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ORIGINAL ARTICLE

A Review: Waste Materials as Sustainable Pavement Materials

*[1,2]Mastura Bujang, [2]Michelle Ting Sze Hui, [1,2]Leong Wen Kam, [1,2]Lim Yong Tat, and [3]Wan Nur Aifa Wan Azahar

[1]Centre of Research for Innovation and Sustainable Development (CRISD), University of Technology Sarawak, 96000 Sibu, Sarawak, Malaysia
[2]School of Engineering and Technology, University of Technology Sarawak, 96000 Sibu, Sarawak, Malaysia
[3]Department of Civil Engineering, International Islamic University Malaysia, 50728 Kuala Lumpur

ABSTRACT - Traditional pavement construction relies heavily on natural aggregates and bitumen, contributing to resource depletion and increased carbon emissions. This review systematically analyses studies published between 2012 and 2024 on the incorporation of various waste materials, namely reclaimed asphalt pavement (RAP), recycled concrete aggregate (RCA), waste tiles, waste plastics, crumb rubber, and waste glass into pavement construction. Using a structured systematic literature review method, the selected research was evaluated and compared based on mechanical performance, durability characteristics, and environmental impacts. Findings from the reviewed studies reveal several notable trends: the incorporation of RAP (10–40%) and RCA (5–30%) generally maintains or improves stiffness and rutting resistance; waste plastics and crumb rubber typically enhance flexibility and fatigue life by 15–40%; and waste glass and waste tiles can improve skid resistance and compressive strength when used as partial aggregate replacements. Additionally, most studies reported reductions in embodied carbon ranging from 10–50% depending on the waste type and replacement level. Overall, the review demonstrates that the utilisation of waste materials is a viable and sustainable strategy to improve pavement performance, reduce reliance on virgin materials, and lower environmental impacts. These insights highlight promising directions for future research and support the potential for large-scale implementation in sustainable pavement engineering.

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INTRODUCTION

Pavement construction plays a crucial role in infrastructure development by ensuring road durability, safety, and operational efficiency [1]. Traditionally, pavements are constructed using natural aggregates, sand, and bitumen due to their availability and proven performance [2]. However, the increasing demand for sustainable practices and environmentally responsible construction has prompted the search for alternative materials [3]. Rising costs and the depletion of bitumen and natural aggregates have become significant barriers to conventional pavement construction, increasing project expenses and exerting pressure on limited natural resources [4]. Moreover, traditional pavements are prone to premature distresses such as rutting, cracking, and stripping under heavy traffic loads and extreme temperature variations, resulting in increased maintenance costs and reduced service life [5]. These issues highlight a critical engineering problem: current pavement practices are no longer economically, environmentally, or structurally sustainable in the long term.

In addition to resource scarcity, waste generation from construction, demolition, and industrial activities has become a pressing global concern [6]. The simultaneous depletion of natural resources and the accumulation of waste present both challenges and opportunities for the construction sector. Repurposing waste materials can reduce dependence on virgin aggregates, conserve natural resources, and mitigate environmental pollution by diverting waste from landfills and lowering the carbon footprint

*Corresponding Author: Mastura Bujang. University of Technology Sarawak (UTS),
Email: mastura.bujang@uts.edu.my

associated with material extraction and processing [7]. As sustainability takes centre stage in modern infrastructure development, the pavement industry due to its large material demand and environmental footprint has been particularly targeted for improvement [8; 9]. Conventional pavement materials contribute significantly to greenhouse gas emissions and resource consumption [10], while also exhibiting structural vulnerabilities that shorten service life. Hence, the incorporation of waste materials into pavement layers offers a promising pathway to address both engineering performance challenges and environmental sustainability goals [11].

Sustainability in pavement engineering refers to meeting present transportation needs without compromising future resource availability, while minimizing environmental impacts throughout the pavement lifecycle [12]. Sustainable pavements emphasize material efficiency, reduced greenhouse gas emissions, and environmentally responsible construction practices [13]. The use of waste materials in pavement construction supports these aims by reducing waste disposal burdens, lowering raw material costs, and potentially enhancing pavement performance [14]. Depending on their properties, waste materials can partially or fully replace aggregates or bitumen in various pavement layers, including the subgrade, base, and surface courses [15]. This substitution can reduce transportation costs, extend pavement longevity, and contribute to overall project cost savings [16]. However, certain waste materials may contain harmful substances, such as heavy metals or toxic compounds that pose health and environmental risks if not properly treated [17; 18]. Proper handling, processing, and evaluation are therefore essential to ensure safe and effective use in pavement applications [19].

