STRATEGIES FOR THE USE OF SUSTAINABLE MATERIALS IN ROAD CONSTRUCTION: A QUALITATIVE DELPHI STUDY

SAYANTHAN. T[1], FERNANDO. S.M.H.[2]*, PERERA. B.A.K.S.[3] & RANADEWA. K.A.T.O[4]
[1,2,3,4] Department of Building Economics, University of Moratuwa, Moratuwa, Sri Lanka
[1]sayanthant.19@uom.lk, [2]fernandosmh.20@uom.lk, [3]kanchana@uom.lk, [4]tharushar@uom.lk

Abstract: The construction industry is increasingly prioritising sustainability, driven by the urgent need to minimise environmental impacts and improve resource efficiency. In line with that, sustainable materials in road construction offer significant potential to reduce carbon footprints, enhance durability, and support circular economy principles. However, despite growing interest, there remains a limited understanding of effective strategies to integrate these materials specifically for improving road durability and overall construction performance. Thus, this study aims to investigate strategies for the use of sustainable materials in road construction. Using a qualitative Delphi method involving two rounds of semi-structured interviews, the research identified 11 commonly used sustainable materials, alongside 23 targeted strategies to enhance road durability and an additional 23 strategies to improve overall road construction practices through sustainable approaches. Notably, these strategies were classified material-wise, providing customised and actionable guidance for each sustainable material. 17 and 11 experts participated in the two Delphi rounds, selected through purposive sampling. The study offers a comprehensive, practical roadmap that bridges theoretical knowledge with real-world application. Key recommendations emphasise fostering collaboration across stakeholders, rigorous technical validation, and the incorporation of lifecycle assessments to promote sustainable material adoption in road construction. This distinguishes the study, making it uniquely valuable for stakeholders seeking effective pathways to advance sustainable road infrastructure.

Keywords: *Durability; Road Construction; Strategies; Sustainable Construction; Sustainable Materials.*

1. Introduction

The global shift towards sustainable development has significantly influenced engineering practices, especially in the construction sector (Fei et al., 2021). Increasing awareness of environmental degradation, resource scarcity, and climate change has led to growing emphasis on incorporating sustainable solutions into infrastructure delivery (Fernando & Perera, 2025; Purohit, 2024). Within this context, road construction has emerged as a critical area for intervention due to its high material consumption, energy use, and environmental footprint. As conventional construction practices continue to deplete natural resources and contribute to carbon emissions, the use of sustainable materials presents a viable path to align road development with broader environmental goals (Sayanthan et al., 2024). Sustainable materials, those sourced from renewable origins or recovered from post-consumer and industrial waste, have become essential in this regard. These materials contribute to reducing resource depletion and also to align with broader ecological and social objectives (Aiguobarueghian et al., 2024). The integration of sustainable materials in road infrastructure presents several advantages. They offer improved air and water quality, minimise greenhouse gas emissions, and contribute to resource conservation (Hussain & Kamal, 2015). Moreover, such integration facilitates the growth of environmentally conscious industries and job creation within the renewable materials sector. Despite these advantages, adoption has been slow due to initial cost burdens and concerns over performance, particularly in terms of durability and strength (Gounder et al., 2021). Thus, it is important to explore strategies to promote the adoption of sustainable materials in road construction.

Durability remains a key priority in road construction, as it directly affects maintenance requirements, safety, and user satisfaction (Skrzypczak et al., 2018). External factors such as climate variability, traffic loading, and construction quality are crucial in determining pavement lifespan (Qiao, 2015). Sustainable materials, when effectively integrated, have shown potential to enhance road performance. According to Han and Thakur (2014), recycled aggregates and geosynthetics contribute to structural stability, while bio-based binders offer better resistance to moisture and temperature fluctuations. However, concerns over cost, quality consistency, and long-term behaviour remain prevalent (Thom & Dawson, 2019). This highlights the need for a more strategic and systematic approach to sustainable material selection and use in road construction. Moreover, the construction industry faces increasing pressure to align with global sustainability goals. In road construction, the adoption of sustainable materials presents an opportunity to reduce lifecycle environmental impacts while promoting economic viability. Nevertheless, successful implementation demands strategic planning, stakeholder engagement, and context-specific adaptation (Sherman & Ford, 2013). Without targeted strategies, practitioners often struggle to balance durability, cost, and environmental considerations. Therefore, identifying and validating strategies for effectively integrating sustainable materials into road construction practices has become a practical necessity.

