasing demand for road network expansion and the significant contribution of greenhouse gas (GHG) emissions from construction and rehabilitation activities, the study introduced the "Carbon Footprint Estimation Tool for Highway Constructions," an Excel-based platform tailored to the Indian context. This tool allows engineers and planners to quantify, monitor, and compare carbon equivalent emissions from different construction materials used across various pavement layers in both rigid and flexible pavements. The study emphasizes that accurate estimation of carbon emissions is critical for making informed decisions on material selection and design strategies, thereby enabling more sustainable highway construction practices. By providing a practical methodology to assess the environmental impact of road construction materials, the research contributes to the broader objective of mitigating global warming and promoting low-carbon infrastructure development in India.

Aliu, Fakuyi, and Williams (2022) investigated the feasibility of using coconut fibers to enhance the strength and load-bearing capacity of concrete. In the study, concrete beams measuring 50 mm × 50 mm × 1000 mm were prepared with varying coconut fiber contents of 1% to 5% by weight as partial replacement for cement. Load testing was conducted on days 7, 14, 21, and 28 to evaluate performance. The results demonstrated that concrete incorporating coconut fibers exhibited improved load resistance and better post-failure integrity, preventing brittle fracture compared to conventional concrete. This study underscores the potential of coconut fibers as an eco-friendly reinforcement material to improve the mechanical performance and durability of concrete in sustainable construction applications.

Navas et al. (2022) examined the replacement of conventional construction materials with sustainable alternatives, emphasizing the urgent need for resource-efficient practices due to rapid urbanization and increasing demand in the construction industry. The study highlighted that traditional materials—such as cement, hollow concrete blocks, bricks, and reinforcement bars—contribute significantly to carbon dioxide emissions during manufacturing and involve high embodied energy, both directly in construction and indirectly through raw material extraction, production, and transportation.

Recognizing that the construction sector consumes over 50% of the earth's extracted raw materials, the authors proposed fully replacing traditional materials with sustainable alternatives to reduce environmental impact, conserve finite resources, and ensure long-term sustainability of the building industry. The study underscores the importance of integrating sustainable materials at all stages of construction to mitigate energy consumption, lower carbon emissions, and promote responsible use of natural resources.

J. U. D. Hatmoko and L. Lendra (2021) study analyzed the environmental impacts of flexible and rigid pavements using the Eco-Indicator 99 (EI99) methodology, offering a comprehensive life cycle-based assessment of pavement sustainability. Environmental impacts were evaluated across the production, construction, and maintenance phases, with particular focus on human health, ecosystem quality, and resource consumption. The findings revealed that rigid pavements exhibited substantially lower total environmental impacts (78.9 kPt) compared to flexible pavements (175.50 kPt), primarily due to their lower resource consumption and reduced maintenance needs. Flexible pavements, in contrast, showed disproportionately high resource consumption, accounting for 91.93% of the total environmental burden, whereas rigid pavements displayed a more balanced distribution across human health (37.43%), ecosystem quality (4.79%), and resource consumption (57.78%). The study concluded that rigid pavements represent a more sustainable option, as their use can significantly mitigate the environmental impacts associated with road construction and maintenance. The authors further emphasized the importance of optimizing rigid pavement design, material selection, and maintenance strategies to enhance long-term sustainability. They also highlighted the critical role of life cycle assessment (LCA) methodologies like EI99 in guiding sustainable infrastructure planning and decision-making.

Arunaa and Rupini (2021) examined potential interventions for reducing carbon footprints in road construction projects, with a particular focus on pilot green highway technologies implemented in Gujarat, India. Their study emphasizes the integration of ecological and sustainable practices within transportation planning, highlighting the role of green highways in addressing urban sprawl, population growth, public health, and environmental sustainability in accordance with standards such as the Green Roads Rating System. Additionally, societal benefits such as solid waste management and landscaping were incorporated to enhance the overall sustainability of the projects. The study highlighted multiple strategies to reduce carbon emissions across the construction, operation, and maintenance phases of highway projects. These include the adoption of energy-efficient technologies such as Warm Mix Asphalt (WMA) and solar-powered solutions, along with material conservation approaches through reuse and recycling. A comparative analysis was conducted between conventional road construction methodologies and green highway practices, with carbon footprints quantified using emission factors and fuel consumption data. The results demonstrated measurable reductions in carbon emissions through green interventions, highlighting net carbon savings and potential carbon credits achievable from adopting sustainable construction techniques. This study provides critical insights into the practical application of green highway technologies in India and underscores the importance of combining material innovations, energy efficiency, and ecological considerations to promote low-carbon and environmentally responsible infrastructure development.

