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Review Article

Sustainable Pavement Materials: A Comprehensive Review of Performance, Environmental Impacts, and Implementation Challenges

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Abstract

Sustainability has become a central focus in pavement engineering, particularly in the selection and design of materials. This review examines advances in sustainable pavement technologies, including recycled aggregates, reclaimed asphalt pavement (RAP), warm-mix asphalt (WMA), bio-binders, industrial byproducts, and other eco-friendly innovations such as recycled rubber and plastics. Studies up to 2022 highlight significant environmental, economic, and performance benefits. RAP and recycled concrete aggregates reduce virgin aggregate demand and greenhouse gas emissions, often without compromising durability. WMA allows asphalt production at lower temperatures, reducing energy use and emissions by 20–75%, while improving workability and accommodating higher recycling rates. Bio-binders derived from renewable or waste resources lower carbon footprints but may require optimization for high-temperature performance. Industrial byproducts like fly ash and slag not only valorize waste but can enhance pavement durability. Life-cycle assessment (LCA) consistently demonstrates that integrating sustainable materials reduces environmental burdens across a pavement's service life compared to traditional materials. Overall, sustainable pavement technologies offer dual benefits: environmental impact reduction and economic viability, while maintaining reliable structural performance. These findings align with global objectives to advance sustainable infrastructure and highlight the critical role of innovative materials in future pavement systems.

Keywords: *Sustainable Pavements; Reclaimed Asphalt Pavement; Warm-Mix Asphalt; Bio-Binders; Life-Cycle Assessment.*

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Introduction

The global pavement infrastructure faces a dual challenge in the 21st century: to meet the growing demand for roads and highways while minimizing environmental and resource impacts. Conventional pavement construction methods are characterized by a substantial reliance on energy-intensive processes and non-renewable materials. The production of hot-mix asphalt (HMA), for instance, necessitates the heating of aggregate and bitumen to temperatures ranging from 150 to 180ºC. This process is associated with significant fuel consumption and the emission of greenhouse gases (Milad et al., 2022). Similarly, the production of Portland cement concrete pavements involves the cement production process, which releases approximately one ton of CO_2 for every ton of cement produced (M.G. et al., 2022). Furthermore, substantial quantities of virgin aggregates are extracted for pavement layers on an annual basis, resulting in millions of tons of discarded materials from previous pavement construction. These practices give rise to concerns regarding climate change, resource depletion, and the need for landfill space. In response to these challenges, the pavement engineering field has increasingly embraced sustainability principles, with a focus on reducing energy use and emissions, conserving natural resources, and recycling or repurposing waste. These principles have been incorporated into the design and maintenance of road materials (Milad et al., 2022).

A significant strategy for sustainable pavements involves the substitution of conventional materials with recycled or renewable materials. In recent decades, researchers and industry practitioners have investigated a diverse array of such materials. For instance, recycled aggregates from construction and demolition waste have been demonstrated to substitute for new quarry stone in base layers or concrete (Milad et al., 2022). Reclaimed asphalt pavement (RAP), which is derived from the milling or removal of distressed asphalt layers, can be reused in new asphalt mixes. This practice directly conserves both aggregate and bituminous binder (Dughaishi et al., 2022). Technologies such as warm-mix asphalt (WMA) have been developed to reduce the production temperature of asphalt mixtures by 10–40°C, thereby substantially decreasing energy consumption and airborne emissions in comparison with traditional hot-mix asphalt (HMA) (Milad et al., 2022). In the domain of binders, bio-binders—defined as binders partially or fully derived from renewable resources such as plant oils or agro-waste—offer the potential to reduce reliance on petroleum-based bitumen and to lower the carbon footprint of asphalt binders (Zhang et al., 2022). Furthermore, a variety of industrial byproducts have been identified as potential components in pavement applications. For instance, coal fly ash and ground-granulated blast furnace slag (GGBFS) have been shown to substitute for Portland cement in concrete or to function as mineral fillers. Additionally, steel slag and foundry sand can be processed into aggregates for asphalt or base courses (Ahmad et al., 2022). Other innovative materials include recycled tire rubber (used in rubberized asphalt mixtures), waste plastic (used as modifiers or aggregate replacements in asphalt), and even reclaimed glass. The objective of incorporating these materials is to improve sustainability by reusing waste and enhancing certain pavement properties.

The early implementation of these sustainable materials has yielded notable benefits. For instance, numerous highway agencies have documented cost savings and performance achievements with moderate RAP contents in asphalt. This is due to the fact that RAP can enhance rutting resistance due to its stiff aged binder (Dughaishi et al., 2022). Warm-mix asphalt has seen widespread adoption globally, thanks to its ability to reduce paving emissions (fumes, CO_2) and to provide better working conditions for paving crews by lowering hot asphalt odors (Milad et al., 2022). Life-cycle assessments have begun to quantify the advantages. One study estimated that combining WMA with RAP could reduce the global warming potential of asphalt pavements by approximately 20–30% and lower material costs by up to 30–40% compared to conventional HMA with all-virgin materials (Farooq & Mir, 2017). In the field of concrete research, the substitution of a proportion of cement with fly ash or slag has been demonstrated to markedly reduce CO_2 emissions and frequently enhance long-term durability (due to diminished permeability). This approach is in alignment with contemporary sustainability and performance objectives (M.G. et al., 2022).

Notwithstanding the evident positive trends, challenges persist that impede the full-scale implementation of sustainable pavement materials. Performance uncertainties persist, as evidenced by the propensity of high RAP content to induce fatigue or thermal cracking in asphalt mixes if not meticulously engineered (Dughaishi et al., 2022). Additionally, certain bio-binders have exhibited substandard high-temperature performance in comparison to neat bitumen (Zhang et al., 2022). However, practical and institutional barriers must also be considered. Variability in waste material quality, a lack of standardized specifications, and the need for contractor education and new equipment are frequently cited as barriers (Ahmad et al., 2022). Economic considerations play a complex role in this context. While many green strategies promise life-cycle cost savings, initial investments (e.g., WMA additives or rejuvenators for RAP, processing for recycled aggregates) can be higher. This necessitates justification and awareness of long-term benefits (Ahmad et al., 2022). Nevertheless, the impetus for sustainable pavements remains robust, bolstered by government policies (e.g., mandates to augment recycling or curtail CO_2 emissions in construction) and corporate sustainability objectives.

In this context, the objective of our review is to provide a comprehensive overview of sustainability in pavement engineering, with a focus on materials. A systematic review of the extant literature on various categories of sustainable pavement materials and innovations was conducted up to 2022. The environmental impact, mechanical performance, and economic viability of these materials were evaluated. The article's structure is as follows: Section 2, entitled "Material Categories," is subdivided into subsections that enumerate the various major categories of sustainable material. These categories include, but are not limited to, recycled aggregates, RAP, WMA, bio-binders, industrial byproducts, and other emerging materials. In the ensuing subsections, an examination is conducted to ascertain the manner in which each material or technology contributes to sustainability. Furthermore, a synthesis of findings from studies on their performance (strength, durability, etc.) and practicality is provided. In Section 3 (Comparative Analysis), a comparative approach is employed to assess the solutions under consideration against a set of common criteria. These criteria include environmental footprint, as measured by Life Cycle Assessment (LCA) results and emissions, mechanical and long-term performance, and cost-effectiveness. Section 4 (Challenges and Opportunities) addresses the implementation challenges encountered for these sustainable materials and highlights future opportunities and research needs. For example, improvements in material processing, guidelines development, and innovative combinations of technologies (such as using bio-based rejuvenators for high-RAP WMA mixes) are discussed. Finally, Section 5 (Conclusion) synthesizes the salient points: sustainable pavement materials have the potential to play a pivotal role in mitigating the environmental impact of road infrastructure while maintaining performance. However, realizing their full potential will necessitate concerted efforts in research, standardization, and industry practice.

Material Categories

Recycled Aggregates in Pavements

A foundational strategy for achieving more sustainable pavements involves the incorporation of recycled aggregates, which serve as a substitute for natural aggregates, particularly in the composition of pavement layers. Recycled aggregates are typically derived from construction and demolition (C&D) waste, including crushed concrete and masonry from decommissioned structures, as well as recycled concrete pavement itself (recycled concrete aggregate, RCA). Following the implementation of the requisite processing procedures (e.g., the elimination of contaminants, the reduction of size through crushing, and the sorting of materials based on size), these materials can be utilized in a variety of pavement applications. These include road base or subbase layers, asphalt mixtures, and new concrete for rigid pavements (Pereira & Vieira, 2022). The motivation for this study is evident: natural aggregate extraction has been demonstrated to have environmental costs, including habitat disruption and the energy required for quarrying and transport. Notably, aggregates constitute the most substantial component of pavement materials by volume, accounting for over 90% by weight in asphalt mixtures and approximately 70% in concrete (Tiza et al., 2022; Zhao, Webber, et al., 2022). The reuse of aggregates from waste has been demonstrated to reduce the demand for new extraction and divert material from landfills, thereby promoting a circular economy in the construction industry.

Recycled Concrete Aggregate (RCA)

One of the most prevalent recycled aggregates is RCA, which is derived from crushed concrete elements. RCA frequently contains not only the original aggregate but also remnants of hydrated cement paste attached to the particles. Notwithstanding, a substantial body of research has demonstrated that RCA can exhibit mechanical properties analogous to those of natural aggregates under specific applications. For instance, when RCA is utilized in unbound granular base or subbase layers, standard laboratory tests (e.g., resilient modulus and shear strength) indicate that properly graded RCA can meet the stiffness and strength requirements similar to conventional base materials (Jayakody et al., 2019).

Jayakody et al. (2019) demonstrated that compacted RCA specimens exhibit steadily increasing stiffness under repeated load, especially at optimal moisture and density conditions. This phenomenon is partly attributable to the angular shape and residual cement, which has the capacity to rehydrate and bind particles. A substantial body of field evidence supports the hypothesis that RCA that has undergone adequate processing can function effectively as a road base. For instance, the Illinois Tollway in the USA reported success using 100% RCA in certain base layers, achieving load-bearing capacity that is equal to or greater than that of traditional aggregate bases (Gillen, 2013).

In the context of concrete pavements, RCA has the potential to substitute for a proportion of virgin coarse aggregate. Researchers advise exercising caution in high percentages due to the possibility of slight reductions in strength or workability; however, moderate replacement has been demonstrated to be feasible. The replacement of 25–40% of the natural coarse aggregate with RCA in concrete mixes has been shown to yield compressive strengths that are within 5–15% of the control (sometimes nearly equal to the control by 28 days) (Kox et al., 2019; Marathe et al., 2021; Shmlls et al., 2022). For instance, a study revealed that substituting 40% of the coarse aggregate with RCA resulted in compressive strengths greater than 29 megapascals (MPa) after 28 days, indicating the material's potential for enhanced durability in pavement concretes (Kox et al., 2019). Higher replacement levels (e.g., 50% or more) can be utilized with meticulous mix design; a study accomplished 50 MPa with 50% RCA by adjusting the mix and ensuring adequate curing (Mikhailenko et al., 2020). The primary concerns associated with RCA in concrete pertain to its elevated water absorption, attributable to the presence of attached old mortar, and the potential reduction in strength if the source concrete exhibits substandard quality. The incorporation of design modifications, such as the utilization of elevated initial water levels or the incorporation of water-reducing admixtures, has been demonstrated to enhance workability. Adherence to suitable replacement limits is instrumental in preserving strength and durability. In essence, RCA has been recognized as a "globally accepted option in the sustainable construction industry" under the condition that its implementation is accompanied by the verification of material properties and the establishment of suitable percentage limits (P. Wang et al., 2023). Many national standards, including those in effect in Europe and certain regions of North America, permit the use of RCA in concrete for specific applications, such as base layers and surface concrete in secondary roads, contingent upon the fulfillment of performance criteria (Federal Highway Administration, 2022).