To address these gaps and challenges, this review aims to provide a comprehensive examination of contemporary practices and research on the incorporation of waste materials in sustainable pavement construction. Specifically, this review focuses on recycled concrete aggregate (RCA), reclaimed asphalt pavement (RAP), waste glass, ceramic tiles, plastics, and crumb rubber, which have been most frequently applied in pavement engineering [20]. The objectives of this review are to:

a) Identify and categorize waste materials used in pavement construction based on material type and potential application within pavement layers (subgrade, base, and surface).
b) Evaluate and compare their mechanical, durability, and environmental performance, including strength properties, longevity, and carbon footprint.
c) Assess economic feasibility, including potential cost savings related to material substitution and reduced maintenance needs.
d) Highlight challenges, limitations, and health or environmental risks associated with waste material utilization.
e) Provide a comparative overview, using tables or matrices, to summarize waste material performance in terms of strength, durability, and cost-effectiveness.
f) Identify research gaps and future directions for the large-scale adoption of waste materials in sustainable pavement engineering.

By examining the characteristics, benefits, and limitations of various waste materials, this review offers valuable insights into their practical application, performance outcomes, and potential to advance sustainable road construction practices [21].

RESEARCH METHOD

A systematic review approach was adopted to provide a structured, objective, and reproducible synthesis of research on the use of waste materials in pavement construction. This method systematically identifies, selects, evaluates, and summarizes relevant studies based on predefined criteria to ensure transparency and reliability in the review process [22; 23]. The Scopus database was selected as the primary source due to its broad indexing of peer-reviewed journals in civil engineering, materials science, and environmental sustainability [24]. The search was conducted using precise Boolean operators to ensure comprehensive coverage of relevant literature. The final search string applied was: ("pavement" AND "waste material*") OR ("sustainable pavement" OR "green pavement") AND ("recycled" OR "reuse" OR "alternative material*"). This search initially yielded 4,820 records. To align the dataset with the review scope, several filters were applied, including publication years (2012–2024), English-language documents, and subject areas restricted to civil engineering, materials science, environmental science, and environmental engineering [25]. Document types were limited to journal articles, research reports, and conference papers that provided primary data.

Predefined inclusion and exclusion criteria were established prior to screening to ensure objectivity and consistency. Studies were included if they involved the incorporation of waste materials into any pavement layer and provided measurable mechanical, durability, or environmental performance outcomes. Only original laboratory or field-based research was considered, and eligible studies had to involve at least one of the targeted waste materials: reclaimed asphalt pavement (RAP), recycled concrete aggregate (RCA), waste tiles, waste plastics, crumb rubber, or waste glass. Studies were excluded if they were not related to pavement engineering, did not involve waste material utilization, lacked quantitative data, or were review articles, editorials, or conceptual papers without experimental evidence. The initial dataset of 4,820 records was reduced to 4,766 after removing 54 duplicates. These records proceeded to title and abstract screening, during which 4,618 studies were excluded. The high exclusion number was justified as the majority of studies focused on waste management applications unrelated to pavements, lacked relevant performance data, or were secondary sources rather than primary experimental research.