Salehi et al. (2021) the study examined the environmental and economic implications of incorporating recycled materials in pavement construction, underscoring the growing importance of sustainable practices in infrastructure development. Two primary assessment frameworks were reviewed—Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA). The LCA approach evaluates the environmental impacts of materials throughout their entire life cycle, encompassing extraction, production, use, and disposal. However, the authors identified inconsistencies in defining system boundaries across various studies, leading to significant variations in outcomes. Conversely, LCCA assesses the total material costs—including production, maintenance, and end-of-life disposal—but most studies were found to focus predominantly on production costs, often neglecting the economic implications of recycling and waste management, which may distort the true cost-effectiveness of sustainable materials.The review also noted that despite the increasing adoption of recycled concrete aggregates, waste plastics, recycled glass, crushed brick, and crumb rubber in pavement construction, their comprehensive environmental impacts remain insufficiently explored. Key shortcomings identified include inconsistent data reporting, omission of critical life cycle phases such as maintenance and disposal, and a lack of long-term sustainability evaluations. The authors concluded that the sustainability assessment of recycled pavement materials remains in an early developmental stage. They emphasized the need for standardized evaluation frameworks, holistic life cycle analyses, and robust policy support to promote accurate, evidence-based decision-making and advance sustainable infrastructure development.

Sizirici et al. (2021) the study provided a comprehensive review of carbon footprint reduction strategies across the full lifecycle of construction projects, encompassing design, construction, operation, maintenance, and deconstruction phases. Recognizing the construction industry as a significant contributor to global greenhouse gas emissions, the authors emphasized the need for sustainable practices at every stage, including material manufacturing, transportation, construction activities, building operation, and end-of-life management.

The review systematically analyzed various carbon mitigation strategies, such as using alternative additives in construction materials, optimizing design and structural practices, recycling construction waste, utilizing non-conventional water sources, and improving building system efficiency. Findings indicate that the implementation of these strategies can reduce CO_2 emissions by up to 90% across different phases, highlighting the considerable environmental benefits achievable through deliberate material selection and process management.Moreover, the study underscores the importance of integrating carbon footprint considerations during the conceptual and design stages, enabling stakeholders to make informed decisions regarding materials, construction techniques, and operational systems. By connecting sustainable material utilization, efficient construction methods, and lifecycle management, this research offers a robust framework for minimizing environmental impacts in the construction sector and promotes heightened awareness of low-carbon practices in both building and infrastructure projects.

Kumar, Puri, and Aggarwal (2020) reviewed sustainable building materials for the construction industry, emphasizing the environmental impact of conventional man-made materials. The study noted that the production of traditional construction materials generates significant emissions of CO_2, CO, NO_2, and other harmful by-products, contributing to environmental degradation and posing risks to human health. With increasing demand driven by urbanization and population growth, the reliance on these materials continues to rise, intensifying their environmental footprint. The authors emphasized the significance of adopting sustainable, eco-friendly materials that are energy-efficient, widely accessible, and environmentally benign. Green building materials are designed to reduce the negative impacts of construction activities, promoting both human health and ecological sustainability while meeting the functional demands of modern infrastructure.