In the field of asphalt mixtures, recycled concrete aggregate has been examined as a potential alternative aggregate. The incorporation of RCA in asphalt, whether as part of the fine or coarse aggregate fraction, has the potential to present challenges if the RCA exhibits residual porous mortar characteristics. This condition may lead to an increase in asphalt absorption, resulting in the mixture becoming dry or susceptible to stripping. Research has indicated that the substitution of natural aggregate with RCA, up to a proportion of 30–60% in asphalt mix, is a feasible proposition. However, this substitution may necessitate an augmentation in the asphalt binder content to account for the absorption phenomenon (Bastidas-Martínez et al., 2022; Jayakody et al., 2019; Polo-Mendoza et al., 2022; P. Wang et al., 2023). Furthermore, Marshall stability of hot-mix asphalt has been observed to increase with RCA usage, which is attributed to the angular, rough-textured nature of RCA improving interlock (Bastidas-Martínez et al., 2022). However, the optimal binder content also rises because RCA absorbs more binder than stone (Polo-Mendoza et al., 2022). An increase in optimum asphalt content by 2–18% (relative) was observed when 15–45% of aggregate was replaced by RCA in warm-mix asphalt, resulting in a slight reduction in net environmental gain due to the increased bitumen requirement (Polo-Mendoza et al., 2022). However, there are notable environmental and cost benefits associated with its use. The implementation of RCA in asphalt has been shown to conserve virgin aggregate and frequently results in reduced material costs, particularly when the RCA source is local, thereby eliminating the need for natural aggregate hauling.

Other Recycled Aggregates

In addition to RCA, other C&D waste management strategies have been explored in the context of pavement maintenance. One example of a suitable aggregate base is a blend of crushed brick or masonry from demolished buildings. Brick is generally softer than rock; therefore, it is typically utilized in smaller-scale applications or in areas with lower traffic volume. A study by Xiao et al. (2022) evaluated building demolition waste (BDW) as a whole, which is a mix of crushed concrete, brick, etc., as unbound granular fill for subbase. The study demonstrated that with proper gradation control, even heterogeneous C&D aggregate could achieve suitable modulus and strength for subbase layers. It was observed that BDW aggregate exhibited a higher proportion of fine material post-crushing, a consequence of the potential degradation of masonry materials. This observation suggests a potential enhancement in water absorption and the necessity for enhanced drainage measures to circumvent freeze-thaw cycles, as previously documented by Xiao et al. (2022). The model developed for predicting the elasticity of BDW-based subbase has facilitated a more profound comprehension of the manner in which particle breakage during the process of compaction influences performance (Xiao et al., 2022). Many transportation agencies permit the incorporation of recycled aggregate in base layers up to 100%, provided it meets the requisite grading and strength specifications. For instance, California's Caltrans allows 100% reclaimed aggregate base, including crushed concrete.

A particular challenge with recycled aggregates pertains to ensuring consistency and implementing effective quality control measures. The composition, hardness, and contamination of aggregates can vary significantly depending on their respective sources. Aggregates may be comprised of concrete, brick, or asphalt pieces, among other materials. Additionally, these aggregates can be contaminated with elements such as wood, drywall, or glass. Consequently, the processes of processing and screening are of paramount importance. However, the environmental benefits of recycled aggregate are substantial. According to certain estimations, the utilization of recycled aggregates in road base can result in a 30–50% reduction in greenhouse gas emissions when compared with the alternative of landfilling the existing material and quarrying new stone. This is due to the avoidance of landfill emissions and the reduction of haul distances for new rock. Furthermore, it has been demonstrated to result in a reduction in the consumption of natural aggregate, a phenomenon that has been observed in regions where such aggregate is becoming increasingly scarce. In the Netherlands and Japan, the recycling rate for construction waste has consistently exceeded 80%, with a significant portion of these materials being utilized in the construction of new roads. This approach effectively demonstrates the comprehensive utilization of materials within a closed-loop system.

In summary, the utilization of recycled aggregates, particularly those derived from RCA, has been demonstrated to be a viable solution in various pavement applications, including the construction of bases, the incorporation of asphalt, and the production of new concrete. This viability is typically observed at partial replacement levels. The mechanical performance of these materials is comparable to that of conventional materials when usage is optimized, as evidenced by replacement percentages and mix adjustments. Furthermore, the environmental benefits of using these materials are evident in their ability to conserve resources. The utilization of C&D waste in pavements is expected to rise in tandem with the intensification of sustainability goals. However, to ensure reliable performance, there is a need for consistent specifications, processing methods, and potentially novel testing methods, such as the monitoring of aggregate abrasion and absorption properties.

Reclaimed Asphalt Pavement (RAP)

Reclaimed Asphalt Pavement (RAP) has emerged as a predominant recycled material within the asphalt industry. RAP is generated by milling or removing existing asphalt layers (during rehabilitation) or by full-depth removal of old pavements. The mixture consists of aged asphalt binder and aggregates that were originally present in the pavement (Arshad et al., 2017). Rather than perceiving this material as waste, it can be reintegrated into novel asphalt mixtures, thereby diminishing the necessity for virgin bitumen and aggregates. The utilization of RAP (reclaimed asphalt pavement) exemplifies the fundamental principle of sustainability: the reuse of materials in a high-value application, thereby achieving cost savings and a reduction in environmental impact. In many jurisdictions, RAP has been routinely utilized for decades at lower percentages (10–30% of the mix), and there is a push to increase these percentages to 50% or more with proper technology (such as rejuvenators or WMA) (Alwetaishi et al., 2019).

Environmental and Economic Benefits

The primary incentive to use RAP is the conservation of resources. RAP contains valuable components, including well-graded aggregates and bitumen. Consequently, substituting a portion of virgin materials with RAP results in direct savings. For instance, the incorporation of every ton of RAP in a new mixture has been shown to result in the conservation of approximately 1 ton of new aggregate and 20 kg (or more) of bitumen (depending on the RAP binder content and effectiveness) (Dughaishi et al., 2022). This phenomenon leads to cost savings, particularly in regions where aggregates or asphalt cement are costly or in short supply. In Oman, as Dughaishi et al. (2022) report, RAP is regarded as an economically viable option due to the scarcity of quality virgin aggregate in certain regions, which necessitates the importation of asphalt binder. Consequently, the recycling of existing pavement emerges as a strategy to ensure material supply and reduce costs. From an environmental perspective, the incorporation of RAP has been shown to reduce the demand for new asphalt binder, which is refined from crude oil and is a significant source of emissions. Additionally, it has been demonstrated that RAP avoids the energy use and emissions associated with the quarrying and hauling of new aggregates. Life-cycle assessment studies consistently find lower energy consumption and greenhouse gas footprints for pavements with RAP. A case study of LCA in the Gulf region revealed that the incorporation of 15% RAP in a WMA blend resulted in "markedly diminished environmental repercussions across all indicators" in comparison to a virgin-materials HMA over the course of a 30-year life cycle (Taha et al., 1999). Furthermore, case studies conducted in the United States and Europe have demonstrated that the incorporation of 20–30% RAP mixes can reduce total life-cycle CO_2 emissions of an asphalt layer by approximately 10–20%, while concurrently decreasing life-cycle costs due to reduced raw material requirements.

Mechanical Performance

A significant concern pertains to the impact of RAP on the performance of novel asphalt mixtures. When RAP is incorporated, the aged asphalt binder it contains undergoes a degree of blending with the fresh binder in the mixture. As a result of the oxidation that occurs during years of service, aged binders exhibit increased rigidity and fragility. Consequently, elevated RAP content has the potential to enhance the overall stiffness of the mixture and augment high-temperature rutting resistance. However, this increase in stiffness may be accompanied by a reduction in low-temperature flexibility and fatigue life, if not adequately mitigated (Tarsi et al., 2020). A multitude of studies have observed this equilibrium. The objective of this study is to examine the impact of RAP on the resistance of rutting, defined as the deformation of materials under load, with a focus on stiffer mixes that exhibit enhanced resistance to rutting. For instance, a study by Boriack et al. (2014) utilized up to 40% RAP, revealing a reduction in rut depth during wheel tracking tests when compared to 0% RAP mixes. This finding corroborates the enhanced rutting performance observed (Dughaishi et al., 2022). Conversely, the impact of this phenomenon on cracking is a subject of varied opinions in the extant literature. A recent study has indicated that the incorporation of moderate RAP (e.g., 20–30%) into mixes can yield a fatigue performance that is comparable to that of virgin mixes, particularly when the fresh binder exhibits a slight degree of softness or when a rejuvenator is utilized. However, other studies have reported that elevated RAP contents (>40%) without any binder grade adjustment or rejuvenation can result in diminished fracture energy and, consequently, augmented susceptibility to thermal and fatigue cracking (Dughaishi et al., 2022). Dughaishi et al. (2022) conducted a review of the extant literature on the effects of RAP on cracking. The authors noted contradictory findings on the subject. Some researchers found decreased thermal cracking resistance at high RAP, while others saw no dramatic loss in fatigue life up to a point (Dughaishi et al., 2022). This finding suggests that factors such as binder grade selection, the incorporation of rejuvenators (additives that restore aged binder ductility), and mix design specifics exert a substantial influence on outcomes.

To address these issues, specifications frequently impose limitations on the content of RAP, unless modifications are made to the binder. For instance, the U.S. asphalt pavement guidelines established by agencies such as the Department of Transportation (DOT) permit the incorporation of up to 15–20% RAP without altering the binder grade, 20–30% RAP with the utilization of a softer binder grade, and greater than 30% RAP exclusively through approved rejuvenation methods or for the application as base layers (Dughaishi et al., 2022). Rejuvenating agents encompass a variety of products, including waste engine oil residues, bio-oils derived from plants or cooking oil, and specialized softening agents. These agents are incorporated into the mixture with the objective of softening the RAP binder. These have demonstrated efficacy in enhancing the blend between RAP and virgin binder, thereby restoring a degree of flexibility (J. Wang et al., 2022). For instance, the combination of a small percentage of waste engine oil with RAP has been found to improve low-temperature performance and fatigue life of high-RAP mixtures (J. Wang et al., 2022). A number of studies have been conducted that explore the potential benefits of integrating RAP with WMA processes. Intriguingly, the findings suggest that WMA can serve as an enabler for enhanced RAP usage. The lower production temperature of WMA ensures that the RAP binder does not undergo excessive aging during the mixing process. Furthermore, the incorporation of WMA additives has been shown to enhance workability, thereby facilitating the compaction of mixes comprising stiff RAP material (Milad et al., 2022). A study cited in the Oman review found that approximately 85% RAP was successfully recycled in-plant using a warm-mix process, achieving comparable properties to a virgin HMA mix (Dughaishi et al., 2022). This high level of reuse, however, likely involved meticulously designed blending charts and rejuvenation processes.

Another potential application of RAP in sustainable pavements is its use in stabilized base or subbase layers. The utilization of RAP aggregates as unbound or cement-bound base material presents a viable alternative to the conventional application of RAP in surface asphalt. A multitude of studies have demonstrated that RAP aggregates, when utilized in isolation, exhibit diminished dry density and strength when compared to conventional base gravel. However, when these aggregates are integrated with a binding agent, such as cement or fly ash, or when they are blended with virgin aggregates, they demonstrate the capacity to perform satisfactorily. For instance, a laboratory study on RAP-aggregate blends for base found that adding 50% virgin aggregate and a small percentage of cement to RAP resulted in a base material with enhanced density and strength. Conversely, 100% RAP aggregate (unbound) exhibited certain limitations in terms of stability (Dughaishi et al., 2022). Many agencies permit the utilization of RAP in base layers, provided it is blended with a proportion of crushed stone to enhance angular interlock and strength.