*Corresponding author: Tel: +94 773145095 Email Address: fernandosmh.20@uom.lk
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Considering the literature gap, a substantial body of literature has explored sustainable materials in construction, addressing their advantages, limitations, and environmental impacts. However, most existing studies focus on individual materials such as recycled aggregates, fly ash, or geopolymer concrete, rather than examining their collective and strategic use in road construction contexts (Xu & Shi, 2018; Wasim et al., 2021). Sayanthan et al. (2024) went further by identifying material-wise impacts, yet their study did not extend to identifying material-specific strategies for effective integration. Moreover, while research by Zhao et al. (2021), Segui et al. (2023), and Bamigboye et al. (2021) provides valuable insights into performance and sustainability characteristics, they offer limited consideration of how such materials can be strategically applied across different operational or environmental settings. Notably, there is a lack of studies that classify strategies based on material type or assess their role in enhancing road durability or overall construction performance. The absence of a comprehensive, material-wise strategy framework that addresses both durability enhancement and broader construction improvements reflects a research gap. Thus, this study aims to investigate strategies for the use of sustainable materials in road construction. To attain this aim, the following objectives are considered: **(i)** to investigate the commonly used sustainable materials in road construction projects, **(ii)** to propose suitable strategies to enhance road durability by incorporating each sustainable material, and **(iii)** to propose suitable strategies to enhance road construction by incorporating each sustainable material. Based on these objectives, the underlying sections of the paper include a literature review, methodology, findings and analysis, discussion and conclusions and recommendations.

2. Literature Review

This section lays the foundation for the next sections of the paper, critically reviewing the concept of the use of sustainable materials in road construction projects.

2.1. USE OF SUSTAINABLE MATERIALS IN ROAD CONSTRUCTION

The integration of sustainable materials in road construction represents a critical pathway towards reducing the environmental footprint of infrastructure development. Defined by attributes such as low life-cycle energy consumption, recyclability, and minimal ecological harm, these materials embody the principles of eco-efficiency and resource circularity (Kumar et al., 2020). Their application supports the mitigation of greenhouse gas emissions and reduces reliance on energy-intensive conventional materials that often contribute to air and water pollution (Hussain & Kamal, 2015). Furthermore, by incorporating post-consumer and industrial waste, sustainable materials offer an avenue for waste minimisation, helping to divert significant volumes from landfills. These materials are also characterised by their potential to enhance long-term durability and structural performance, thereby reducing maintenance cycles and associated environmental impacts (Han & Thakur, 2014). While they provide considerable promise, the widespread adoption of sustainable materials remains challenged by issues such as limited guidance, higher initial costs, and uncertainty in large-scale application (Kibert et al., 2016). These barriers are further exacerbated in the road construction sector, where performance reliability under varying environmental and traffic conditions is critical. Therefore, beyond technical advantages, their integration demands a strategic approach, one that considers cost-benefit trade-offs, context-specific implementation, and long-term environmental objectives. In this regard, sustainable materials are alternatives and strategic tools that, when correctly selected and applied, can transform road construction practices into more resilient, resource-efficient, and environmentally responsible systems. Table 2 illustrates the list of sustainable materials identified.

2.2. THE IMPORTANCE OF ROAD DURABILITY

Road durability is a foundational attribute of effective infrastructure, directly influencing performance, safety, lifecycle cost, and long-term socio-economic outcomes. It refers to the road's ability to resist deterioration under stress, and to its overall functional integrity over time, withstanding cumulative traffic loads, climatic stresses, and environmental exposure (Skrzypczak et al., 2018). A durable road surface demonstrates resistance to fatigue, deformation, thermal cracking, and moisture-related damage, all of which are critical to ensuring minimal maintenance interventions and consistent serviceability. This durability translates into significant cost savings through reduced repair frequencies and lower consumption of materials and energy during maintenance cycles (Giustozzi et al., 2012). Moreover, durable roads underpin economic productivity by ensuring uninterrupted transportation, trade facilitation, and regional connectivity, particularly in developing contexts where poor road conditions can inhibit market access and service delivery (Guo, 2022). Their contribution extends to enhancing resilience against extreme events and climate variability, thereby reinforcing infrastructure reliability during emergencies. In addition, by lowering wear on vehicles and reducing travel disruptions, durable pavements offer indirect economic benefits to users through decreased operational and maintenance costs. Conversely, poorly maintained roads can escalate fuel consumption, increase accident risks, and amplify rural isolation, contributing to broader issues such as poverty, limited access to education, and health challenges (Kaiser & Barstow, 2022). Importantly, the significance of durability extends to associated elements such as bridge decks without just limiting to pavements, where longevity ensures structural safety and cost-effectiveness over extended lifespans (Breunig & Kuhlmann, 2017). As such, road durability serves as a linchpin in the pursuit of sustainable infrastructure, supporting economic efficiency, social well-being, and environmental stewardship. Thus, the integration of strategic design, material selection, and policy frameworks is essential to fully realise the benefits of durable roads within modern transport systems.