Pillay, Olalusi, and Mostafa (2020) the study explored the use of paper mill waste ash (PMA) as a partial cement replacement in concrete, particularly for rigid pavement applications, in response to the rising demand for sustainable construction practices. It emphasized the significant environmental impact of cement production and the urgent need for alternative materials to lower carbon emissions. With its pozzolanic properties, PMA was identified as a sustainable binder with the potential to improve concrete performance. Review findings indicated that concrete incorporating PMA achieved competitive mechanical properties, with tensile strengths ranging from 2.68 to 3.98 MPa and flexural strengths between 4.04 and 5.01 MPa, making it suitable for rigid pavements. Beyond mechanical benefits, PMA offers environmental advantages by minimizing CO_2 emissions and repurposing industrial waste, contributing to sustainable construction and effective waste management. The study also noted challenges, including variability in ash quality and potential effects on setting time and workability, underscoring the need for further research on long-term durability, performance under diverse environmental conditions, and comprehensive life cycle assessments. Overall, the study concluded that paper mill waste ash (PMA) is a viable and eco-friendly supplementary binder for producing sustainable concrete in pavement applications.

Yue Xiao et al. (2020) provided an overview of a special issue in *Materials* dedicated to recent advancements in sustainable pavement materials, highlighting the growing importance of eco-friendly practices in construction for sustainable infrastructure development. The special issue encompasses a diverse collection of studies that focus on integrating environmentally responsible approaches into pavement design and construction. Key themes include the recycling of industrial solid wastes as alternative construction materials, promoting the reuse of existing asphalt and concrete to minimize virgin material consumption, and innovations in modifying pavement materials to enhance durability, resistance to aging, and skid performance. The study also highlights the evaluation of asphalt performance with respect to sustainability and load-bearing capacity, along with advancements in defect detection and maintenance strategies aimed at extending pavement service life. Contributions address various pavement types, including both asphalt and cement concrete, reflecting a comprehensive approach to sustainable practices across the industry. The editorial concludes by stressing the critical need for continued research and development in sustainable pavement materials, demonstrating how recycling, material modification, and innovative technologies collectively contribute to reducing the environmental footprint of pavement construction while maintaining performance standards.

Busari et al. (2019) investigated the potential of using de-hydroxylated Kaolinitic clay (DHKC) as a partial replacement for cement in self-compacting concrete (SCC) for rigid pavement construction, aiming to develop eco-friendly alternatives that reduce construction costs without compromising structural performance. DHKC is derived from kaolin, a naturally occurring clay mineral, which when subjected to elevated temperatures (around 750 °C), undergoes de-hydroxylation, producing a material with properties suitable for concrete applications. Recognizing the role of supplementary cementitious materials (SCMs) in enhancing sustainability, the study performed a comprehensive experimental analysis to evaluate the rheological, mechanical, and microstructural characteristics of SCC containing varying DHKC percentages (0%, 5%, 10%, 15%, 20%, and 25%). Rheological properties were assessed using slump flow, L-box, and V-funnel tests, while mechanical performance was evaluated through compressive, split tensile, and flexural strength tests.

Microstructural analysis was conducted to examine density and permeability changes due to DHKC incorporation. The results showed that replacing 10% of cement with DHKC notably enhanced both early- and late-age mechanical strengths. However, higher replacement levels adversely impacted the workability of self-compacting concrete (SCC), particularly its filling and passing abilities, causing it to fall short of EFNARC standards. Furthermore, DHKC contributed to a denser and smoother concrete matrix, reducing permeability—a desirable attribute for rigid pavement durability. Using response surface analysis, the researchers optimized the mechanical performance, predicting a maximum flexural strength of 4.86 MPa at a specific metakaolin content and concrete age, with compressive strength peaking at 110 days of curing. The study concluded that DHKC is a viable, sustainable, and effective supplementary material for rigid pavement construction, highlighting its potential to enhance mechanical properties while promoting environmental sustainability in modern infrastructure projects.

Nehdi (2018) highlighted the critical role of sustainable building materials and construction practices in addressing the environmental impacts of the built environment, which is among the most energy-intensive sectors globally. The study emphasized that Portland cement production alone is the third-largest contributor to anthropogenic CO_2 emissions, underscoring the need for eco-efficient alternatives. Given the significant threats that climate change poses to ecosystems, biodiversity, and human health, the study advocates for energy-efficient construction practices and the adoption of sustainable building materials. Key areas of focus include carbon-neutral and eco-efficient materials, utilization of recycled content, valorization of industrial by-products and waste, and materials with improved mechanical, durability, and thermal performance. The study called for both experimental and modeling research to develop innovative solutions that enhance the sustainability of building construction, promoting environmentally responsible practices while maintaining structural and functional performance.