Current Usage and Trends

RAP is the most recycled product per ton in the United States. According to the results of annual asphalt industry surveys, over 80 million tons of asphalt pavement are reclaimed each year, and a significant percentage is reused in new pavements, making it a notable recycling success story (Williams & Willis, 2020). Analogous trends have been observed in Europe and Asia, though usage rates exhibit variation by country. By 2020, some U.S. states, including Missouri and Texas, had adopted the practice of incorporating approximately 30% RAP (Reclaimed Aggregate Pavement) in surface mixes. Additionally, trial sections containing 50% RAP have demonstrated satisfactory performance when subjected to the application of rejuvenators. Recent advancements in the field have been witnessed in the Gulf region, as evidenced by the incorporation of RAP in highway projects by the United Arab Emirates (Dughaishi et al., 2022). For instance, approximately 15% of the layers in a newly constructed road have been found to contain RAP. Additionally, there has been a notable surge in regional interest in formalizing guidelines for RAP usage, a practice that has historically been limited.

Implementation Challenges

While RAP offers clear benefits, challenges include ensuring uniform quality of RAP (given its potential to originate from disparate sources with varying gradations and binder properties), stockpile management (to prevent contamination or excessive aging in stockpiles), and mix design complexity (blending charts for binder, etc.). Another salient issue pertains to the feasibility of recycling asphalt on multiple occasions. Research on multi-recycled RAP indicates that asphalt can be recycled multiple times; however, the binder becomes progressively stiffer with each cycle. Each cycle likely requires additional rejuvenation to maintain the material's viability (Dughaishi et al., 2022). Another challenge that must be addressed is the convincing of stakeholders regarding the performance of RAP mixes. Some road owners fear that high RAP mixes may be less durable. Nevertheless, the gradual emergence of successful pilot projects and a substantial corpus of supportive research have begun to modify this perception. In summary, RAP is a cornerstone of sustainable pavement engineering. When used with proper engineering controls, it yields pavements that are cost-effective and environmentally friendly without sacrificing performance.

Warm-Mix Asphalt (WMA)

Warm-Mix Asphalt (WMA) is a term used to describe a range of technologies and additives that facilitate the production and placement of asphalt mixtures at temperatures that are substantially lower than those required for traditional hot-mix asphalt. Conventional HMA is typically produced at temperatures ranging from 150 to 180°C to ensure the asphalt binder maintains sufficient fluidity for coating aggregates and the mixture remains workable for compaction purposes (Thives & Ghisi, 2017). WMA technologies have been shown to reduce production temperatures by approximately 10–40°C (with typical WMA production temperatures ranging from 110–140°C) while maintaining comparable coating and workability (Milad et al., 2022). The introduction of WMA was largely driven by the desire to reduce energy consumption and emissions in asphalt paving, which aligns perfectly with sustainability goals (Milad et al., 2022).

Types of WMA Technologies

The methods employed by WMA can be categorized into three distinct classifications. The following three categories of additives are employed: (1) Foaming processes, in which small amounts of water are introduced (either directly or via hydrophilic additives like zeolites) to create foam in the hot binder, thereby temporarily expanding its volume and reducing viscosity at lower temperatures; (2) Organic additives (waxes or fatty acid amides), which melt at around 90–120°C and act as viscosity reducers at that range; and (3) Chemical additives (surfactants, emulsifiers), which improve coating and workability through chemical modification of binder properties (Milad et al., 2022). The efficacy of these technologies has been demonstrated through various means. For instance, Sasobit (a synthetic wax) and Aspha-Min (a zeolite) were among the early WMA additives, and each can enable mix production about 20–30°C lower than HMA (Milad et al., 2022). Modern proprietary chemical additives (e.g., Evotherm™ and Rediset™) have also gained widespread adoption due to their ease of use and additional benefits, such as moisture resistance.

Environmental Benefits

The most immediate benefit of WMA is the reduction in fuel/energy consumption at the asphalt plant, since the mixing temperature is lower. This phenomenon directly correlates with a reduction in greenhouse gas emissions and air pollution. Research has documented energy savings ranging from 20 to 35% when comparing WMA to HMA production. Milad et al. (2022) summarized that WMA can reduce energy use by anywhere from 20% up to 75%, depending on factors like the specific technology and the extent to which the temperature is lowered. As less fuel is burned, CO_2 emissions are correspondingly reduced. Additionally, emissions of asphalt fumes, volatile organic compounds (VOCs), and other hazardous pollutants are significantly curtailed at the plant and paving site (Milad et al., 2022). For instance, a field trial conducted in the United States revealed that the adoption of WMA led to a substantial reduction in visible smoke, with measured decreases in CO_2 and carbon monoxide reaching approximately 30%. A reduction in mixing temperature corresponds to a decrease in paving temperature, thereby offering workers a reduction in exposure to heat and fumes. This, in turn, results in an enhancement of health and safety conditions on site (Milad et al., 2022). The aforementioned factors contribute to the classification of WMA as a more sustainable, "green" asphalt technology.

Of particular significance is the fact that WMA's environmental advantages extend to facilitating other sustainable practices: As previously mentioned, WMA has been demonstrated to effectively accommodate higher RAP contents (Milad et al., 2022) and can enhance the compatibility of other additives, such as crumb rubber or plastics, by reducing the thermal degradation they might experience at HMA temperatures (some polymers or bio-additives may volatize or break down at very high heat). By increasing the use of RAP or other recycled materials, WMA indirectly enhances sustainability benefits through a synergistic effect.

Mechanical Performance and Durability

It is reasonable to hypothesize that decreasing the production temperature could pose a risk of inadequate drying of aggregates or incomplete binder coating. Historically, these factors have given rise to concerns regarding moisture damage (stripping) and reduced strength. However, extensive research and field performance data have demonstrated that when designed appropriately, WMA can equal HMA performance in most aspects (Milad et al., 2022). A substantial body of research has been dedicated to the comparison of WMA and HMA mixes in terms of rutting, fatigue, and low-temperature cracking. The results of these studies have generally shown comparable outcomes (Fakhri & Ahmadi, 2017; Fakhri & Hosseini, 2017; Padula et al., 2019; Saberi.K et al., 2017; Vargas-Nordcbeck & Timm, 2012). In certain instances, WMA mixes exhibit marginally diminished stiffness at the onset (a consequence of diminished binder aging during manufacturing and augmented retained volatiles in the binder). Nevertheless, this can result in enhanced cracking resistance without substantial repercussions on rutting performance in temperate climates.

It is imperative to note that moisture susceptibility is a pivotal parameter that must be closely monitored. Due to the reduced heating of WMA aggregates, there is a possibility of enhanced moisture retention. Concurrently, the viscosity of the binder exhibits an increase at lower temperatures, which may result in a diminished degree of initial bonding. Preliminary research has indicated that certain WMA blends exhibit a reduced Tensile Strength Ratio (TSR), a metric used to assess moisture damage resistance, in comparison to HMA. Fortunately, there are extant solutions to this problem. Numerous WMA additives include anti-strip components, and the mixture can incorporate traditional anti-stripping agents (e.g., liquid amines or hydrated lime) to counteract this phenomenon (Cheng et al., 2011; Mohd Hasan et al., 2015). Modern WMA products frequently promote enhanced adhesion properties. Evotherm, a chemical WMA additive, contains adhesion promoters that, in many cases, improve moisture resistance compared to HMA with no anti-strip. In a particular study, WMA treated with a specific surfactant exhibited higher TSR in comparison to the control HMA (Milad et al., 2022). Furthermore, minor adjustments to the mixture, such as ensuring aggregates are adequately dry and employing gradations that are less susceptible to moisture retention, can alleviate these issues. It has become increasingly prevalent for WMA mixes to align with the moisture damage criteria established for HMA in specifications, often necessitating the incorporation of a modest amount of anti-strip if required (Milad et al., 2022).

Another salient issue is compaction: The use of WMA has been demonstrated to enhance the process of field compaction. This is primarily due to the fact that the mixture remains workable for a longer duration as it undergoes a more gradual cooling process from a lower initial temperature. Additionally, the incorporation of additives into the mixture serves to reduce the viscosity of the binder, thereby enhancing its overall effectiveness. Contractors have frequently reported that they achieve target densities more easily with WMA than HMA (Goh et al., 2007). Proper compaction is imperative for the longevity of pavements. The correlation between density and parameters such as low permeability and high fatigue life underscores the significance of adequate compaction. In conditions of extreme cold or when dealing with thin lifts, there have been instances where WMA cools down too rapidly. However, the prevailing opinion suggests that WMA prolongs the paving season and facilitates extended hauls or thicker lifts due to its enhanced workability (Milad et al., 2022).

Global Adoption and Experience

Since its introduction in the early 2000s, WMA has seen widespread acceptance. Europe was an early adopter of this technology, with several technologies having been developed there. In contrast, the U.S. conducted a large-scale implementation effort in the late 2000s. By 2013, approximately 30% of asphalt production in the U.S. was WMA, and this figure has increased since then, as evidenced by data from the NAPA survey. In a similar vein, countries such as China and India have initiated the incorporation of WMA in highway development projects with the objective of reducing air pollution and fuel consumption. Numerous highway agencies have modified their specifications to permit the utilization of WMA as a substitute for HMA, with minimal alterations to existing procedures. The performance track record is positive. Numerous field trials demonstrate that WMA pavements exhibit comparable distress development (e.g., rutting, cracking) over time to HMA.

It is also noteworthy that there exist technologies for producing half-warm and cold mix asphalt, which utilize emulsions or foamed bitumen at ambient temperatures, yet these are typically employed for base layers or roads with low traffic volume. WMA, which exhibits comparable performance to HMA, has emerged as the predominant solution for mainstream surface asphalt layers on heavily trafficked roads (Environmental Protection Agency, 2022).

Challenges

The challenges posed by WMA are relatively minor and have largely been surmounted. These challenges primarily entail ensuring that contractors receive adequate training in the proper use of WMA, which is often a straightforward process involving the addition of an additive or water. Another key challenge is ensuring that plant equipment can effectively handle the introduction of additives or foaming apparatus. Finally, verifying that mixes meet all criteria at lower temperatures is essential, and this is typically the case for the majority of mixes. Economic considerations encompass the cost of additives or equipment in relation to the savings in fuel. In many cases, these economic factors offset each other, leading to financial savings, particularly during periods of elevated fuel prices (Milad et al., 2022). Furthermore, the augmented production of coolers enables paving in cooler weather without compromising density, thereby extending the construction season. This phenomenon offers an indirect economic benefit by allowing for greater flexibility in scheduling.

In summary, WMA has been demonstrated to be a mature, widely validated green technology in pavement engineering. By reducing the necessary heat, there is a considerable decrease in emissions and energy consumption, thereby contributing to sustainability objectives, such as a diminished carbon footprint in road construction (Milad et al., 2022). Furthermore, it functions as an enabler for other sustainable practices, including higher RAP and improved worker health. The future of WMA research entails the exploration of increasingly environmentally friendly additives, such as bio-based WMA additives, to substitute for the prevailing chemical agents. The review by Milad et al. (2022) recommends exploring "renewable, environmentally friendly, and cost-effective materials such as biomaterials as alternatives to conventional WMA additives." This suggests that the next generation of WMA could integrate with bio-binders or other green modifiers, merging two sustainability approaches for compounded benefits.

Bio-Binders and Bio-Asphalt

The substantial reliance on petroleum asphalt binder in pavements (which constitutes approximately 4–6% of hot mix asphalt by weight; Alsolieman et al., 2021) has prompted exploration into bio-binders or bio-asphalt as sustainable alternatives. Bio-binders are materials derived from renewable biological sources (e.g., plants, algae, animal waste) that have the capacity to either supplant a portion of petroleum bitumen or function as a modifier to enhance or soften asphalt binder. The objective is twofold: first, to curtail the consumption of non-renewable bitumen (thereby reducing the carbon footprint and reliance on crude oil); and second, to identify binders that boast a superior environmental profile during production and subsequent paving (e.g., reduced emissions, potentially more biodegradable components).