2.3. STRATEGIES TO ENHANCE THE USE OF SUSTAINABLE MATERIALS IN ROAD CONSTRUCTION

Enhancing the use of sustainable materials in road construction requires a strategic approach that addresses technical, regulatory, educational, and institutional dimensions. One of the most frequently cited strategies is investment in innovative materials and construction methods, which can unlock performance improvements and cost savings while reducing environmental impacts (Bocci, 2022; Gounder et al., 2021). These investments support research and development and also enable the transition from conventional to green construction technologies. Complementing this, the implementation of supportive legislative frameworks, including laws mandating or favouring sustainable practices, emerges as a critical strategy (Thom & Dawson, 2019). Furthermore, fiscal tools such as tax incentives and subsidies can further encourage adoption, especially where initial costs are a barrier (Montgomery et al., 2014; Gounder et al., 2021). On the social front, public education campaigns and professional training programs are essential to cultivate awareness, shift mindsets, and build capacity among stakeholders (Hancock & Nuttman, 2013). Effective implementation also hinges on collaboration among government agencies, private firms, and academic institutions, which can facilitate knowledge transfer and joint innovation (Zhong & Zong, 2024). From a technical standpoint, lifecycle-based environmental assessments enable more informed material selection by quantifying impacts across production, use, and end-of-life phases. Establishing standards and updating guidelines to reflect recent advances ensures consistency, improves quality assurance, and supports compliance across the industry (Mwelu et al., 2018). Collectively, these strategies form a comprehensive roadmap for integrating sustainable materials into road construction, offering environmental, economic, and operational benefits while aligning the sector with broader sustainability goals.

3. Methodology

The qualitative research choice was adopted for this study due to its appropriateness in exploring complex, context-driven issues such as the strategies for the use of sustainable materials in road construction projects (Saunders et al., 2023; Yin, 2011). As Creswell (2014) defines, qualitative research focuses on understanding the meanings individuals or groups assign to a human or social problem. Dawson (2007) further emphasised the goal of qualitative research as obtaining in-depth comprehension of a study area, which aligns well with the study's objective to understand the strategies for the use of sustainable materials in road construction. In line with this, initially, a comprehensive literature review was conducted to identify the sustainable materials used in construction projects, and strategies with respect to road durability and overall road construction. Thereafter, semi-structured expert interviews were conducted. To explore expert opinions and establish consensus, the Delphi technique was selected as the core data collection method, conducted over two rounds using semi-structured interviews lasting approximately 60 to 75 minutes each. Semi-structured interviews were deemed appropriate due to their flexibility and capacity to elicit rich, detailed responses, a point supported by Iyamu and Mutudi (2022), who noted their value in fostering in-depth dialogue. The Delphi technique, originally developed to reduce the influence of group dynamics and encourage independent expert thinking (Gray, 2016), provided an iterative and anonymous platform to refine expert inputs and reach consensus. Naisola-Ruiter (2022) noted this method's strength in reducing conformity pressure, while Shariff (2015) underscored its ability to synthesise diverse viewpoints, making it ideal for multidisciplinary topics like this one. The method's affordability and iterative nature further support its use in decision-making and policy research (Brady, 2015; Avella, 2016). Given the study's aim to incorporate professional insights over general population responses, the Delphi method, as described by Zare et al. (2023), was appropriate for achieving a rigorous, consensus-based outcome.

Experts were selected using purposive sampling to ensure informed contributions, a strategy suited for Delphi studies, where the focus is on depth over representativeness (Sezgin et al., 2022). Participants, including engineers, architects, and quantity surveyors with over five years of experience, represented relevant sectors such as road construction and sustainability. Their details are illustrated in Table 1, along with the objectives of each Delphi round and phase.

Table 1: Profile of the Experts

Code	Designation	Mandatory Qualifications (2/2)		Additional Qualifications (At least 3/5)					Participation	
		Q1	Q2	Q3	Q4	Q5	Q6	Q7	R1	R2
R1	Civil Engineer	✓	✓	✓	✓	✓	✓	✓	✓	✓
R2	Civil Engineer	✓	✓	✓	✓	✓	✓	✓	✓	✓
R3	PhD Scholar	✓	✓	✓	✓	✓	✓	✓	✓	✓
R4	PhD Student	✓	✓	✓	✓	✓	✓	✓	✓	✓
R5	Research Assistant	✓	✓	✓	✓	✓	✓	✓	✓	✓
R6	Quality Control Manager	✓	✓	✓	✓	✓	x	✓	✓	✓
R7	Cost Manager	✓	✓	✓	✓	✓	x	✓	✓	✓
R8	Civil Engineer	✓	✓	✓	✓	✓	✓	✓	✓	✓
R9	Quantity Surveyor	✓	✓	✓	✓	✓	x	✓	✓	x
R10	Quantity Surveyor	✓	✓	✓	✓	✓	✓	✓	✓	x