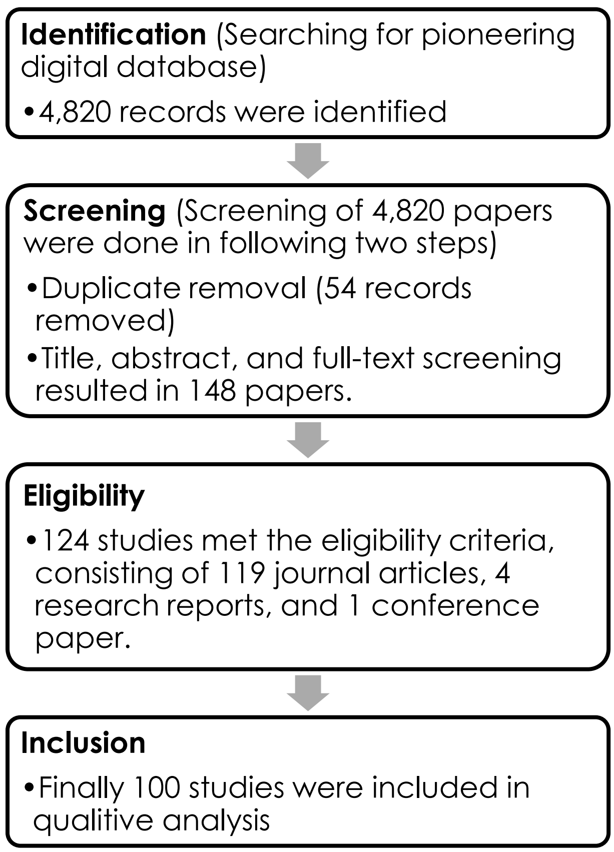

Figure 1. Systematic review process and outcomes

A total of 148 full-text articles were retrieved for detailed eligibility assessment. Each study was evaluated for methodological quality, relevance to waste material uses in pavements, clarity of experimental procedures, and completeness of performance data. A standardized evaluation checklist was used to maintain consistency during assessment. After applying all criteria, 124 studies were selected for final inclusion. These comprised 119 peer-reviewed journal articles, four technical research reports, and one conference paper. Although journal articles were prioritized, research reports and the conference paper were included when they contributed original and region-specific experimental data, provided adequate methodological transparency, and fulfilled all eligibility requirements. Their inclusion strengthened the comprehensiveness of the review, particularly in areas where innovative pavement research is often first disseminated through institutional reports.

The final dataset consisted of studies published between 2012 and 2025, with approximately 75% appearing after 2020, reflecting a growing research focus on sustainable pavement technologies. The year 2021 recorded the highest publication output (n = 22). Overall, the systematic and transparent selection process ensured that only high quality and relevant studies were incorporated, and a detailed overview of this process is presented in Figure 1.

TYPE OF WASTE MATERIALS UTILIZED

Every country has its standards and requirements for the materials used in pavement construction [27]. These standards ensure that the pavement construction is safe, durable, and capable of withstanding the intended loads and environmental conditions [28]. Applications of waste and recycled materials in pavement construction have developed into a field of study and practice, driven by the need to reduce environmental impacts and promote sustainability [29].

Recycled materials, such as Reclaimed Asphalt Pavement (RAP), Recycled Concrete Aggregate (RCA), waste tiles, waste plastic, crumb rubber, and waste glass, are being increasingly utilized as substitutes for conventional materials like natural aggregates and bitumen. These materials undergo a thorough examination to evaluate their characteristics and properties to ensure they meet the same performance standards as conventional materials. This involves rigorous testing to assess strength, stability, durability, and resistance to different mechanical and environmental stresses [30].

The performance improvements observed in waste-modified asphalt mixtures are primarily attributed to the physical and chemical interactions between waste particles and the asphalt binder. Materials such as crumb rubber and plastic enhance elasticity through polymer chain interaction, improving binder flexibility at high temperatures [31]. In contrast, mineral-based wastes like RCA and RAP act as rigid fillers, increasing stiffness and load-bearing capacity [32]. These mechanisms collectively contribute to reduced deformation, enhanced bonding, and improved resistance to moisture and temperature variations in the pavement structure.

The objective is to ensure that the finalized pavement product fulfills the minimum requirements for performance, regardless of whether waste resources are used wholly or partially in place of new components [33]. The use of recycled materials must not compromise the structural integrity or longevity of the pavement [34]. Therefore, rules and regulations are implemented to help integrate waste resources efficiently while preserving the required performance and quality standards [35]. Tables 1 and 2 present the conventional bitumen and aggregate materials replaced with various waste materials. Additionally, Table 3 will highlight the research gaps identified in this review.