Sources and Types of Bio-Binders

A plethora of bio-resources have been thoroughly investigated for their potential application as binders. Among the most salient of these are:

- Vegetable oils and their derivatives are a subject of interest in this study. Used cooking oil (WCO), soybean oil, corn oil, palm oil, and the like are often chemically modified (e.g., transesterification) to yield a bio-oil that can blend with asphalt (Ramadhansyah et al., 2020). These oils exhibit insufficient viscosity in their native state; however, through the processes of air-blowing or polymerization, they can acquire a more bitumen-like consistency.

- Tall oil and resinous byproducts resulting from the wood pulping process (from the paper industry) have been utilized in commercial rejuvenators and, on occasion, as partial binders.

- Lignin is a solid powder that is derived from woody biomass. This biomass is a byproduct of biofuel or paper production. Lignin has been demonstrated to function as a partial binder modifier, exhibiting a complex aromatic polymeric structure that can enhance stiffness and act as an antioxidant, thereby retarding the aging process of asphalt (Xue et al., 2021).

- The process of bio-asphalt production entails the pyrolysis of biomass, yielding bio-fluxes. Illustrative examples of biomass sources include pyrolyzed swine manure, waste wood, and agricultural waste. The resultant product is a black, tar-like bio-oil. Subsequent refinement of this oil can occur to remove excess water and adjust viscosity, thereby producing a "bio-binder" that has the potential to replace a portion of asphalt cement (Zhang et al., 2022).

- A discussion of natural asphalt substitutes is warranted. Natural asphalts, exemplified by Trinidad Lake asphalt and Gilsonite, are not bio-based due to their natural occurrence as fossil bitumen. However, it is noteworthy that certain formulations employ a combination of natural bitumen and bio-oils to yield hybrid binders.

Zhang et al. (2022) provide a comprehensive review of bio-binders, noting that bio-oils can be obtained via processes like pyrolysis, and the source materials range widely—wood biomass, waste cooking oil, and even animal manure have all been converted to bio-binders. The following definitions are provided for the aforementioned terms: bio-oil, defined as the raw product from biomass liquefaction; bio-binder, defined as the processed bio-oil that is ready to be used in asphalt, often after undergoing treatment such as oxidation or polymer modification; and bio-asphalt, defined as the final binder that results from blending bio-binder with petroleum asphalt, or sometimes fully replacing it (Zhang et al., 2022).

Environmental Perspective

The appeal of bio-binders is rooted in their capacity for renewable production. It is evident that plants absorb CO_2 during their growth cycle. Consequently, the utilization of a binder derived from plants can contribute to a carbon-neutral cycle, with the exception of the energy required for processing. Furthermore, a significant proportion of bio-binders employ waste products (e.g., WCO or animal manure) in their manufacturing processes, a practice that confers a distinct advantage in terms of sustainability by circumventing the potential environmental consequences associated with improper waste disposal (Zhang et al., 2022). The production of certain bio-binders can be conducted at temperatures lower than those employed in the refining of bitumen, a process that has the potential to result in significant energy savings. The substitution of bio-binders for a proportion of petroleum asphalt results in an immediate decrease in the demand for bitumen, a product of crude refining that is characterized by its substantial energy consumption and emission intensity. Life-cycle studies have indicated that partial substitution of asphalt with a bio-binder (e.g., 20% from vegetable oil) can reduce the carbon footprint of the binder component by a similar proportion, though the overall percentage reduction is smaller (since binder is a minor component of the total mix mass). Nevertheless, even the most modest contributions can contribute to the paving of millions of tons of asphalt.

Mechanical Performance

The pivotal inquiry concerns the capacity of bio-binders to perform at a level comparable to that of asphalt. A predominant finding is that bio-asphalt binders exhibit a tendency to be more malleable at elevated service temperatures and demonstrate reduced temperature sensitivity. Zhang et al. (2022) provided a summary of the findings, concluding that, in comparison to conventional asphalt, bio-modified binders generally exhibit "lower high-temperature performance, as well as higher low-temperature performance and aging resistance." In summary, the incorporation of bio-oil has been demonstrated to exert a dual effect on the physical properties of binder. Specifically, it has been observed to curtail the rigidity of the binder at elevated temperatures, a phenomenon that can potentially exacerbate rutting. Concurrently, bio-oil has been shown to enhance the flexibility of the binder at low temperatures, thereby mitigating the risk of thermal cracking. Moreover, the addition of bio-oil has been shown to diminish the propensity of the binder to undergo oxidative aging. This protective effect can be attributed, in part, to the antioxidant properties of certain bio-oils or to their ability to merely dilute asphaltenes. (Zhang et al., 2022). For instance, a bio-asphalt composed of swine manure oil was observed to decrease the dynamic shear modulus at elevated temperatures, resulting in a softer and less resistant material to rutting. However, the fracture temperature was notably enhanced in bending beam rheometer tests, indicating enhanced performance in cold weather conditions. In a similar manner, the utilization of waste cooking oil as a rejuvenator has been demonstrated to restore ductility to aged binders. However, it should be noted that excessive amounts of this rejuvenator can result in undesirable outcomes, such as bleeding or the formation of soft mixes (Ramadhansyah et al., 2020). Consequently, numerous bio-binders are being regarded as partial replacements or modifiers rather than complete substitutes, with the objective of achieving a balanced equilibrium in properties.

However, exceptions to this general rule have been observed. Specifically, the addition of certain bio-based additives, such as chemically processed vegetable oils, has been shown to enhance the stiffness and viscosity of the binder (e.g., lignin has been observed to increase stiffness and viscosity) (Xue et al., 2021). It has been demonstrated that these substances can enhance the performance of high-temperature applications; however, their utilization in isolation has been observed to potentially compromise the integrity of low-temperature cracking mechanisms. A creative approach by Xue et al. (2021) combined a stiff bio-additive (lignin) with a soft bio-additive (waste engine oil, which is petrogenic but considered a "waste-derived" modifier) to balance out effects. The findings revealed that lignin led to an augmentation in viscosity and an enhancement in elasticity, while waste oil exhibited a reduction in viscosity and an improvement in performance at low temperatures. The amalgamation of these two substances resulted in a modified binder that exhibited commendable overall properties (Xue et al., 2021).

Mixture Performance

Preliminary investigations have indicated encouraging outcomes for asphalt mixtures incorporating bio-binders in short-term assessments. Rutting: It has been observed that certain combinations of bio-binders result in slightly elevated rut depths in wheel tracking when compared to conventional mixtures. This phenomenon is particularly evident when the bio-binder is rendered excessively soft. However, when only a portion of the mixture is bio (for example, 5–20% replacement of bitumen), rutting performance frequently remains within the acceptable range (Zhang et al., 2022). Cracking: The utilization of bio-modified mixes frequently results in enhanced fatigue life, attributable to the augmented ductility of the binder phase. Additionally, the phenomenon of aging resistance implies that, over the course of years, the binder may not harden as rapidly, which could result in a protracted lifespan for the pavement. Indeed, a number of studies have noted that bio-binders have the capacity to act as rejuvenators for RAP, thereby combining two sustainable practices: the use of bio-oil to refresh aged RAP binder. For instance, a critical review of waste cooking oil as a modifier to enhance binder properties revealed its effectiveness in restoring low-temperature performance for high-RAP content mixes (Ramadhansyah et al., 2020).

Notwithstanding the encouraging laboratory findings, as of 2022, there remains a paucity of long-term field data concerning bio-binders. The majority of these implementations have been in the form of trial sections. Questions persist regarding the long-term behavior of bio-binders, including their potential for biodegradation, moisture susceptibility, and compatibility with existing paving practices and recycling streams. It is noteworthy that certain bio-binders may exhibit heightened sensitivity to water, as evidenced by the observation that a bio-oil may not adhere to aggregates with the same efficacy as bitumen. In such instances, the incorporation of anti-stripping agents may be a requisite measure.

Challenges and Considerations

The variability of biomass sources poses a significant challenge. Petroleum asphalt is a relatively consistent material, with specifications that define certain ranges for parameters such as penetration and softening point. In contrast, bio materials may exhibit variability from batch to batch. The chemical composition of bio-oil from wood, algae, and waste cooking oil differs significantly (a mixture of fatty acids, esters, aldehydes, etc. in varying proportions) (Zhang et al., 2022). This indicates that bio-binders may exhibit variable behavior, complicating their standardization. Concurrent efforts are being made to establish grading systems for bio-binders or bio-modified binders that align with Superpave PG grading. Some have proposed the inclusion of extended parameters to account for the distinct behavior exhibited by bio-binders.

Another salient issue pertains to the blending and compatibility of these bio-oils with asphalt. It has been observed that certain bio-oils exhibit a propensity to blend readily with asphalt, while others demonstrate a lack of such compatibility, which can result in phase separation during the blending process. For instance, the addition of unmodified vegetable oil to asphalt can result in separation, as its polarity is lower than that of the asphalt. This separation can be prevented by ensuring proper reaction or emulsification of the vegetable oil. Techniques such as partial oxidative blending or the addition of compatibilizer polymers have been demonstrated to be effective in this regard (Zhang et al., 2022).

From an economic perspective, the cost-effectiveness of bio-binders is notable, particularly those derived from waste materials such as used cooking oil. The utilization of waste cooking oil in paving not only addresses the issue of waste disposal but also provides a cost-effective rejuvenator (Ramadhansyah et al., 2020). The market dynamics of other bio-based products, such as specialized crop oils and lignin, are subject to fluctuations. Lignin, for instance, is produced in significant quantities by the pulp industry and is relatively inexpensive. However, its processing into a form suitable for use as an asphalt additive (i.e., a fine powder or liquid derivative) incurs additional costs.

Notable Successes

The Netherlands recently conducted a trial involving the implementation of a fully bio-based asphalt in a bicycle road. This trial utilized lignin to substitute for a substantial proportion of bitumen, reaching up to 50% binder replacement. According to the reports, the performance of this asphalt proved to be satisfactory for its application, which exhibited low stress. In France, the Eco² asphalt initiative employed a blend of RAP and a bio-based rejuvenator to formulate asphalt with a substantially diminished carbon footprint. This blend exhibited comparable performance to conventional mixes over the course of several years of monitoring. These examples suggest that, with meticulous engineering, bio-binders can be practically implemented.

According to Zhang et al. (2022), future research endeavors should prioritize the maximization of bio-binder content in asphalt while maintaining performance standards, thereby extending the boundaries of current capabilities. Additionally, there is a call for further exploration into the chemical interplay between bio-binder and petroleum asphalt at the molecular level, with the objective of ensuring optimal compatibility. This research is accompanied by the proposal of establishing unified standards for bio-asphalt technology (Zhang et al., 2022). The identification of bio-binders with the potential to substitute for asphalt in the future is a subject of interest for research (Zhang et al., 2022). While the aspiration of a fully bio-derived asphalt binder that meets all performance requirements remains somewhat idealistic, incremental progress (e.g., 20% replacement, then 30%, etc.) is being made in a steady and consistent manner.

In summary, bio-binders offer a promising route to make pavements more sustainable by tapping renewable resources and recycling waste into binder material. These additives have been shown to enhance low-temperature performance and mitigate aging, though they frequently result in a compromise in high-temperature stiffness. To address this challenge, current methodologies involve the incorporation of these additives in conjunction with conventional asphalt (or with modifiers) to achieve a balanced property profile (Zhang et al., 2022). Continued research and development is necessary to refine bio-binder formulations, ensure consistency, and validate long-term field performance. However, the concept aligns well with global sustainability goals, such as reducing fossil fuel use and emissions. As these technologies continue to develop, the implementation of partial bio-asphalt pavements may become prevalent, particularly in regions with a plentiful supply of bio-feedstocks.