R11	Senior Contract Manager	✓	✓	✓	✓	✓	✓	✓	✓	✓
R12	Project Engineer	✓	✓	✓	✓	✓	x	✓	✓	✓
R13	Planning Engineer	✓	✓	✓	✓	✓	x	✓	✓	✓
R14	Senior Engineer	✓	✓	✓	✓	✓	✓	✓	✓	x
R15	Planning Engineer	✓	✓	✓	✓	✓	✓	✓	✓	x
R16	Civil Engineer	✓	✓	✓	✓	✓	✓	✓	✓	x
R17	Senior Quantity Surveyor	✓	✓	✓	✓	✓	✓	✓	✓	x

Mandatory Qualifications
- Q1 - At least 5 years of working experience in the construction industry or academia
- Q2 - At least 2 years of industry/academia experience in sustainable construction/ road construction

Additional Qualifications
- Q3 - Bachelor's Degree in the built environment
- Q4 - Professional qualification in the built environment sector
- Q5 - Postgraduate qualification in the Built Environment
- Q6 - Knowledge and interest in road construction
- Q7 - Interest in knowing about sustainable materials

Delphi Objectives
- Round 1 Phase I (R1PI)- Identify commonly used sustainable materials in road construction projects
- Round 1 Phase II (R1PII) - Propose suitable strategies to enhance the road durability by incorporating sustainable materials
- Round 1 Phase III (R1PIII) - Propose suitable strategies to enhance road construction by incorporating sustainable materials
- Round 2 Phase I (R2PI) - Propose suitable strategies to enhance the road durability by incorporating each sustainable material
- Round 2 Phase II (R2PII) - Propose suitable strategies to enhance road construction by incorporating each sustainable material

For data analysis, manual content analysis was employed to ensure close engagement with the textual data. Content analysis is widely used for qualitative studies as it allows researchers to interpret meaning from text while maintaining contextual integrity (Bengtsson, 2016). By manually coding the data, the analysis-maintained focus on the substance of expert input rather than being constrained by software processes, as recommended by Cope (2014). Linneberg and Korsgaard (2021) also recognised content analysis as particularly effective in generating meaningful interpretations from qualitative data. Directed content analysis was applied, drawing on literature-derived themes that were adapted and expanded based on the experts' perspectives, allowing for theoretical alignment while accommodating emergent insights, a method in line with Humble (2009). To uphold methodological rigour, a response threshold of 75% was used to determine consensus, as recommended by Alkaissy et al. (2021), ensuring that only broadly supported insights were incorporated into the final analysis. After two iterative rounds, expert consensus was sufficiently achieved to address the study objectives, marking the end of data collection.

4. Findings and Analysis

The collected data were carefully analysed via manual content analysis, and in this section, the main findings of the study have been presented under three main topics as follows:

4.1. COMMONLY USED SUSTAINABLE MATERIALS IN ROAD CONSTRUCTION PROJECTS (R1PI)

The findings from the Delphi Round 1 Phase I revealed a refined and contextually grounded list of sustainable materials considered most suitable for road construction. Following a literature validation and expert consultation process, eleven materials emerged as commonly used in road construction. In here, the previously identified fifteen sustainable materials from the literature review were presented to the experts to validate (illustrated in Table 2, not highlighted in bold). Out of these, only nine materials received a consensus of more than 75%. Moreover, the experts proposed four other materials (**in bold**), out of which only two received the minimum consensus. Thus, eleven sustainable materials were identified as commonly used sustainable materials in road construction projects, as shown in Table 2.

Table 2: Commonly used sustainable materials in road construction projects

No	Sustainable Materials	Total
1	Recycled Tires	≥75%
2	Construction and demolition waste (CDW)	≥75%
3	Waste Plastics	≥75%
4	Fly Ash	≥75%
5	Recycled Glass	≥75%
6	Polyethylene terephthalate (PET) plastic bottles	≥75%
7	Asphalt shingles	≥75%

No	Sustainable Materials	Total
8	Cement kiln dust	≥75%
9	Colliery spoils	≥75%
10	**Recycled Asphalt**	≥75%
11	**Warm Mix Asphalt (WMA)**	≥75%
12	Bio-oils	<75%
13	Steel slag	<75%
14	Aluminium dross	<75%
15	Mine tailings	<75%
16	Incineration bottom ash	<75%
17	Blast furnace slag	<75%
18	**Sand**	<75%
19	**Quarry dust**	<75%