Reclaimed Asphalt Pavement (RAP)

Reclaimed asphalt pavement (RAP) is produced by milling or eliminating pre-existing asphalt pavements made of a recycled aggregate and aged asphalt binder mixture [36]. The global construction industry is increasingly exploring sustainable and environmentally friendly materials, with RAP emerging as a key alternative in road construction [37]. Pavement maintenance is essential but often expensive; incorporating recycled materials like RAP can reduce maintenance costs and environmental impact [38]. One of the primary technical advantages of RAP-modified asphalt mixtures is their enhanced stiffness, achieved through blending aged (hardened) and conventional asphalt binders [39]. Using recycled materials like RAP may save expenses and decrease the environmental effect of maintaining pavement, which is important but prohibitively costly [40].

Researchers have reported that optimizing 35% of RAP content is crucial for maximizing asphalt mix performance [41]. Daryaee, Ameri, and Mansourkhaki indicated that the asphalt mixture with 50% RAP will increase the moisture resistance, rutting resistance, and fatigue life of the pavement [42]. Researcher T. Calabi-Floody et al. demonstrated that adding RAP to asphalt mixtures reduces carbon monoxide (CO) and carbon dioxide (CO_2) emissions while also lowering energy consumption by 13% compared to conventional asphalt mixes [43]. A stiffer asphalt mastic and a significant reduction in the mastic's linear viscoelastic strain limits can be achieved by adding RAP to the asphalt mixture [44].

Compared to other waste materials, RAP demonstrates strong binder compatibility and ease of incorporation into new asphalt mixtures, as it already contains aged bitumen and aggregate [45]. RAP exhibits superior binder compatibility but slightly lower moisture resistance, indicating that its use is more suitable for base and surface layers under dry conditions [46]. However, RAP is more suitable for base or binder layers, while materials like crumb rubber and plastics are preferred for surface layers that require higher flexibility and rutting resistance [47; 48].

Recycled Concrete Aggregate (RCA)

Recycled concrete aggregate (RCA) is obtained from demolished concrete building materials, such as bridges, buildings, and pavements, which are primarily crushed concrete with tiny amounts of brick, stone, and other inert elements [49]. Due to the increased need for construction and reconstruction driven by population growth, conventional materials are disposed of, and new ones are sourced for new projects [50]. The disposal of RCA is a substantial loss of strategic and financial resources, and its potential toxicity can harm ecosystems [51]. Utilizing RCA for pavements helps to decrease the infrastructure demands and effectively manage construction waste [52].

The utilization of RCA in road construction could offer substantial environmental benefits, emphasizing the importance of prioritizing durability and minimal environmental impact in future construction [51]. Dilbas, Şimşek and, Çakır investigated that 30% of RCA replaced with natural aggregate shows the optimum results for the tensile splitting strength and compressive strength of the samples [53]. Sheen et al. conclude that 14% to 24% of RAC as a replacement material affects various properties, including reduced compressive strength and unit weight, higher air content and absorption, and notable differences in performance based on whether the aggregates are washed or unwashed [54].

Similar to RAP, RCA also utilizes reclaimed materials but exhibits different structural characteristics. RCA provides higher stiffness and compressive strength through the presence of residual cement paste, which offers higher load-bearing capacity [55]. However, its higher porosity and water absorption might reduce durability compared to less porous alternatives such as waste glass or tiles. RCA is therefore well-suited for base and subbase layers, while RAP or rubber-modified mixtures are more suited for flexible surface courses [56; 57].

Waste Tiles

Waste tiles are generated by crushing ceramic tiles during transportation and installation for roofs, walls, and floors [58]. Disposing of waste tiles, which are abundant due to their widespread use in construction, creates a critical challenge for landfills [59]. Researchers suggest that utilizing recycled ceramic aggregates can enhance road stability and improve visual appearance, thus potentially mitigating environmental impact in pavement construction [58; 60].

The utilization of waste tiles into secondary aggregates at 20-100% by weight can enhance the mechanical properties of the asphalt mixture compared to traditional limestone aggregates [61]. While considering the financial constraints of asphalt, researchers found that ceramic waste can be utilized in asphalt mixtures up to 30% by weight [62]. Researchers Feng, Yi, and Wang also suggested that the addition of waste tiles into asphalt mixtures benefits pavement engineering by reducing thermal conductivity, thereby moderating temperature gradients within the pavement structure and satisfying performance requirements with up to 40% substitution of natural coarse aggregates [63].