Industrial Byproducts (Fly Ash, Slag, and Others)

The utilization of industrial byproducts in construction materials has been a persistent practice, with pavement engineering being a notable example. The utilization of byproducts such as fly ash (from coal combustion), slag (from iron and steel production), and silica fume, red mud, phosphogypsum, and others has the potential to generate sustainability benefits. These benefits include the diversion of waste from landfills and the reduction in the necessity for energy-intensive virgin materials. In this study, the primary focus is on the most prevalent byproducts in pavements, namely fly ash and slag. Additionally, the utilization of steel slag aggregates and foundry sand is examined.

Fly Ash in Cementitious Stabilization and Concrete

Fly ash, a pozzolanic powder, is collected from the flue gases of coal-fired power plants. In pavement construction, its primary application is as a supplementary cementitious material (SCM) in concrete or cement-stabilized layers. Class F fly ash, characterized by its low calcium content derived from the combustion of bituminous coal, and Class C fly ash, distinguished by its high calcium content originating from sub-bituminous coal or lignite, have demonstrated the capacity to substitute for Portland cement in concrete mixtures to a certain extent. This practice has been thoroughly researched and is well-established; typically, 15–30% of cement by mass can be replaced by fly ash in pavement-quality concrete without compromising strength (Taylor, 2019). Indeed, fly ash has been shown to enhance workability and the later-age strength and durability of concrete, while concomitantly reducing heat of hydration (a beneficial effect in mass pours). For rigid pavements, the utilization of Class F fly ash is frequently employed to mitigate alkali-silica reaction and enhance long-term strength gain. In certain instances, Class C, which possesses inherent cementitious properties, can even permit higher replacement levels.

The sustainability impact of replacing cement with fly ash is significant. According to M.G. et al. (2022), replacing every ton of cement with fly ash avoids approximately one ton of CO_2 emissions. This is due to the fact that cement production is carbon-intensive. Consequently, high-volume fly ash concrete (HVFAC) is regarded as a sustainable material. For instance, a high-volume fly ash concrete (with 50% cement replacement) was utilized in a demonstration pavement in Minneapolis. This material exhibited adequate strength development and reduced permeability; however, it demonstrated slower early strength gain. This can be managed by mix design or curing practices. Life-cycle assessments have been utilized to corroborate the findings, demonstrating that such combinations exhibit a significantly reduced embodied energy and emissions.

Additionally, fly ash has found application in the stabilization of soil or bases. The integration of fly ash with soft soils has been demonstrated to enhance their bearing capacity. Specifically, Class C fly ash has been observed to undergo hydration and cementation processes, resulting in the consolidation of soils. In certain countries, fly ash is dispersed and amalgamated into clay subgrades with the objective of fortifying subgrade support for highway infrastructure. Furthermore, the utilization of fly ash as a filler in asphalt has been a subject of investigation, including the incorporation of Municipal Solid Waste Incineration (MSWI) fly ash. Zhao, Ge, et al. (2022) conducted a study in which they examined MSWI fly ash as a potential mineral filler in asphalt mixtures. The investigation revealed that the substitution of conventional filler with fly ash exhibited minimal impact on low-temperature properties. However, it was observed that fly ash significantly enhanced high-temperature performance, a phenomenon that can be attributed to the increased stiffness provided by fly ash as a filler. Specifically, as fly ash content increased, the asphalt mixture exhibited enhanced stiffness and rut resistance, though its low-temperature fracture tolerance exhibited a slight decrease, indicative of a typical trade-off. Additionally, it was noted that the use of excessive fly ash without implementing anti-stripping measures may result in a deterioration of moisture stability (Zhao, Ge, et al., 2022). However, the incorporation of fly ash in asphalt or concrete has been demonstrated to effectively mitigate the necessity for extracting additional mineral filler or cement. This approach is regarded as an eco-efficient utilization of a byproduct that would otherwise be considered waste.

Blast Furnace Slag and Steel Slag

Slag is another significant byproduct of this process. Ground-granulated blast furnace slag (GGBFS), a byproduct of iron production, has been utilized in a manner analogous to fly ash as a cement replacement. It possesses latent hydraulic properties and, upon activation (typically by the alkalinity of cement or other activators), can undergo hydration and enhance its strength. Slag cement (GGBFS) has been demonstrated to substitute for 30–50% of Portland cement or more in concrete applications. Slag has long been utilized in Europe for the construction of durable pavements, where its use is well-documented. The primary benefits of slag include enhanced long-term strength and reduced permeability. However, it should be noted that the early strength gain of slag is often slower in comparison to other materials, such as fly ash. Additionally, under certain conditions, there is a possibility of increased risk of scaling, unless proper curing procedures are followed. The substitution of cement with slag has been demonstrated to significantly reduce the carbon footprint of concrete pavements. This is due to the fact that slag is a repurposed industrial waste that only requires grinding, not calcination. GGBFS has been shown to impart a lighter color to concrete, a property that can prove beneficial for high-albedo "cool pavements."

Steel slag, a byproduct of steelmaking processes, characteristically manifests in a crystalline structure. This material can be processed to yield aggregate of varying sizes. The material under consideration is characterized by its high density and hardness, which renders it particularly well-suited for use as an aggregate, especially in applications where polish resistance and high stability are paramount, such as in the production of heavy-duty asphalt or skid-resistant stone mastic asphalt. However, unprocessed steel slag contains free lime and periclase (MgO), which have the potential to hydrate and expand over time. The utilization of steel slag without undergoing aging or treatment can result in a series of undesirable consequences, including expansion and disintegration of pavements. This phenomenon has been documented in previous studies (Huang et al., 2022). To ensure the safe utilization of steel slag, methodologies such as weathering (subjecting slag to the elements for an extended period to facilitate the hydration of the lime/MgO prior to its application) or chemical treatment have been employed. Huang et al. (2022) conducted a study to examine the efficacy of treating steel slag with oxalic acid. The primary objective of this study was to neutralize the free lime present in the steel slag and thereby enhance its stability in asphalt. The application of acid treatment led to a substantial reduction in the propensity of the slag to undergo swelling. Additionally, it enhanced the water resistance of the slag aggregate within the asphalt mixture. Consequently, the performance of the slag-asphalt mixture was rendered comparable to that of a conventional aggregate mix (Huang et al., 2022). The treated slag asphalt demonstrated commendable stiffness and fatigue performance, and notably, exhibited no substantial expansion.

From a sustainability perspective, the utilization of steel slag aggregate represents a strategy for conserving natural aggregate and repurposing a byproduct that would otherwise be discarded. Indeed, Japan and several European nations employ steel slag in asphalt after subjecting it to proper aging (as reported by the Nippon Slag Association, which notes a high rate of slag utilization in roadways). The high density of steel slag, which results in higher transport costs per volume, is a minor drawback. However, its strength has the potential to allow for thinner layers.

Foundry Sand

Waste Foundry Sand (WFS) is derived from metal casting industries and is a high-quality silica sand that has been utilized with binders for molds. Following a series of uses, the device is disposed of. The WFS technique has been applied in both asphalt and concrete contexts. In essence, it functions as a fine aggregate substitute. According to the extant research, it appears that a maximum of 20% of the fine aggregate in concrete may be substituted with foundry sand without compromising its strength. A study revealed that up to 20% WFS had no substantial impact on the compressive or flexural strength of concrete, though it did result in a slight increase in water demand (Dash et al., 2016). The gradual replacement of 30% of the original material with a fine replacement gradually reduces strength and necessitates the addition of water or admixtures. This is due to the potential for WFS to contain residual binder, such as bentonite or chemicals. However, positive effects such as increased abrasion resistance have been observed in WFS concrete, potentially attributable to the presence of hard fine particles (Dash et al., 2016). In the context of asphalt, WFS has the capacity to function as a mineral filler. Its efficacy has been demonstrated in the context of hot mix asphalt (HMA) applications, with certain highway departments specifying its incorporation into the binder-stabilized aggregate (B-SA) or mineral filler (MF) categories. The advantages of this approach are manifold, including the reduction of virgin sand required, the mitigation of landfill waste from WFS, and the potential for cost savings.

Red Mud, Phosphogypsum, etc.

The utilization of alternative byproducts, which are less prevalent, is confined to specific applications. Red mud, a byproduct of alumina production, is highly caustic and has limited application. However, experimental studies have demonstrated the potential for stabilization with activators for use as a road base material. Phosphogypsum, a byproduct of the fertilizer industry, has found application in road base construction in areas where natural gypsum or calcium sources are beneficial, particularly in rural road construction where cost-effectiveness is a priority. These materials are not commonly used due to challenges in their handling, such as concerns regarding radioactivity in phosphogypsum.

Geopolymer and Full Replacement of Cement

An innovative application of fly ash and slag involves the use of geopolymer concrete, which entirely replaces Portland cement with an alkaline-activated binder derived from fly ash and slag. Research has demonstrated that geopolymer concrete exhibits a strength comparable to that of conventional concrete (Tayeh et al., 2022). In the context of pavement construction, the utilization of geopolymer concretes has emerged as a promising avenue for mitigating cement-related CO_2 emissions. Recent studies have indicated that the performance of fly ash/slag geopolymer concrete can be comparable to that of traditional concrete in structural applications (Almutairi et al., 2021). However, further field validation is necessary to ascertain its behavior under various exposure conditions, such as freeze-thaw cycles or sustained high temperatures, and to determine its long-term properties. Nonetheless, geopolymer technology offers a promising avenue for the utilization of industrial byproducts in the creation of a novel binder, exhibiting a substantially diminished carbon footprint—reportedly achieving up to 80% CO_2 reduction relative to OPC concrete, contingent upon the incorporation of ambient cured geopolymer in the fabrication of pavement.

Summary of Benefits

The incorporation of industrial byproducts in pavement construction offers a multifaceted approach to sustainability. The primary benefit of resource efficiency is the conservation of natural materials, such as cement and aggregate, for every ton of byproduct utilized. The secondary benefit is the reduction of waste, which prevents the accumulation of large volumes of industrial waste and enables its productive use. The tertiary benefit is often performance gains, as many byproducts offer durability benefits, such as fly ash reducing permeability and slag improving later strength. The utilization of fly ash and slag as construction materials can result in economic advantages due to their cost-effectiveness in comparison to cement, particularly when sourced from local materials. In certain instances, contractors may receive financial incentives for the disposal of specific waste materials.

Challenges

It is important to note that variability can be observed in each byproduct. For instance, the quality of fly ash is known to vary according to the coal source, and the properties of slag are contingent on the specific conditions of the furnace. Quality control and, on occasion, preliminary processing (i.e., grinding, slag aging, and the filtration of fly ash impurities) are requisite procedures. The availability of certain byproducts is constrained to specific regions. For instance, areas lacking coal power may experience a lack of fly ash, though the global transition away from coal is progressing. Consequently, the future supply of fly ash may decrease, thereby posing a sustainability challenge for fly ash concrete. The process may encounter regulatory impediments, such as the classification of materials as hazardous. For instance, some MSWI ashes contain heavy metals that necessitate encapsulation within the pavement to prevent leaching.

In practice, the utilization of fly ash and slag in concrete has been a well-established standard in many regions, with these materials being a component of durable concrete specifications. The utilization of steel slag and foundry sand in asphalt is not as prevalent as other methods, but it is increasing as advancements in processing techniques are made. In the future, as the pavement industry endeavors to achieve carbon neutrality, it will be imperative to maximize the incorporation of such byproducts. One could envision a future in which pavement structures are constructed with all layers containing recycled or industrial byproduct content. For example, a base could be stabilized with fly ash, a concrete pavement could contain 50% slag cement, or an asphalt surface could utilize WMA, RAP, and steel slag aggregate. These materials would combine to significantly reduce the embodied energy of the road.