Kumar and Goyal (2018) The study conducted a comprehensive literature review on the carbon footprint of road construction, highlighting the rising environmental impact of transportation infrastructure in India driven by globalization and increasing vehicle usage.The study highlights that vehicles operating on newly constructed and expanded road networks predominantly consume non-renewable fossil fuels, contributing significantly to greenhouse gas (GHG) emissions, particularly CO2. The authors underscore that the carbon intensity of road construction and maintenance has prompted transportation agencies to adopt more sustainable and environmentally conscious practices. The paper reviews the concept of carbon footprinting in the context of highway infrastructure and evaluates CO2 emissions and energy consumption associated with the production of road pavements, including both bituminous and concrete roads. By synthesizing findings from existing literature, the study provides insights into strategies for reducing life cycle GHG emissions, promoting greener construction methodologies, and informing policy frameworks for sustainable highway development. This review emphasizes the importance of lifecycle assessment approaches to quantify environmental impacts, thereby enabling transportation engineers and planners to optimize construction practices, material selection, and maintenance strategies for lower carbon emissions in the road sector.

Chhillar et. al. (2017) discussed sustainable construction materials for buildings, emphasizing the importance of adopting materials and products that reduce natural resource consumption and minimize waste generation. Sustainable construction not only enhances environmental performance but also improves the resilience and efficiency of the construction industry by promoting the use of readily available materials. Examples include steel and other metals, glass, prefabricated components, and recyclable alternatives for concrete. The study highlighted that sustainability should be integrated from the planning and design stages, with active involvement of developers, builders, designers, and relevant specialists. Effective implementation requires knowledge sharing, capacity building, and skill development throughout the construction value chain to ensure high safety and quality standards. The authors concluded that a holistic approach to sustainable construction—including material selection, design planning, and workforce development—is essential to achieve both environmental and structural performance objectives.

Dimoula et al. (2016) conducted a holistic assessment of carbon emissions from road and rail transport systems in Greece, emphasizing the critical role of the transport sector as the second-largest contributor to greenhouse gas (GHG) emissions after energy. The study evaluated emissions generated throughout both the construction and operational phases of major road and rail infrastructure, providing a life-cycle perspective on transport-related environmental impacts. Findings revealed that highway construction contributes less to environmental degradation compared to railway construction; however, rail operations are considerably more environmentally friendly than highway operations, highlighting the trade-offs between infrastructure type and operational efficiency. The study underscores the importance of integrating GHG considerations into transport planning, including optimal route design, vehicle efficiency improvements, and lifecycle impact assessment of infrastructure projects. By adopting a comprehensive approach that accounts for vehicle manufacturing, end-of-life disposal, and operational use, the research demonstrates that holistic planning is essential to achieve long-term GHG reductions in the transport sector.

These insights are particularly relevant for policymakers and engineers aiming to design low-carbon transportation systems while balancing construction and operational environmental impacts.

Parikh, Modi, and Desai (2016) highlighted the potential of bamboo as a sustainable and low-cost construction material for India. Bamboo exhibits a high strength-to-weight ratio, making it suitable for lightweight constructions, and possesses tensile strength comparable to steel. Additionally, bamboo composites can be engineered to further enhance its mechanical properties. The material demonstrates excellent earthquake resistance, contributing to safer structural performance in seismic regions.

The study also noted significant economic advantages, estimating that using bamboo as a primary structural material could reduce construction costs by approximately 40%, positioning it as a viable, eco-friendly alternative for affordable and sustainable housing solutions.