Compared with other mineral-based waste like RCA or glass, waste tiles exhibit high hardness and abrasion resistance, making them an excellent replacement for coarse aggregate in surface layers [64]. However, their brittleness and angular shape can cause compaction and bonding challenges, especially when compared to RAP or plastics, which provide better flexibility [65]. Therefore, waste tiles are often blended with softer materials or bituminous modifiers to balance stiffness and durability.

Waste Plastics

Waste plastic comes from discarded plastic items and packaging. Incorporating waste plastic into asphalt mixtures could improve high-temperature performance while benefiting the economy and environment [66]. Plastics are widely used in various sectors due to their durability, cost-effectiveness, lightweight, and simplicity of processing compared to other materials [67]. Utilizing waste plastic as a replacement material for construction, such as combining it with binders to the asphalt mixtures because of its high melting point, resistance to decomposition, and UV light, which is a workable solution that effectively utilizes waste plastic and lowers the requirement for new bitumen in the asphalt production process [20].

Researcher Gautam et al. stated that 5% of plastic waste in an asphalt mixture can show excellent Marshall stability and flow results [35]. Lee and Le investigated that 5% of the plastic-modified mixture has more water resistance and less abrasion value than the conventional asphalt mixture, which enhances the strength and durability of the pavement [68]. Furthermore, waste plastic enhances high-temperature performance by increasing stiffness, as measured by the Dynamic Shear Rheometer (DSR), while maintaining a comparable modulus at low temperatures [69].

Compared with inorganic materials such as RCA, glass, or tiles, waste plastics significantly enhance flexibility, fatigue life, and resistance to rutting due to their thermoplastic nature [70]. The addition of waste plastics would improve elasticity and deformation resistance of asphalt. However, excessive plastic content may cause segregation or uneven coating, unlike crumb rubber, which blends more uniformly with bitumen [71]. Waste plastics are particularly effective for surface course modification, providing a balance between strength, flexibility, and sustainability [72].

Crumb Rubber

Crumb rubbers are a recyclable material that comes from old and scrap tires and undergo a granulation process [73]. The rise in vehicle numbers worldwide has led to increased road usage and asphalt pavement breakdown [74]. Incorporating crumb rubber into asphalt mixtures has enhanced durability, improved pavement performance, and addressed environmental concerns associated with tire waste [75]. Rubberized asphalt has become increasingly common because of the large supply of recycled rubber, the need to lessen negative environmental effects, and initiatives to lessen the use of virgin materials in road building [76].

Rubberized asphalt will recover energy from discarded tires, provide superior durability, and decrease tire-road noise [77]. Researchers Khaled, Aboud, and Al-Hamd state that adding crumb rubber to bituminous mixtures significantly enhances asphalt pavement's resistance to rutting and moisture damage, with 24% CR providing the highest rutting resistance and 20% CR yielding the highest tensile strength ratio (TSR). Additionally, incorporating 12% crumb rubber into asphalt mixtures has been shown to increase Marshall Stability values while enhancing pavement longevity and performance [75].

Crumb rubber-modified asphalt generally outperforms RAP and RCA mixtures in terms of elasticity, fatigue resistance, and rutting performance. Compared with waste plastics, crumb rubber provides better binder compatibility and enhanced temperature stability but may require higher mixing temperatures and longer curing times [78; 79]. As a combination with silica-based materials such as glass or tiles, crumb rubber can help improve flexibility and reduce cracking susceptibility, leading to balanced mechanical and environmental performance [80].

Waste Glass

Waste glass is a significant threat to the environment because of its substantial annual volume and slow degradation rate [81]. Repurposing it for building materials has gained popularity recently as a sustainable solution to waste accumulation and to promote environmental responsibility, especially in asphalt mixtures for pavement construction [82]. Utilizing discarded glass in pavement construction offers an eco-friendly approach that supports circular economy principles and reduces landfill accumulation [83].