Other Green Technologies and Innovations

Beyond the major categories previously mentioned, there are several other innovative materials and technologies that contribute to sustainability in pavements. These include the use of recycled rubber, recycled plastics, waste glass, and even more novel ideas like photocatalytic additives or carbon-sequestering concrete.

Crumb Rubber Modified Asphalt (CRMA)

The utilization of ground tire rubber from waste tires in asphalt has been a subject of interest since the 1960s. This approach effectively addresses the disposal issue of millions of scrap tires. The incorporation of crumb rubber can be achieved through two distinct methodologies: the "wet process," which involves the dissolution of rubber particles into a molten asphalt binder, thereby yielding a rubberized binder, and the "dry process," which entails the incorporation of rubber as an aggregate substitute in the mixture. Rubberized asphalt has been shown to offer several advantages in performance, including enhanced resistance to rutting and reduced reflective cracking due to the elastic nature of the rubber. A recent review by Bilema et al. (2023) concluded that "CR-modified asphalts had superior performance and longer service life" compared to traditional mixes. Specifically, crumb rubber has been shown to increase the viscosity and stiffness of binder at high temperatures, thereby reducing the incidence of rutting. Additionally, it has been demonstrated to enhance the elasticity of the material, which can lead to an improvement in fatigue life. However, the presence of rubber can also complicate binder management due to its high viscosity. If the rubber particles are not adequately digested, they have the potential to induce workability concerns. A further consideration pertains to the environment. The mixing of rubber generally necessitates elevated temperatures (particularly in the wet process, which reaches approximately 190°C). This can result in an increase in emissions at the manufacturing facility unless measures are implemented to mitigate the issue. However, certain waste management strategies have been employed to address this concern in the context of rubber mixes. However, a comprehensive life-cycle assessment indicates that rubber asphalt generally offers a more favorable environmental profile, primarily due to its ability to extend the service life of pavements, thereby reducing the frequency of rehabilitation. Additionally, the utilization of rubberized asphalt has been shown to address critical tire waste issues, with each lane-kilometer of such asphalt capable of replacing thousands of tires. Numerous US states (e.g., Arizona, California) and countries (e.g., China, Italy) have utilized rubber-modified asphalt extensively. From a sustainability perspective, rubber asphalt has been shown to reduce road noise significantly, thereby contributing to a more favorable environmental outcome in urban settings, as it reduces the necessity for noise barriers.

Recycled Plastic in Asphalt

Recently, there has been a surge of interest in incorporating waste plastics (e.g., packaging, bottles, bags) into asphalt mixtures as a modifier or partial aggregate replacement. A number of companies have developed plastic additive pellets made from mixed recycled plastics that can be added to asphalt mix. The concept is appealing in light of the global plastic waste issue. Research has demonstrated that specific plastics, particularly those of a harder consistency, such as HDPE, or those that mimic the behavior of fibers, can enhance asphalt's resistance to rutting and augment its stiffness (J. Wang et al., 2022). For instance, shredded waste plastic (e.g., polyethylene) can act as a polymer modifier, thereby increasing the mix's stability (Xu et al., 2021). A study referenced by J. Wang et al. (2022) observed that plastic-modified asphalt exhibited effective high-temperature performance; however, low-temperature performance could be compromised if the plastic renders the binder excessively rigid. Ensuring adequate plastic dispersal is paramount to avert potential complications, such as particle clustering or melting issues. Additionally, concerns have been raised regarding microplastics. In the event that plastic does not fully bind into the asphalt matrix, it is possible that it could fragment and release contaminants. Current evidence suggests that when properly mixed, the plastic is well encapsulated by bitumen; however, long-term environmental studies are required to ascertain the full extent of its environmental impact. It has been reported that certain municipalities (e.g., in India, the UK, and the Netherlands) have initiated a pilot program involving roads that utilize waste plastic-modified asphalt. These municipalities have documented positive outcomes, indicating that this innovative approach may offer a viable solution for addressing the challenges associated with waste management and infrastructure development. In a notable development, India has mandated the incorporation of plastic waste in road construction for specific projects, signifying a strategic approach to sustainable development.

Waste Glass

Crushed waste glass (cullet) has been demonstrated to function as a substitute for aggregate in asphalt and as a partial fine aggregate in concrete. Glass is a 100% recyclable material; however, not all glass is recycled due to contamination or economic factors. Consequently, its use in road construction is a viable option. Glass in asphalt, also referred to as "glasphalt," has been employed in certain instances as a substitute for a portion of the aggregate, typically amounting to 10–15% of the fine aggregate. This incorporation of glass introduces angularity and, notably, has been observed to enhance skid resistance due to its high hardness. However, excessive use of glass can result in stripping of the surface, which can compromise the adhesion properties. Additionally, glass is susceptible to breakage, which can lead to raveling issues. Consequently, usage is typically restricted, and the incorporation of anti-stripping agents is advised. Concretely, finely ground glass can exhibit pozzolanic properties (akin to fly ash) if ground sufficiently fine (i.e., to a powder consistency). The incorporation of coarser glass as sand in concrete has been demonstrated to be susceptible to alkali-silica reaction, a phenomenon that can be mitigated by maintaining a low cement content or by other measures. This susceptibility arises from the inherent reactivity of glass, which is rich in silica. However, certain studies have utilized up to 20% glass sand in pavement concrete, yielding satisfactory outcomes, particularly when supplementary cementitious materials are incorporated to mitigate ASR.

Photocatalytic Pavements

An innovation that has the potential to enhance sustainability during the utilization phase is the incorporation of titanium dioxide (TiO_2) into pavement surfaces (typically concrete or, on occasion, asphalt coatings). This addition serves as a photocatalyst, which means it can facilitate the breakdown of air pollutants, such as NOx, released by vehicles. While this approach does not directly contribute to the conservation of materials or energy in construction, it does play a crucial role in enhancing environmental sustainability by promoting improved air quality. A number of trials in Europe of TiO_2-containing "smog-eating" pavements have demonstrated reductions in NO2 concentrations near roads by 20–30% under ideal sunlight conditions. The cost and long-term efficacy of this approach are currently under evaluation. The primary focus at this stage is on sustainability in terms of environmental and health impact, rather than on resource conservation.

Carbon-Sequestering Materials

Researchers are exploring cement alternatives that have the capacity to absorb CO_2 during the curing process. Examples include magnesium-based cements and carbonated aggregates. For instance, one company produces artificial aggregates by mixing CO_2 with steel slag fines, thereby creating a carbonate aggregate – a process that utilizes waste CO_2 and waste slag. These aggregates can subsequently be utilized in pavement layers, thereby effectively sequestering carbon in the pavement. Although these technologies are nascent and not yet prevalent, they signify the subsequent domain of sustainable materials.

Cool Pavements

Lighter-colored pavement or special coatings (not a different material, often just a pigment or binder choice) that reflect more sunlight can reduce the urban heat island effect and thus indirectly conserve energy (less cooling is required in nearby buildings, etc.). The utilization of slag, lighter aggregates, or concrete in lieu of asphalt, in addition to the incorporation of reflective pigments, are methodologies employed to achieve the objective of "cool pavements." This is a design choice that has sustainability implications in the context of climate adaptation. **Figure 1** provides a synopsis of the pavement layers associated with each waste material.

Comparative Analysis

In this section, a synthesis and comparison of the sustainable pavement materials previously discussed across key dimensions is presented: environmental impact, mechanical performance, and economic considerations. This comparative analysis elucidates the contributions of each material or technology to sustainability, as well as the trade-offs or benefits it offers relative to conventional materials. **Table 1** presents a synopsis of the comparison of pavement materials.

Figure 1. Sustainability Strategies and Associated Pavement Layers

Environmental Impact and Life-Cycle Assessment (LCA)

Recycled Materials (RAP, RCA, etc.)

The primary environmental benefit of this approach is the conservation of raw resources and the reduction of waste. The findings of numerous studies have demonstrated that the incorporation of recycled aggregates (RAP) in pavement construction leads to a reduction in the embodied energy and emissions associated with this process. For instance, the incorporation of 30% RAP in an asphalt surface has been shown to reduce the total energy consumption and CO_2 emissions of that layer by approximately 15–20% (Tarsi et al., 2020). This reduction is primarily attributed to the offset of the production of new bitumen and aggregate, which are energy-intensive to produce and transport. The incorporation of recycled concrete aggregate in the base or concrete has been demonstrated to reduce the need for quarrying and mitigate landfill emissions associated with the disposal of excess concrete. However, the transportation of recycled materials must be considered. If RAP or RCA must be hauled over long distances to be used, this could offset some benefits. Typically, RAP is reused on-site or locally, such as when it is milled from a road and reused in the same project or nearby. This approach ensures a high degree of efficiency in its reuse.

Warm Mix Asphalt (WMA)

The environmental benefits of WMA are most evident during the construction phase, as this phase is associated with reduced fuel consumption at the plant and decreased emissions. A comparative life cycle assessment (LCA) of WMA and HMA revealed that WMA exhibited approximately 15% lower global warming potential (GWP) and comparable reductions in air pollutant emissions, attributable to its 30°C lower production temperature (Milad et al., 2022). It is important to note that WMA does not significantly alter the composition of the pavement materials (with the exception of additives), thereby ensuring its operational efficacy. When utilized in conjunction with RAP, as has been observed in several studies, the LCA benefits are cumulative. A particular study identified that a blend of WMA and 50% RAP resulted in a greenhouse gas (GWP) emissions reduction of approximately 30–40% when compared to a hot-mix containing solely virgin materials (Dughaishi et al., 2022). This reduction is substantial and noteworthy. WMA has the potential to reduce environmental impacts during paving by decreasing the release of fumes and odors, thereby enhancing local air quality for workers and nearby residents. This is a sustainability aspect that is not always included in an LCA; however, it is a significant aspect of sustainability.

Table 1. Comparison of Sustainable Pavement Materials by Environmental, Mechanical, and Economic Criteria

Material Category	Environmental Benefits	Mechanical Performance	Economic Impact
Recycled Aggregates (RCA)	High (reduced resource extraction, waste diversion)	Moderate to High (strength comparable if well-processed)	Cost-effective (low transportation costs if local)
Reclaimed Asphalt Pavement (RAP)	High (resource conservation, reduced emissions)	High (rutting resistance improved; fatigue depends on design)	High (significant cost savings)
Warm-Mix Asphalt (WMA)	Moderate to High (lower energy use, emissions)	Comparable to traditional HMA	Neutral or cost-saving (fuel savings offset additive cost)
Bio-binders	Moderate (renewable resources, reduced petroleum)	Moderate (improved low-temp performance, softer at high-temp)	Moderate (higher initial cost, depends on source availability)
Industrial Byproducts (Fly Ash, Slag)	High (reduces cement production emissions)	Moderate to High (improves durability, strength)	Cost-effective (often cheaper than cement, dependent on local availability)
Crumb Rubber	Moderate (solves tire disposal issue, reduces noise)	High (improves rutting and fatigue resistance)	Moderate (higher initial cost offset by long-term savings)
Recycled Plastics	Moderate (addresses plastic waste)	Moderate to High (improved stiffness, rutting resistance)	Moderate (dependent on processing costs and local policies)

Bio-Binders

The environmental benefits of bio-binders are evident in the material production phase, wherein the utilization of renewable or waste inputs supplants the use of petroleum. A comprehensive life cycle assessment (LCA) of bio-binders would encompass the cultivation and collection of biomass, in addition to its processing. A number of studies have examined the potential of utilizing waste cooking oil as a rejuvenator for asphalt, with findings indicating an overall reduction in greenhouse gas (GHG) emissions. This is attributed to the significant reduction in the production of virgin bitumen, which far outweighs the environmental impacts associated with processing the waste oil. In the event that the bio-binder is derived from a waste material, such as WCO or manure, it frequently exhibits a minimal attributed environmental burden, given that the waste would otherwise be subjected to treatment or landfilling. The primary challenge lies in the quantification of land use or indirect emissions in scenarios where crops are cultivated for binder production. Typically, the majority of proposals employ waste or byproducts to circumvent this issue. In summary, the substitution of a portion of asphalt with a bio-binder has the potential to reduce the binder's carbon footprint by the replaced fraction. For instance, a 30% bio content might result in a ~25–30% reduction in CO_2 for the binder component (Zhang et al., 2022). Given that binder constitutes a smaller part of the overall mixture, the mixture's overall greenhouse gas (GHG) reduction may be on the order of a few percent to approximately 10%. However, if bio-binders also enable the use of more RAP (rejuvenating it), they can indirectly amplify environmental benefits.