Waste Plastics, CDW and recycled tires were unanimously supported by all experts, underscoring their practicality and environmental value. As noted by R1, "*CDW is not just abundant; it significantly reduces the need for raw aggregates and supports waste minimisation goals*." Similarly, R2 added, "*Recycled tires are an effective alternative due to their resilience and ability to enhance road surface flexibility*." The expert panel also endorsed materials like waste plastics and PET bottles, which were praised for their ability to improve bitumen bonding and decrease plastic waste. R4 noted, "*Integrating PET in asphalt mixes not only utilises waste but also enhances road performance under varying climatic conditions*." These views reinforce the strategic shift in material selection based on sustainability benefits and performance improvements rather than conventional cost criteria alone. Experts further highlighted the contribution of fly ash to improved durability and reduced carbon intensity in cementitious mixes. R3 emphasised, "*Fly ash brings value through both workability and environmental impact; it is a smart substitution for cement*." WMA was another key addition, introduced through expert suggestion and subsequently validated. R7 observed, "*WMA operates at lower temperatures, which directly cuts down energy usage and emissions; a clear step toward greener construction*." Recycled asphalt also gained strong consensus for its role in promoting circular material use. According to R8, "*Reusing asphalt isn't just a cost-saving measure; it's about material responsibility and lifecycle thinking*." The consensus reached highlighted the importance of shifting toward engineered sustainability, where material choices are not only about ecological credentials but also practicality, performance, longevity, and regional adaptability. Materials such as cement kiln dust, colliery spoils, and asphalt shingles also received high levels of acceptance due to their local availability and prior use in infrastructure works, confirming their feasibility in mainstream applications. R6 aptly noted, "*Cement kiln dust is often seen as waste, but when harnessed correctly, it performs comparably to more expensive binders*." Furthermore, R9 stated, "*Colliery spoils are often incorporated in sub-base and embankment layers in regional road projects, while asphalt shingles are reused in asphalt mixes for local paving works, making both materials practical and accessible options for sustainable construction in many countries*."

This expert-led evaluation validated existing literature and expanded the sustainable material pool based on real-world practices, resulting in a carefully curated list shaped by evidence and expert judgement. While eight (8) materials, including bio-oils, steel slag, Aluminium dross, mine tailings, incineration bottom, ash, blast furnace slag, sand and quarry dust, did not meet the consensus threshold, their exclusion highlights the importance of practical relevance over theoretical endorsement. R5 explained, "*It's not that these materials are unusable; it's that logistical or performance limitations outweigh their potential benefits.*" This statement underpins the rationale of the Delphi process, where iterative expert input filters academic propositions through the lens of their experience. Ultimately, eleven materials were taken forward from R1PI.

4.2. SUITABLE STRATEGIES TO ENHANCE ROAD DURABILITY BY INCORPORATING EACH COMMONLY USED SUSTAINABLE MATERIAL (R1PII, R2PI)

The identification of suitable strategies to improve road durability through the integration of sustainable materials was carried out in Round 1 Phase II and Round 2 Phase I. Notably, the literature review revealed no direct strategies in this domain, highlighting the significance of expert contributions in this area. Thus, in R1PII, 26 strategies were proposed, of which 23 received consensus. Then, in R2PI, the initially identified strategies were categorised according to the specific sustainable materials to which they apply. These are illustrated in Table 3, below.

Table 3: Strategies to enhance road durability with sustainable materials in road construction projects

Delphi Round 1 Phase II		
#	**Strategies to enhance the durability**	**%**
S1	Collaborate with waste management/construction firms to collect and reuse waste.	≥75%
S2	Develop standardised protocols for sorting and processing waste for road construction.	≥75%
S3	Balance recycled materials with virgin materials in mix designs to meet performance.	≥75%
S4	Establish criteria for selecting key material properties.	≥75%
S5	Disseminate technical information on sustainable material use.	≥75%
S6	Conduct life cycle assessments of alternative road construction materials.	≥75%
S7	Model engineering behaviour of sustainable materials.	≥75%

S8	Introduce incentive programs to encourage proper waste disposal.	≥75%
S9	Invest in R&D to enhance the performance and durability of sustainable mixes.	≥75%
S10	Foster collaboration between the vehicle and road infrastructure industries.	≥75%
S11	Ensure waste is processed and sized for effective mixing with asphalt or other materials.	≥75%
S12	Develop mix designs to maximise durability without compromising properties.	≥75%
S13	Improve flexibility and crack resistance in road materials.	≥75%
S14	Partner with industries to streamline the collection of sustainable materials.	≥75%
S15	Explore novel applications of materials in road construction.	≥75%
S16	Promote innovative recycling technologies for high-quality material recovery.	≥75%
S17	Collaborate with manufacturers to incentivise recycling and material collection.	≥75%
S18	Establish mechanisms for testing constructability and verifying field performance.	≥75%
S19	Explore alternative uses for waste materials to reduce landfill reliance.	≥75%
S20	Ensure optimal particle size distribution in mixes for improved performance.	≥75%
S21	Introduce test methods to measure water susceptibility.	≥75%
S22	Optimise binder quantities to prevent rutting or cracking.	≥75%
S23	Use additives to improve adhesion and prevent moisture damage.	≥75%
S24	~~Launch public campaigns to gather household and industrial waste for road experiments~~	<75%
S25	~~Use artificial intelligence to predict materials~~	<75%
S26	~~Organise events where participants propose alternatives~~	<75%