Incorporating 50% glass fiber reinforcement as a replacement for fine aggregate in asphalt mixtures has significantly enhanced rutting and crack resistance, durability, and tensile strength compared to conventional asphalt mixtures [84]. Moreno-Navarro et al. observed that increasing the recycled glass content leads to a decline in stability and an increase in air voids due to the low absorption capacity of recycled glass [85]. This effect weakens aggregate-binder adhesion, resulting in less efficient compaction and reduced load-bearing capacity. Consequently, the performance of the asphalt mixture becomes more reliant on binder stiffness rather than aggregate interlock.

Similarly, waste glass shows comparable characteristics to tiles but with differences in particle size and chemical reactivity. Waste glass offers improved stiffness, skid resistance, and stripping resistance and greater durability and impermeability than RAP and RCA [86]. However, its smooth surface and potential for alkali–silica reaction (ASR) may reduce adhesion with bitumen compared to crumb rubber or plastics, which enhance binder interaction [87]. To offset this, fine glass powder is occasionally used as a filler or blended with waste materials such as silica fume or rubber powder to improve bonding and flexibility [88].

Table 1. Aggregate Replacement Materials

Materials	Author	Application	Bitumen Grade	Aggregate Type	Replacement Proportion	Optimum Replacement
Waste Tiles	Muniandy, Ismail and Hassim (2017) [61]	Hot Mix Asphalt Pavement	Grade 80/100	Granite	20%, 40%, 60%, 80% and 100%	20%
	Cabalar, Hassan and Abdulnafaa (2016) [89]	Hot Mix Asphalt Pavement	Grade 50/70	Natural Aggregate	10%, 20%, 30%, and 40%	30%
RCA	Tahmoorian and Samali (2018) [90]	Hot Mix Asphalt Pavement	-	Basalt	25%, 50% and 75%	75%
	Pasandín and Pérez (2014) [91]	Hot Mix Asphalt Pavement	Grade 50/70	-	100%	100%
RAP	Plati and Cliatt (2018) [92]	Asphalt Concrete Pavement	-	Virgin Aggregate	50% and 100%	50%
	Daryaee, Ameri and Mansourkhaki (2020) [42]	-	Grade 60/70	Limestone	50%	50%
	Colbert and You (2012) [70]	Hot Mix Asphalt Pavement	PG 58-28	Virgin Aggregate	15%, 35% and 50%	35%
Glass Waste	Kalampokis *et al.* (2023) [82]	Surface Pavement Layer	Grade 50/70	Diabase coarse aggregates	10% and 15%	10%
	Cheng *et al.* (2021) [86]	Microsurfacing	AH-90	Basalt	5%, 10%, 15%, and 20%	10%

Table 2. Bitumen Replacement Materials

Materials	Author	Application	Bitumen Grade	Aggregate Type	Replacement Proportion	Optimum Replacement
Crumb Rubber	Eltwati, Hossein and Danil Nasr (2020) [94]	Hot Mix Asphalt Pavement	Grade 60/70	AC-16	16%, 20%, 24%, and 28%	20-24%
	Intan Jasmin Rosli and Abd Sukor Sarif (2021) [95]	Hot Mix Asphalt Pavement	Grade 60/70	-	8%, 10%, and 12%	10%

	Ahmad et al. (2019) [96]	Asphalt Concrete Pavement	Grade 60/70	AC-20	4.0%, 8.0%, 12.0%, 16.0% and 20.0%	12%
Plastic Waste	Verma (2021) [97]	Polymer-modified bitumen	Grade 60/70	-	2%, 4%, 6%, 8%, and 10%	8%
	Hake, Damgir and Awsarmal (2020) [98]	Flexible Pavement	Grade 60/70 and 80/100	-	7.5%, 10%, 12.5% and 15%	10%
	Rajneesh Kumar and Maaz Allah Khan (2020) [99]	Hot Mix Asphalt Pavement	Grade 80/100	Artificial Aggregates	8% and 10%	10%