Industrial Byproducts (Fly Ash, Slag)

These materials have been demonstrated to be effective in reducing the environmental impact of concrete pavements and cement-stabilized layers. The incorporation of fly ash or slag, replacing 40% of the cement, has been demonstrated to reduce CO_2 emissions of concrete materials to a nearly proportional extent. This is due to the fact that the production of fly ash/slag is considered "allocatively free" from an LCA standpoint. This means that the emissions are allocated to the primary product, such as electricity or steel (M.G. et al., 2022). A significant proportion of LCAs of concrete have documented a 30–40% GWP reduction for a 50% GGBFS or fly ash mix in comparison to conventional concrete. Furthermore, the utilization of industrial byproducts serves to address issues related to disposal, as exemplified by the environmental concerns posed by fly ash in ponds and slag in landfills.

Crumb Rubber & Plastics

The environmental assessment of rubberized asphalt can be complex. On the one hand, the utilization of waste tires (a strategy that effectively addresses a significant environmental concern while reducing the necessity of incineration or landfill disposal) is a notable advantage. Conversely, the production of rubber asphalt can be more energy-intensive due to the necessity of elevated temperatures and extended mixing times. The preponderance of studies indicates that the utilization phase's advantages, including enhanced longevity and reduced maintenance requirements, and the mitigation of tire waste, collectively substantiate its net positive impact. In the context of recycled plastics, as this is a relatively recent field of study, the availability of LCA data is limited. In instances where the plastic is destined for landfill or incineration, its use in road construction can circumvent the associated disposal impacts and potentially eliminate the need for the production of certain polymer modifiers. However, it is imperative to consider any requisite processing, such as cleaning, shredding, or pelletizing plastic, in order to ensure the optimal functionality of the system. The efficacy of these measures would determine their potential benefit. Additionally, it is imperative to exercise caution in the context of LCA, particularly in scenarios where the utilization of plastic leads to microplastic generation or necessitates specialized handling at the end of its lifecycle. It is crucial to acknowledge that the methodologies for addressing these concerns are still in a state of development and refinement. **Figure 2** provides a synopsis of the life-cycle CO_2 emission reductions for the waste materials in comparison to conventional pavements.

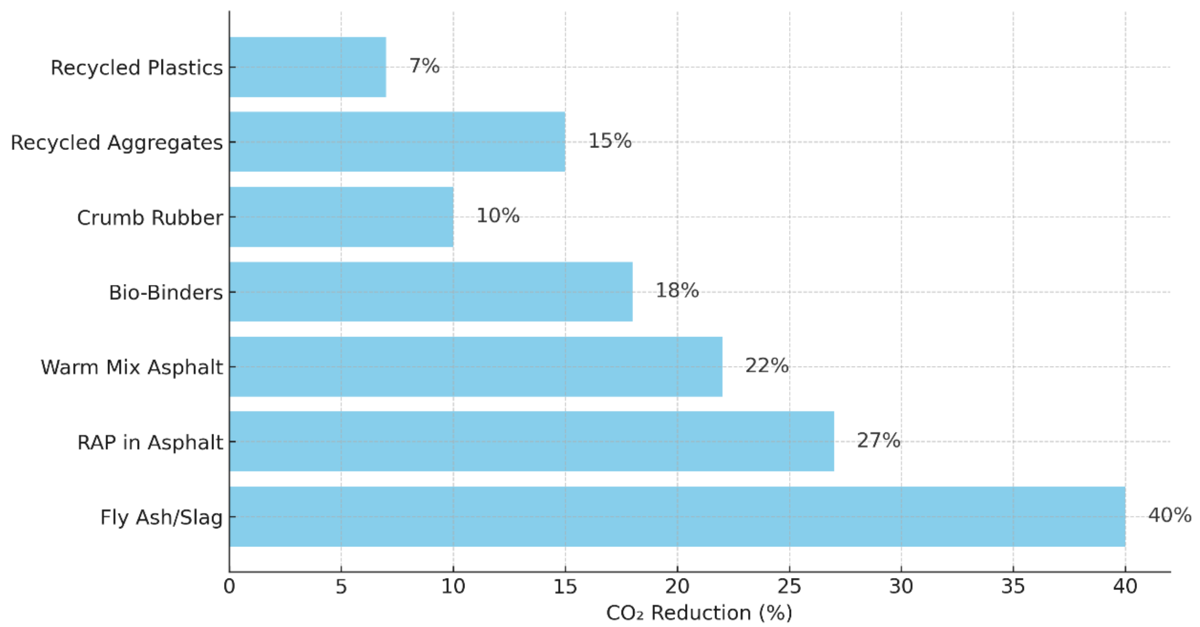

Figure 2. Life-Cycle CO_2 Emission Reductions Compared to Conventional Pavement Materials

Mechanical and Durability Performance

Structural Capacity and Stiffness

Recycled aggregates (RCA, RAP in base) have been shown to provide comparable structural support when utilized in accordance with established guidelines. RCA in base exhibits marginally lower specific gravity but can be compacted to comparable levels of stiffness; any discrepancy can be mitigated by blending or stabilization (J. Wang et al., 2022). RAP in its base (unbound) state exhibits a lower degree of rigidity compared to virgin aggregate (comprised of more flexible particles of coated rock), necessitating stabilization measures. In the case of surface layers, the use of RAP has been shown to enhance the stiffness of the mixture. This property is advantageous in terms of load-bearing capacity, although it can potentially compromise the distribution of stress due to an increased propensity for brittle fracture. Typically, WMA does not induce adverse effects on long-term stiffness. While initial laboratory stiffness may be marginally lower due to reduced aging, subsequent periods of service result in the convergence of WMA and HMA stiffness as the WMA binder ages to comparable levels (Milad et al., 2022). The utilization of slag and fly ash in concrete has been demonstrated to enhance later-age stiffness, a consequence of sustained pozzolanic reactions.

Rutting Resistance

The majority of these innovations have been shown to either maintain or improve rutting resistance. It has been demonstrated that the incorporation of RAP and rubber into the soil composition enhances its resistance to rutting (Dughaishi et al., 2022). This enhancement is attributed to the increased stiffness provided by RAP and the higher viscosity and elasticity characteristics of rubber. Historically, there have been some concerns about the potential for increased rutting in younger WMA binder materials. However, field results demonstrate that when properly designed, WMA rutting can be comparable to that of HMA. In some cases, WMA allows the use of stiffer binders or more RAP, which can result in similar rutting performance (Milad et al., 2022). The incorporation of plastic additives has been demonstrated to enhance the resistance of materials to rut, a process that involves the deformation of materials due to the action of moisture and temperature. These additives function as stiffeners, contributing to the improved resistance of the materials under stress. Among the available options, Bio-binders present a particular concern due to their potential for rutting. This issue can be mitigated by either reducing dosage or by incorporating harder base asphalt in conjunction with the bio-oil.

Cracking and Fatigue

This is the point at which greater variability becomes evident. In the absence of mitigation measures, elevated RAP levels have been observed to exacerbate fatigue and thermal cracking resistance, resulting in an increased propensity for cracking. This issue can be mitigated by employing softer binders or rejuvenators. Research has demonstrated that up to ~30% RAP can be utilized without compromising fatigue performance, provided that a moderately softer binder grade is employed (Dughaishi et al., 2022). The incorporation of rubber and plastics has been demonstrated to enhance fatigue life. Specifically, crumb rubber has been shown to improve ductility and toughness, thereby delaying crack initiation in the mix (Bilema et al., 2023). The efficacy of WMA in enhancing cracking performance is not significantly impacted, with the exception of its ability to reduce aging. Theoretically, this results in WMA exhibiting slightly higher resistance to cracking (as evidenced by the observation that certain field cores demonstrate WMA binders to be less aged and somewhat more ductile). Bio-binders have been shown to enhance low-temperature cracking, a property that renders binders more flexible. Consequently, bio-binders have been found to improve the thermal cracking performance of mixes in laboratory cooling tests. The presence of fly ash and slag in concrete has been observed to result in a marginal reduction in the likelihood of early-age cracking, attributed to the reduction in thermal stress caused by decreased heat. However, concerns have been raised regarding the potential increase in shrinkage cracking if adequate curing procedures are not employed. This is due to the prolonged setting time characteristic of fly ash and slag blends, which, in instances where curing is inadequate, can lead to shrinkage.

Moisture Damage

A prevalent challenge is moisture susceptibility. The addition of RAP (residual aggregate material) does not result in a substantial alteration of the moisture sensitivity of asphalt, provided that the binder coats are adequately activated during the mixing process. In fact, a particular reference has indicated that elevated levels of RAP can potentially mitigate moisture-induced damage in certain instances, a phenomenon that may be attributed to the enhanced binding capacity of aged binder with aggregates (Milad et al., 2022). However, if RAP has a binder that is susceptible to stripping, or if it is not thoroughly blended, it may result in the introduction of some stripped particles. As previously discussed, WMA has historically encountered challenges in this regard. However, the incorporation of additives and anti-strips has led to the successful passing of moisture damage tests (TSR) for WMA mixes. In certain instances, the incorporation of additional anti-stripping agents may be necessary in rubber-asphalt compositions. While a rubber binder may exhibit slightly elevated levels of hydrophobicity, this is typically not a significant concern when employing conventional anti-stripping methodologies. Depending on the type of additive, they may either inertly sit in the mix or, in the case of polyolefins, not affect moisture much. However, if plastic replaces bitumen, it is essential to ensure that the aggregate is still properly coated. Specifically, the addition of fly ash has been observed to enhance vulnerability to deicer scaling in certain instances if not adequately cured. However, in general, its incorporation is beneficial, as it can enhance impermeability, leading to a reduction in water ingress and, consequently, freeze-thaw issues.

Durability and Longevity

A significant proportion of sustainable materials are designed to enhance longevity, a goal that is inherently sustainable due to the reduction in the necessity for reconstruction. In regions such as Arizona, the primary advantage of rubberized asphalt over conventional asphalt was its enhanced fatigue life, which was reported to be 2-3 times longer (Bilema et al., 2023). This enhanced fatigue life was attributed to the increased resistance of rubberized asphalt to crack formation and propagation, resulting in a longer lifespan for overlays and other asphalt-related infrastructure. RAP mixes, if marginally more fragile, could potentially diminish longevity if not meticulously designed. However, judicious use of RAP, in amounts deemed modest, can be employed without any discernible decline in performance. Some states have documented instances of equivalent performance up to 30% RAP. The longevity of WMA appears analogous to that of HMA. Long-term pavement performance studies in the US have demonstrated that WMA sections exhibit no significant differences in distress compared to HMA sections over an 8-year period or more. Concrete that incorporates fly ash and slag frequently exhibits enhanced durability, characterized by superior sulfate resistance, reduced alkali-silica reaction (ASR), and diminished permeability. Consequently, its lifespan can be extended, contingent upon ensuring sufficient curing. Prior to the occurrence of any unfavorable consequences, such as diminished strength gain, these combinations have the potential to exhibit enhanced durability in the presence of chemical stress.