Delphi Round 2 Phase I		
#	**Sustainable Materials**	**Strategies to enhance the durability**
1	Recycled Tires	S7, S8, S9, S10
2	Construction and demolition waste (CDW)	S1, S2, S3, S4, S5, S6
3	Waste Plastics	S11, S12, S13, S4, S7
4	Fly Ash	S14, S15
5	Recycled Glass	S16, S17, S7, S18, S5
6	Polyethylene terephthalate (PET) plastic bottles	S12, S11, S18, S6, S17
7	Asphalt shingles	S5, S17, S18
8	Cement kiln dust	S15, S18, S19
9	Colliery spoils	S11, S12, S18
10	Recycled Asphalt	S3, S20, S21, S4, S7, S18, S5, S6
11	Warm Mix Asphalt (WMA)	S22, S23, S4, S18, S6

The implementation strategies depicted in Table 3 offer a practical and material-specific approach to enhance road durability through sustainable practices. Several strategies share common thematic elements, such as the emphasis on collaboration, testing, standardisation, and life cycle analysis. For instance, CDW, Fly Ash, Recycled Glass, and PET plastics all benefit from strategies like "Model engineering behaviour of sustainable materials," "Disseminate technical information on sustainable material use," and "Establish mechanisms for testing constructability and verifying field performance." This alignment suggests a systemic need for better technical validation and shared knowledge across material types. Supporting this, E4 said, "*Durability isn't only in the material, it's in the system that tests, applies, and manages that material.*" Moreover, the strategies also reflect a rational balance between material-specific interventions and overarching system improvements. Recycled tires and plastics call for innovations in mix design and flexibility enhancement, whereas materials like cement kiln dust and recycled asphalt demand refined binder ratios and particle size control. Furthermore, the strategy "Establish criteria for selecting key material properties" is common across multiple materials, indicating a shared durability concern over physical and mechanical performance thresholds. Simultaneously, market-driven and supply chain considerations emerge, i.e., collaborations with coal plants for fly ash or beverage companies for glass. This dual approach: technical optimisation paired with ecosystem support, provides a comprehensive pathway to integrating sustainable materials effectively. Furthermore, with respect to LCC, E5 said, "*Life cycle assessments are no longer optional; they are essential to justify the use of sustainable materials beyond just cost*." This highlighted the importance of LCC for materials including CDW, PET plastic, recycled asphalt and WMA.

4.3. SUITABLE STRATEGIES TO ENHANCE ROAD CONSTRUCTION BY INCORPORATING EACH COMMONLY USED SUSTAINABLE MATERIAL (R1PIII, R2PII)

In the previous subsection, strategies concerning 'Durability' were discussed, but here, the whole 'Road Construction' is considered. For this, first, in Round 1 Phase III, the experts were given 11 strategies identified from the literature review. In addition to these strategies, the experts proposed 12 more strategies (**in bold**), which resulted in a total of 23 strategies. All these strategies received 75% consensus. These are illustrated in Table 4, below.

Table 4: Strategies to enhance road construction with sustainable materials in road construction projects

Delphi Round 1 Phase III		
#	**Strategies to enhance road construction**	**%**
S1	Invest in innovative, sustainable materials and methods	≥75%
S2	Implement laws favouring sustainable road construction	≥75%

S3	Offer tax breaks or subsidies for sustainable projects	≥75%
S4	Educate the public on the benefits of eco-friendly infrastructure	≥75%
S5	Train professionals in sustainable construction practices	≥75%
S6	Foster partnerships between the government, private sector and research institutions	≥75%
S7	Showcase successful sustainable road construction examples	≥75%
S8	Evaluate materials' environmental impact throughout their lifecycle	≥75%
S9	Develop and promote standards for sustainable materials	≥75%
S10	Update guidelines to incorporate the latest sustainable advancements	≥75%
S11	Technology enhancement for increasing sustainable material usage	≥75%
S12	**Financial subsidies to stakeholders**	≥75%
S13	**Develop a secondary material market for road construction materials**	≥75%
S14	**Incentivise the use of regional secondary materials (Reduces transport)**	≥75%
S15	**Require sustainability impact assessments at inception**	≥75%
S16	**Encourage circular economy system flows**	≥75%
S17	**Implement quality assurance protocols**	≥75%
S18	**Government incentives and policies**	≥75%
S19	**Research and development funding**	≥75%
S20	**Public awareness and education campaigns**	≥75%
S21	**Certification and recognition programmes**	≥75%
S22	**Incorporating sustainable materials in the planning and designing stage**	≥75%
S23	**Use sustainable materials in profitable industries and promote them to the rest**	≥75%