Sreedhar et al. (2016) conducted a comprehensive investigation into the carbon footprints associated with highway construction materials in India, highlighting the urgent need to integrate sustainability into transportation infrastructure development due to the increasing urbanization and rising living standards in the country. The study emphasized that with the expansion of roadway networks, energy consumption and greenhouse gas (GHG) emissions are expected to escalate significantly, thereby necessitating advanced technical knowledge on carbon emissions from pavement systems. To address this, the authors developed a specialized toolkit, termed the "Carbon Footprint Calculator," designed to quantify the carbon footprints of various pavement systems employed in highway construction. This innovative tool incorporated critical contributors to GHG emissions, including pavement design parameters, material production processes, transportation from source to site, construction practices, and anticipated vehicular operations over the pavement's design life. Furthermore, a mathematical model was formulated to estimate the total GHG emissions in terms of kgCO2 equivalent (kgCO2e), facilitating a life cycle assessment approach to evaluate the environmental impact of different pavement systems in India. The study underscored that such a tool could serve as a practical aid for design engineers, enabling the optimization of pavement designs and construction practices to minimize carbon emissions. By linking material choices, construction methodology, and operational efficiency, this research provides a critical framework for advancing sustainable highway construction practices in the Indian context, promoting a greener and environmentally conscious approach to infrastructure development.

Baek et al. (2015) examined the potential carbon reductions achievable through the application of green highway technologies in road construction, focusing on innovations developed by the Carbon Neutral Road Technologies Research Group in Korea. The study introduced three specific technologies: (A) carbon-absorbing road facilities using activated industrial by-products, (B) low-carbon non-cement soil pavements employing industrial by-products and inorganic binders, and (C) low-carbon soil pavements using polymer concrete. To quantify the environmental benefits, the authors employed the Green Highway Technology Investment Evaluation System (G-TIES) to calculate carbon reduction in both construction and operation phases. For instance, technology A applied to 1 km of curbs reduced 2.69 tCO2 during construction and 24.75 tCO2 during operation over a 30-year period, totaling 27.44 tCO2 in reductions. Technologies B and C applied to 1 km of pavement achieved reductions of 598 tCO2 and 404.97 tCO2, respectively. The study highlights that these green technologies not only provide substantial carbon savings but also offer practical methodologies for evaluating their effectiveness, thereby serving as a benchmark for researchers and practitioners aiming to integrate low-carbon strategies in highway design and construction. The research underscores the importance of incorporating innovative materials and sustainable construction techniques to achieve measurable reductions in greenhouse gas emissions in road infrastructure projects.

Naveen Kumar et al. (2015) investigated the incorporation of human hair fibers into M40-grade concrete to enhance its mechanical properties. The experimental study identified an optimum fiber content of 1.5%, with observations indicating notable improvements in compressive strength, flexural strength, and split tensile strength as the fiber percentage increased up to 2% by weight of cement. The findings suggest that human hair fibers can serve as an effective reinforcement material in concrete, contributing to enhanced structural performance and promoting the use of unconventional, sustainable resources in construction applications.

Nema (2015) reviewed state-of-the-art methodologies for reducing the carbon footprint in the road construction industry in India, emphasizing the critical environmental and economic implications of greenhouse gas emissions. The study identifies carbon dioxide and other GHGs as major contributors to climate change and highlights the vulnerability of the road construction sector in contributing to these emissions. Nema underscores the importance of adopting optimization techniques and sustainable practices to mitigate carbon emissions, with a particular focus on life cycle assessment (LCA) as a robust method for quantifying the carbon footprint throughout the pavement lifecycle. The review discusses the growing pressures on the road sector to evaluate current construction practices and adopt strategies to reduce emissions, especially in light of the increasing preference for concrete roads, which typically exhibit higher carbon footprints compared to asphalt roads.

By synthesizing existing methodologies, including material selection, construction process optimization, and operational strategies, the study provides a roadmap for transportation agencies and engineers to implement environmentally responsible practices, reduce GHG emissions, and support sustainable infrastructure development in India.

Raj (2015) conducted an experimental study to examine the effect of fibers on reinforced concrete, addressing the inherent shortcomings of conventional concrete, such as low tensile and flexural strength, poor toughness, and high brittleness. The research focused on fiber-reinforced concrete (FRC) as a composite material that enhances flexural and tensile strength, toughness, and permeability. The study specifically evaluated the impact of steel, glass, and polypropylene fibers on the compressive, split tensile, and flexural strength of concrete. The use of fibers to control cracking has historical precedence, with materials like straw and horsehair incorporated into mud bricks and mortars. Modern fiber reinforcement seeks to mitigate both plastic shrinkage cracks, caused by rapid surface water evaporation during setting, and shrinkage cracks in hardened concrete due to volume changes. The findings emphasize that incorporating fibers significantly improves the mechanical performance of concrete, making it more durable and resilient for structural applications.