Table 3. Research Gap

Author	Materials	Test Parameters	Results
Muniandy, Ismail and Hassim (2017) [61]	Waste Tiles	Marshal stability and flow, thermal properties test, and resilient modulus	Improves asphalt mixture performance and reduces pavement temperature
Cabalar, Hassan and Abdulnafaa (2016) [89]		Unconfined Compressive Strength, California Bearing Ratio, compaction, oedometer, and swelling tests	Enhance performance with an increase of CBR value, dry unit weight, and reducing water content and void ratio
Tahmoorian and Samali (2018) [90]	RCA	Water absorption test, crushing value, strength, flakiness index, wet and dry strength variation, and particle density	RCA can enhance the workability and deformation resistance in asphalt mixtures, but exhibits high water absorption and strength variation
(Pasandín and Pérez, 2014) [91]		Binder bond strength tests, water boiling test, and RA surface roughness	Higher filler ratios and RCA reduced bond strength but increased the aggregate surface roughness
Plati and Cliatt (2018) [92]	RAP	Maximum Dry Weight (MDD), and Optimum Moisture Content (OMC), and resilient modulus	RAP performs comparably to virgin aggregates in resilient modulus and offers lower density and moisture content
Daryaee, Ameri, and Mansourkhaki (2020) [42]		Resilient modulus test, dynamic creep test, strength test, and fatigue test	Improve fatigue resistance, rutting resistance, and moisture susceptibility, while maintaining high-temperature performance
Colbert and You (2012) [93]		Rotational viscosity, temperature and frequency sweep tests, and dynamic shear rheometer	High RAP content increases stiffness and viscosity of asphalt binders
Kalampokis *et al.* (2023) [82]	Glass Waste	Stiffness, cyclic compression tests, and indirect tensile strength test	Reduced stiffness and resistance to permanent deformation
Cheng *et al.* (2021) [86]		Wet stripping test, wet track abrasion test, load wheel tracking test, and skid resistance test	Increases skid resistance but decreases wear and rutting resistance
Eltwati, Hossein and Danil Nasr (2020) [94]	Rubber Tires	Marshall test, wheel tracking test, moisture test, and strength test	Enhance the stiffness modulus which increases the pavement's bearing capacity under heavy traffic loads
Intan Jasmin Rosli and Abd Sukor Sarif (2021) [95]		Penetration test, softening test, ductility test, Marshall stability test, and indirect tensile strength test	The addition of crumb rubber will improve pavement strength, quality, and performance

Ahmad *et al.* (2019) [96]		Marshall stability, air voids, and stiffness properties	Enhance the Marshall stability, density, flow, and stiffness, while reducing air voids
Verma (2021) [97]	Plastic Waste	Rutting resistance, fatigue resistance, moisture resistance, low-temperature performance, and compatibility	Increase the rutting, fatigue, and moisture resistance but challenges with compatibility and low-temperature performance
Hake, Damgir and Awsarmal (2020) [98]		Marshall Test	Enhance the mixture performance, increase road lifespan, and reduce costs
Rajneesh Kumar and Maaz Allah Khan (2020) [99]		Bitumen test and Marshal stability test	Enhanced road performance with reduced rutting and pothole formation, leading to improved durability and traffic resistance

Extensive research has been conducted on using various waste materials in pavement construction, highlighting their potential benefits and practical applications [100]. The above table has examined the potential of waste tiles, RCA, RAP, glass waste, crumb rubber, and plastic waste in improving pavement properties. For instance, waste tiles improve thermal properties and resilient modulus, leading to better asphalt mixture performance and reduced pavement temperatures. Similarly, RCA enhances workability and deformation resistance, though its high water absorption and strength variability require careful mix design optimization. RAP is comparable to virgin aggregates in resilient modulus and offers the advantages of lower density and moisture content, which can be particularly beneficial for specific pavement applications.

Despite the promising results, each material presents unique challenges that need to be addressed. For example, glass waste improves skid resistance but reduces stiffness and resistance to permanent deformation, emphasizing the need for balanced material properties in the final asphalt mix. Crumb rubber enhances stiffness modulus and increases pavement's bearing capacity under heavy traffic loads, but it requires careful management of mixed properties to avoid over-stiffening. Meanwhile, plastic waste has been shown to enhance rutting, fatigue, and moisture resistance; however, compatibility issues and poor low-temperature performance remain significant concerns.