Delphi Round 2 Phase II		
#	**Sustainable Material**	**Strategies**
1	Recycled Tires	S3, S1, S17, S13
2	Construction and demolition waste (CDW)	S1, S14, S19, S4
3	Waste Plastics	S10, S7
4	Fly Ash	S13, S18, S19
5	Recycled Glass	S1, S3, S7, S17
6	Polyethylene terephthalate (PET) plastic bottles	S1, S20
7	Asphalt shingles	S1, S18, S14
8	Cement kiln dust	S19, S6
9	Colliery spoils	S7, S1, S18
10	Recycled Asphalt	S19, S17
11	Warm Mix Asphalt (WMA)	S1, S19, S20

As illustrated in Table 4, under CDW, experts stressed the importance of systemic collaboration. E2 noted the need to "*provide incentives for the use of regional CDW and secondary materials*," which aligns directly with strategies like S13 and S14. E6, E7, and E10 all emphasised that "*waste management organisations and construction companies should collaborate and form partnerships*," supporting S6. E3 advocated for technical integration, stating the need to "*develop optimum mix designs that use CDW*," suggesting the application of S22. Furthermore, E8 recommended "*regular performance monitoring and maintenance programs*", although durability-related, this highlights the broader operational integration CDW demands. These strategies are material specific. For recycled tires, several experts proposed strategies addressing both processing and adoption. E3 suggested "*Incentive schemes that motivate people and companies to dispose of used tires correctly*," relating to S12 and S13. E4 advised to "*Establish a secondary material market specifically for recycled materials*," which enhances commercial viability. E5 went further, advocating that governments should "*Allocate funding for R&D initiatives focused on improving the performance and durability of rubberised asphalt mixes*," directly supporting S19. These anchor the material-specific nature of strategies such as S11, S13, and S19. With regard to waste plastics, the integration was both technical and structural. E3 emphasised "*Developing mix designs that incorporate waste plastic in the right proportions,*" while E5 added the need for "*Extensive testing and research to determine the ideal plastic-to-asphalt ratio*," supporting S22 and S11. E7 stressed material innovation, proposing to "*Explore innovative binder technologies that enhance the compatibility and bonding of waste plastic*," again validating S11 and suggesting strong material-level intervention. These views justify allocating strategies such as S11, S19, and S22 under this material. Likewise, under each material, strategies were identified as illustrated in Table 4.

Furthermore, the analysis revealed a set of common strategies that are not exclusive to any single sustainable material but serve as foundational strategies for promoting sustainable road construction practices more broadly. Strategy S1 was identified under recycled tires, CDW, recycled glass, PET plastic bottles, WMA and asphalt shingles. Similarly, S19 was observed across five materials: CDW, fly ash, cement kiln dust, recycled asphalt, and WMA, underscoring the central role of financial support in enabling technical advancements and validating material performance. S13 – Develop secondary material markets was relevant to both recycled tires and fly ash, highlighting the importance of supply chain infrastructure for wider adoption. Although these strategies were referenced by multiple experts, they were considered common to more than one sustainable material, as they apply to the overall ecosystem rather than to the unique characteristics of individual sustainable materials. In contrast, eleven strategies were not linked to any single material but were discussed in general terms by multiple experts. They are S2, S5, S8, S9, S11, S12, S15, S16, S21, S22 and S23. While expert quotes like E6's statement, "*Public awareness and education campaigns are pivotal*", support these strategies, they are overarching strategies and not tied exclusively to any one material. Their generic nature makes them critical for policy formulation, capacity-building, and industry-wide shifts.

5. Discussion

Previous studies have consistently identified a range of sustainable materials for road construction, including fly ash, recycled asphalt, construction and demolition waste, and plastic-based additives (Sayanthan et al. 2024; Torshizi et al., 2022). These materials are often recognised for reducing environmental burdens, conserving resources, and improving certain performance attributes. However, many of these studies did not evaluate these materials within a coherent or context-specific framework. In contrast, this study applied a systematic, expert-informed validation process, which led to the refinement and filtering of an initial list of fifteen materials. Eleven were identified as commonly used, showing overlap with earlier literature, such as fly ash and recycled asphalt, but also revealing the relevance of materials like PET bottles, asphalt shingles, and cement kiln dust, which were less emphasised in prior work. While Hussain & Kamal (2015) and Han & Thakur (2014) highlighted the environmental and resource benefits of sustainable materials, this study demonstrated that local experts also prioritise performance, durability, and material availability, illustrating a more practice-oriented selection. Notably, the rejection of materials like bio-oils, steel slag, Aluminium dross, mine tailings, incineration bottom ash and blast furnace slag, despite their mention in earlier studies, demonstrates a divergence in practical applicability versus theoretical endorsement. Thus, while this study supports much of the existing literature, it also provides a more targeted and filtered list derived through expert consensus, offering a practice-oriented perspective. This confirms that despite the technical potential of certain materials reported in literature, field-level considerations such as supply chain constraints, mix compatibility, and performance under local climatic and traffic conditions determine actual adoption of sustainable materials in road construction.