III. RESEARCH GAP

The comprehensive review of prior research highlights significant advancements in sustainable materials and carbon footprint reduction strategies within the construction and pavement industries, yet several gaps remain that warrant further investigation. Kumar, Puri, and Aggarwal (2020) and Nehdi (2018) emphasize the environmental impact of conventional construction materials and the critical need for eco-efficient alternatives to reduce CO_2, CO, NO_2, and other harmful emissions. While these studies highlight the advantages of green building materials, there is limited empirical evidence on their application in rigid pavement construction, particularly in the Indian context, where rapid urbanization and infrastructure expansion demand context-specific solutions. Similarly, studies investigating alternative binders, such as paper mill waste ash (Pillay et al., 2020) and de-hydroxylated kaolinitic clay (Busari et al., 2019), demonstrate promising improvements in mechanical properties and environmental performance; however, challenges remain regarding variability in material quality, workability, setting times, and long-term durability under diverse environmental conditions. Research on natural fibers—including bamboo (Parikh et al., 2016), coconut (Martinelli et al., 2023; Aliu et al., 2022), and human hair (Naveen Kumar et al., 2015)—shows potential for enhancing tensile strength, crack resistance, and post-failure performance, yet the optimal dosages, treatment methods, and standardized testing protocols remain underexplored. Additionally, carbon footprint analyses of road construction materials (Sreedhar et al., 2016; Kumar and Goyal, 2018; Dimoula et al., 2016; Nema, 2015) provide essential insights into emissions from material production, transportation, and construction processes, but many studies focus on discrete phases or specific materials, leaving integrated, full life-cycle assessments incomplete. Innovations in green highway technologies, such as low-carbon soil pavements, carbon-absorbing facilities, and polymer concrete (Baek et al., 2015), highlight potential emission reductions, yet large-scale, field-based validations are scarce, and socio-economic feasibility remains under-investigated. Further, while research emphasizes recycled materials like fly ash, GGBFS, RCA, and polymeric additives (Al-Hindawi et al., 2023; Shadab Akhtar et al., 2023; Raj, 2015; Jakhar and Meena, 2023), comprehensive guidelines on their optimal combinations, processing techniques, and long-term structural performance are lacking. Similarly, Yue Xiao et al. (2020) underscore the importance of integrating recycled and modified materials to improve durability, skid resistance, and load-bearing capacity, but systematic studies evaluating simultaneous mechanical, environmental, and economic performance in rigid pavement applications are limited. Despite advances in simulation tools, digital technologies, and LCA approaches (Lou et al., 2025; Sizirici et al., 2021), their practical implementation across all construction stages, from material selection to maintenance, is insufficiently documented. Collectively, these gaps indicate a critical need for integrated research that evaluates sustainable material alternatives, fiber reinforcements, industrial by-products, and recycled components in combination, while quantifying full life-cycle carbon emissions, durability, cost-effectiveness, and practical applicability in real-world rigid pavement construction. Addressing these research gaps will facilitate the development of environmentally responsible, low-carbon, high-performance pavements suitable for both urban and rural infrastructure needs, ultimately supporting sustainable development objectives in the construction sector.

IV. CONCLUSION

This review establishes that substantial carbon reduction in road construction is achievable through sustainable materials, advanced technologies, and comprehensive life-cycle-based decision-making. Industrial by-products like fly ash, GGBFS, PMA, and DHKC reduce cement dependency; natural fibers such as coconut, bamboo, and human hair enhance mechanical properties while utilizing renewable or waste materials; and recycled aggregates significantly reduce embodied emissions.

Technological interventions including warm mix asphalt, BIM–LCA integration, emission calculators, and green highway innovations enable precise tracking and mitigation of carbon emissions across construction phases. However, widespread adoption requires harmonized standards, long-term performance studies, and large-scale field applications, particularly in countries experiencing rapid urbanization such as India. The findings highlight the urgent need for integrated frameworks combining sustainability, cost efficiency, durability, and policy support to achieve carbon-neutral road infrastructure. Advancing these solutions will align the transportation sector with global climate commitments and contribute to resilient, eco-efficient infrastructure development.