Addressing these research gaps is essential to successfully and sustainably integrate waste materials in pavement construction to reduce the use of natural resources and environmental impact [35]. This strategy lowers the cost of traditional materials while improving pavement performance, which benefits the economy and encourages ecological sustainability. In the end, it helps create more sustainable infrastructure [101]. Further research is required to evaluate the long-term environmental impact and durability of waste-modified asphalt mixtures.

Recent studies have also explored the combined use of multiple waste materials to capitalize on their complementary properties. For instance, combination of crumb rubber and silica fume or waste plastic may increase elasticity as well as stiffness, achieving better balance between rutting and fatigue resistance [102]. Similarly, RAP combined with RCA enhanced workability and cost efficiency. Although research on hybrid modifications remains limited, initial results indicate that multi-material methods may further improve asphalt mixture sustainability and mechanical properties.

The combined use of different waste materials such as rubber with glass or RAP with RCA has shown potential to balance stiffness and flexibility, achieving better overall performance [103]. However, more long-term field studies are required to confirm their durability and environmental impact. This synthesis indicates that no single waste material is universally superior; rather, its suitability depends on mixture composition, service conditions, and application layer.

Overall, the comparative assessment of the reviewed waste materials highlights distinct performance advantages depending on their type and intended pavement layer. Crumb rubber and waste plastics generally enhance flexibility, elasticity, and rutting resistance, making them particularly suitable for surface layers subjected to heavy traffic loads. In contrast, mineral-based materials such as RCA, RAP, waste tiles, and waste glass provide higher stiffness and structural strength, which are advantageous for base and subbase layers where load support is critical. Therefore, integrating waste materials in a targeted and layer-specific manner represents an effective approach toward achieving sustainable and durable pavement construction.

CONCLUSIONS

The incorporation of waste materials in pavement construction presents a promising pathway toward sustainable and resource efficient road infrastructure. Overall, evidence from recent studies shows that certain waste materials can enhance specific aspects of pavement performance for example, recycled asphalt improves stiffness and structural capacity, while plastics and rubber enhance flexibility and deformation resistance. Mineral-based wastes such as ceramic and glass generally increase stiffness and load-bearing capacity. However, a closer comparative assessment reveals that the effectiveness of each waste material is highly dependent on its application layer and replacement level. Bitumen-based modifiers (e.g., crumb rubber, plastic) tend to perform better in surface layers requiring flexibility, whereas aggregate-based wastes (e.g., RCA, RAP, glass) are more suitable for base and binder layers due to their stiffness contributions.

Despite these positive outcomes, the literature demonstrates several limitations and conflicting findings that require careful consideration. Excessive incorporation of RAP or RCA has been associated with reduced fatigue life, increased brittleness, and lower workability, particularly when replacement levels exceed recommended thresholds. Similarly, high contents of plastic or rubber may lead to poor compatibility with bitumen, phase separation, or inconsistent rheological behaviour. These inconsistencies highlight that performance improvements observed in laboratory conditions do not always translate directly into field performance, especially under diverse traffic loads, climatic variations, and long-term aging processes. This remains one of the most significant knowledge gaps.

Environmental and health concerns also present notable challenges. While waste utilization reduces landfill dependency, improper processing of plastics, rubber, or industrial wastes may introduce microplastics, leachates, or heavy metals into the environment. Furthermore, many studies lack comprehensive life-cycle assessments, making it difficult to conclusively quantify the net environmental benefit of each waste material.

A synthesis of existing evidence indicates that waste materials offer substantial potential, but their performance is neither universal nor guaranteed. Instead, their suitability depends on material type, processing method, mixture design, and layer specific application. To advance practical implementation, future research should focus on the long term field validation under real traffic and climate conditions to bridge the gap between laboratory and field behavior, standardized the mix design procedures to improve consistency and comparability across studies, comprehensive environmental and health assessments, particularly regarding microplastic generation, leachability, and pollution risks, and life-cycle cost and carbon analyses to quantify true sustainability benefits.

In conclusion, while waste materials hold strong potential to advance sustainable pavement engineering, their adoption must be guided by evidence-based design, environmental safeguards, and long-term performance validation. A more critical and systematic approach to evaluating waste-derived pavements will help transition these materials from promising research concepts to reliable, large-scale solutions in sustainable road construction.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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