Considering the strategies to enhance road durability, this study is one of the first to discuss this. Strategies were focused on strengthening the long-term performance of sustainable materials through procedural and technical enhancements. Key expert-derived strategies included rigorous quality assurance protocols at the material selection and processing stages, alongside performance-based mix design adjustments tailored to the properties of each sustainable input. Comparing these strategies with literature, while Hussain & Kamal (2015) and Han & Thakur (2014) emphasised durability improvements in general terms, this study specified material-wise interventions and actionable procedures validated by practitioners. The experts also highlighted the importance of life-cycle assessment tools to monitor long-term degradation and recommended the use of pilot trials to simulate real-world stress conditions before full-scale deployment. The overall emphasis was placed on ensuring that the materials not only meet sustainability criteria but also deliver structural resilience over time. These recommendations were based solely on expert feedback and practical insight, without influence from literature.

With respect to strategies to enhance road construction using sustainable materials, previous studies have proposed a range of strategies, often emphasising regulatory alignment, life cycle thinking, and technical standards. Alkaissy et al. (2021) underscored the need for material certification systems and performance-based standards, while Torshizi et al. (2022) highlighted long-term cost efficiency and environmental compliance as drivers for sustainable material integration. In alignment with these, this study revealed expert-backed strategies such as the need for clear specification guidelines, early design-stage integration, and performance monitoring mechanisms, showing consistency in recognising the importance of structured technical governance. Furthermore, while Kibert et al. (2016), Thom & Dawson (2019), and Bocci (2022) emphasised overarching frameworks, legislation, and R&D incentives, this study identified that practical adoption also requires material-specific strategies, demonstrating that policy alone is insufficient without expert-informed technical and operational measures. What sets this research different from the previous ones is the fact that it classified the strategies material-wise. This material-wise allocation of strategies challenges the assumption in previous research (Kibert et al., 2016; Thom & Dawson, 2019; Bocci, 2022) that broad policy measures or standards alone are sufficient. This study identified that without linking strategies directly to individual material characteristics, sustainability initiatives risk being theoretically sound but practically ineffective. Furthermore, this study expanded on implementation strategies by introducing practical, process-focused interventions, such as embedding digital modelling tools, encouraging contractor incentives tied to sustainability targets, and enhancing workforce awareness through targeted training programmes. These process innovations were not strongly emphasised in prior work, suggesting a more operational and practitioner-oriented approach emerging from the expert consensus. While the literature provided a strong foundation on policy and assessment tools, this study complemented it by adding practical site-level and procurement-level actions necessary for scalable adoption, material-wise.

6. Conclusions and Recommendations

This study is among the first studies to investigate strategies for the use of sustainable materials in road construction, material-wise. Based on the findings, 11 commonly used sustainable materials were identified as applicable to road construction projects, including CDW, recycled tires, waste plastics, fly ash, Recycled Glass, PET plastic bottles, Asphalt shingles, Cement kiln dust, Colliery spoils, Recycled Asphalt and WMA. In terms of advancing road durability through these materials, 23 targeted strategies were identified, including improvements in binder modification, moisture resistance treatments, and enhanced material grading, all grounded in expert consensus with no direct precedence in existing literature, highlighting a notable contribution of this study. Similarly, 23 strategies were proposed to enhance the overall road construction process, where comparisons with previous studies show consistency in the emphasis on performance standards and material specifications, while diverging by introducing practical actions like incentivising contractors and integrating digital tools such as BIM for sustainable material planning. It is therefore recommended that policymakers and practitioners update current design codes to reflect the validated materials. In parallel, it is recommended to implement the proposed strategies to address both durability and construction process enhancements, enabling a more sustainable and efficient transformation of road construction practices.

Considering the impact of the study, it offers clear industry guidance by identifying practical materials and strategies that enhance road durability and construction efficiency. For research, it fills a gap by introducing expert-driven, context-neutral strategies not previously explored in literature. Societally, it promotes sustainability by reducing environmental impact and encouraging resource-efficient practices in road infrastructure development. When considering further studies, it is recommended to explore the long-term performance and cost-effectiveness of the identified sustainable materials and strategies in diverse conditions. Additionally, quantitative studies could validate the expert-driven findings and assess their scalability in large infrastructure projects. Concerning the limitations, this study's qualitative nature limits the generalisability of its findings to broader contexts; however, it provides a valuable framework for future research. Additionally, the study's focus on specific sustainable materials and strategies may not encompass all emerging innovations in the field.

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