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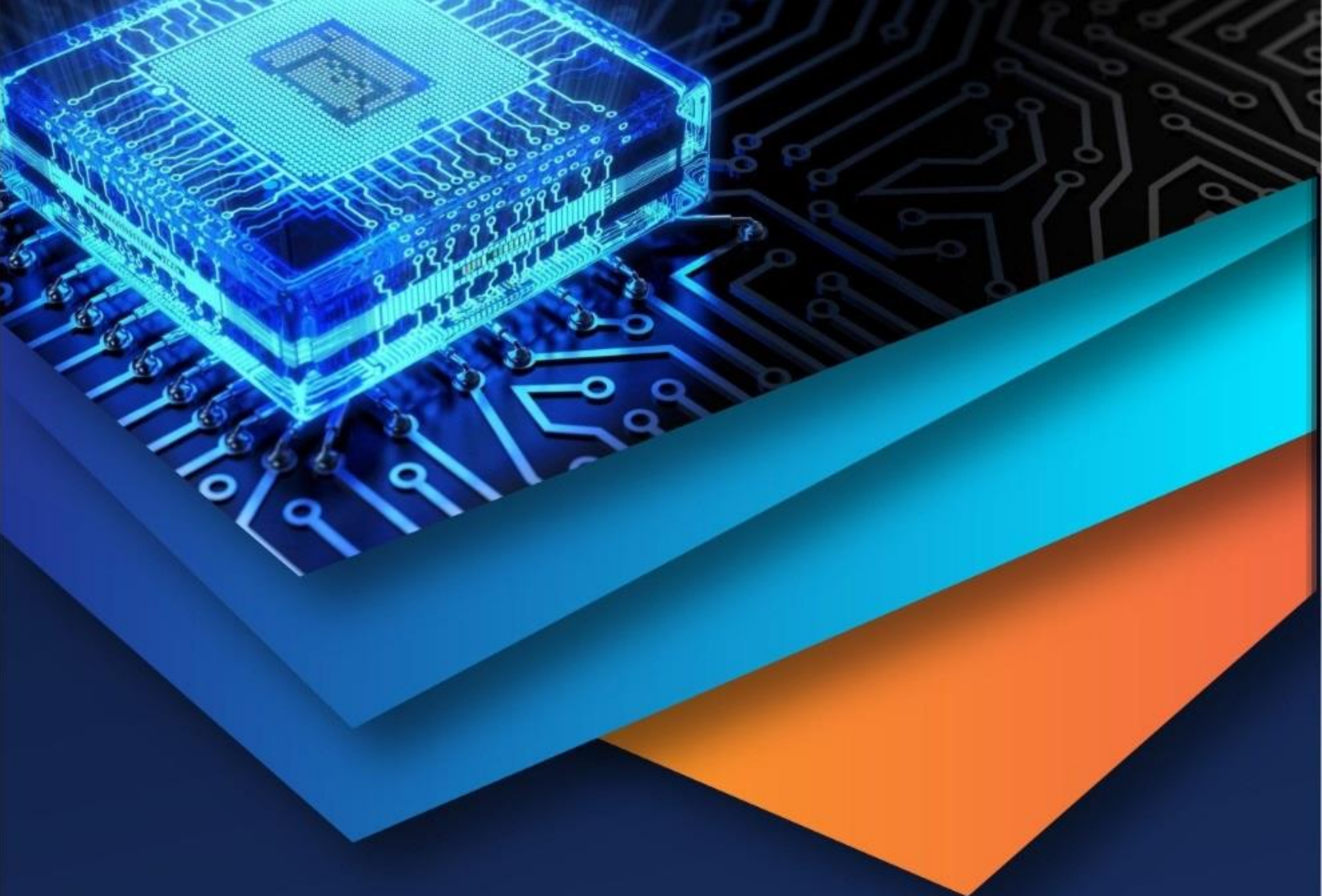

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