Economic Considerations

The economic aspect of sustainable materials can be intricate. It is imperative to consider not only the material unit costs but also the life-cycle costs, which encompass factors such as maintenance frequency, and external costs, including the potential avoidance of disposal costs, which, although they may not be directly evident in a contractor's budget, represent societal savings.

Initial Material Costs

A significant reduction in material costs can be achieved through the incorporation of recycled materials. RAP is a more economical option compared to new asphalt, often regarded as "black gold" by contractors due to its ability to substitute expensive bitumen. The utilization of recycled aggregates, such as RCA, when available on site, can result in significant cost savings due to the elimination of expenditures associated with the procurement and transportation of new rock. The utilization of fly ash and slag as cement substitutes has been demonstrated to be a cost-effective solution in numerous instances. In many cases, the cost of fly ash per ton is lower than that of cement, often by a margin of fifty percent or more, unless there is a limited supply of cement. Slag cement, a byproduct of the steel-making process, is a cost-effective alternative, with regional variations in pricing. The incorporation of crumb rubber modifiers can, on occasion, result in an increase in cost, attributable to the expenses associated with rubber processing and additional handling. However, in regions where tire recycling programs are in place, the use of ground rubber can be incentivized or priced at a reduced rate to promote its utilization. The incorporation of WMA additives does incur a financial obligation, though the cost associated with water-based foaming is relatively negligible. Contractors must consider this against the fuel savings. Studies indicate that the fuel savings from lower temps often offset the cost of the chemical additives, making WMA roughly cost-neutral or even slightly cheaper in net. To illustrate, if WMA additive costs $3 per ton of mix, but fuel savings are $2 per ton, the net cost would be $1, a figure that might be justified by other benefits. When these differences are applied to a project, they do not result in significant variations.

Construction and Operational Costs

The implementation of sustainable practices has been demonstrated to result in a reduction of construction costs. For instance, the use of Wildland-Urban Interface (WMA) has been shown to extend the time windows for paving, thereby facilitating expedited project completion and minimizing cooling delays. This, in turn, has the potential to generate cost savings in areas such as labor and traffic management. The utilization of RAP has been demonstrated to result in a reduction of hauling costs for both waste and new materials, a benefit that is particularly evident when a mobile crusher is employed on the premises. Conversely, certain techniques necessitate a substantial financial outlay, such as the integration of a foaming kit within an asphalt plant for the purpose of WMA, the acquisition of apparatus for the feeding and regulation of RAP, or the establishment of storage facilities for multiple binders (including softer grades for RAP mixes). These expenses are typically amortized as one-time costs by larger contractors.

Life-Cycle Cost Analysis (LCCA)

A comprehensive evaluation of economic sustainability is only possible through the examination of LCCA. The utilization of sustainable materials, such as rubber to enhance the longevity of pavements or slag concrete to augment durability, has been demonstrated to extend the lifespan of these infrastructure elements. Consequently, this approach has the potential to reduce the subsequent costs associated with rehabilitation and user delay (Bilema et al., 2023). For instance, the implementation of a rubberized asphalt overlay might incur a 30% higher initial cost (merely illustrating the potential cost implications of incorporating a rubber additive), yet if it exhibits a 50% longer lifespan before succumbing to cracking, its life-cycle cost could be reduced. LCCA studies for RAP generally demonstrate its cost-effectiveness due to its lower initial cost and comparable performance. The WMA LCCA is frequently marginally favorable. This is due to the fact that energy savings and the potential for an extended paving season can lead to a reduction in project time and cost. From an economic perspective, it is noteworthy that certain byproducts, such as fly ash, can incur costs for the contractor. For instance, the power plant may remunerate the contractor or provide fly ash at no cost to avoid the disposal of this byproduct. This can significantly encourage utilization.

The Oman RAP review explicitly states that reusing RAP is "economically attractive" due to raw material shortages and the cost of virgin materials in that region (Dughaishi et al., 2022). In the United States, RAP is highly prized, prompting asphalt plants to compete for RAP stockpiles. Some have devised pricing formulae that estimate the cost savings from utilizing RAP, with NAPA suggesting that the incorporation of 1% RAP can reduce the cost of a mix per ton by approximately $0.50, contingent on oil price fluctuations. This suggests that the use of 20% RAP could potentially result in a savings of $10 per ton in material costs. Consequently, elevated oil prices result in amplified RAP savings. Conversely, a significant decline in oil prices, specifically bitumen, would result in a modest reduction in the incentive.

The utilization of industrial byproducts in concrete has the potential to reduce costs, provided that the byproducts are locally available and inexpensive. Historically, fly ash has been comparatively inexpensive when measured against cement; however, as coal-fired power plants have been decommissioned, there has been an increase in fly ash prices in certain regions due to reduced supply. Slag cement is moderately priced; it can sometimes be a bit less than Portland cement, but not always—this depends on local production. However, when considering the enhanced durability that results from the reduced maintenance requirements, the cost-benefit analysis frequently favors this option.

Risk and Reliability Costs

In some cases, agencies may incorporate a risk premium, which leads to conservative valuation of the life of the material or the requirement of additional testing, which results in financial expenditure. However, as technology continues to evolve, these perceived risks are gradually diminishing.

In conclusion, economically, most sustainable pavement materials are attractive in the long run, with many yielding direct cost savings (e.g., RAP, fly ash, WMA) and others requiring a bit of upfront investment but paying off over time (e.g., rubber, depending on local pricing). The life-cycle cost perspective demonstrates a strong inclination toward sustainable options, owing to the prolongation of service lives and the mitigation of raw material procurement needs throughout the pavement's lifespan.

To illustrate, if an agency were to employ higher RAP and WMA, it could potentially resurface roads with greater infrequency and utilize more economical materials. This would result in long-term benefits for taxpayers. A significant number of DOTs have now incorporated LCCA into their decision-making processes. This development has facilitated the selection of sustainable options that, while potentially incurring equal or marginally higher initial costs, offer reduced future expenditures.

A comprehensive review of the extant literature was conducted to inform the development of **Figure 3**, which provides a summary of the acceptable replacement level for each waste material, with this determination informed by environmental, mechanical, and economic considerations.

Implementation and Scalability

A brief comparative analysis of implementation strategies follows. The utilization of RAP is relatively straightforward, as the industry possesses the necessary infrastructure. Similarly, the adoption of WMA is uncomplicated due to the ubiquity of the necessary technology. Bio-binders and certain novel recycled materials (plastics) continue to encounter challenges related to scalability, namely the assurance of a consistent supply and the demonstration of performance at large scales. The utilization of industrial byproducts has a long-standing tradition in the concrete industry; however, its application in asphalt could be further explored, particularly in the context of using slag aggregate when available. The optimal mix of these strategies varies by region, contingent on the availability of materials (e.g., coal fly ash in India, but none in Iceland; plastic waste in abundance everywhere, etc.). A sustainable strategy frequently integrates a variety of approaches. For instance, the production of asphalt can be performed at elevated temperatures, incorporating RAP (reclaimed asphalt pavement), bio-oil rejuvenator, and crumb rubber. This multifaceted approach is designed to optimize sustainability. The compatibility of these methods is demonstrated by the documented outcomes of studies that have utilized RAP, WMA (warm mix asphalt), and additives, yielding favorable results (Milad et al., 2022).

In summary, the findings of the comparative analysis indicate that sustainable pavement materials typically offer environmental benefits, exhibiting minimal to manageable impacts on performance. These materials can be cost-effective, particularly when assessed over the entire life cycle of the pavement. It has been demonstrated that significant advancements in sustainability, such as substantial carbon reductions, can be achieved by substituting high-impact materials, such as cement and virgin bitumen, with suitable alternatives, including fly ash/slag, RAP, and bio-binder. These innovations can be conceptualized as a toolkit, allowing engineers to select the combination that is optimal for a specific project. For instance, in the context of an urban street project, the priority might be low emissions and the utilization of recycled materials. In contrast, a highway project might prioritize durability and the incorporation of RAP (Reclaimed Asphalt Pavement). As illustrated in **Table 1**, which would conceptualize these comparisons if included, the most suitable options for each purpose have been outlined in narrative form.

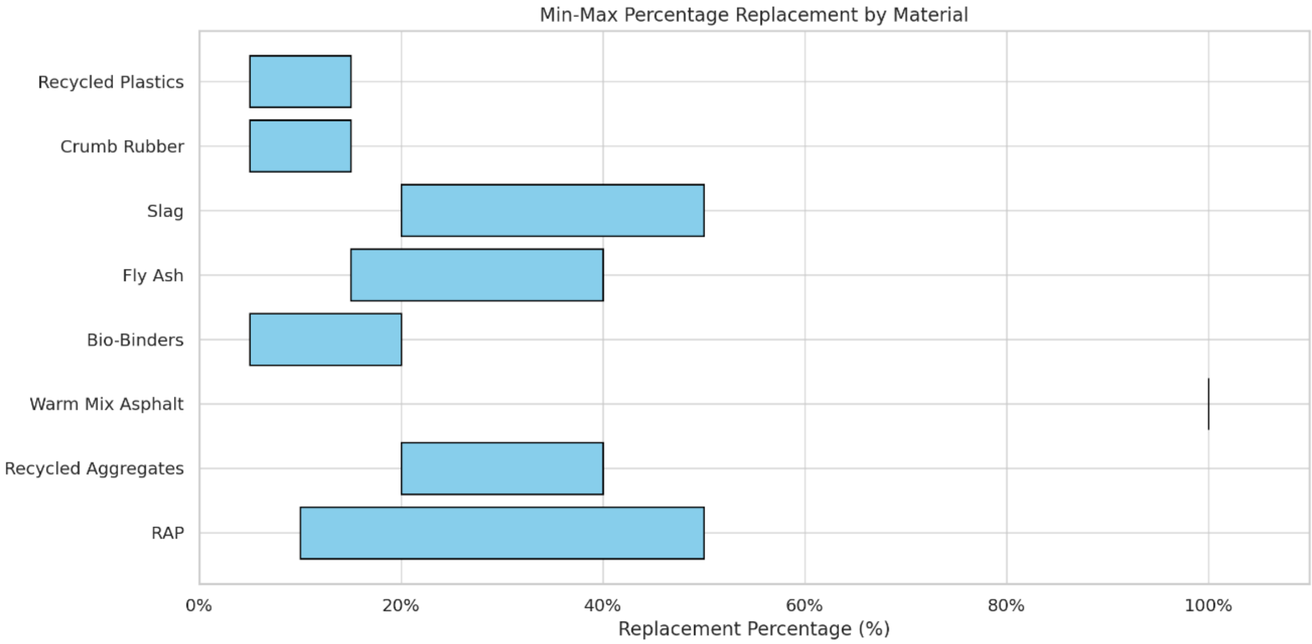

Figure 3. Typical Percentage Replacement and Optimal Applications of Sustainable Materials

- RAP: The product has been demonstrated to be highly effective in terms of cost-effectiveness and environmental impact. Its use has been shown to effectively mitigate rutting and prevent cracking, thus ensuring optimal performance and durability.

- WMA is considered to be an optimal solution for the environment during the construction phase. Its performance is regarded as neutral, and the slight added cost can be offset.

- Bio-binders: The product's environmental impact, as indicated by its material composition, is beneficial. Its performance, particularly under low-temperature conditions, can be enhanced. However, further validation is necessary to ensure its effectiveness. At present, the product's cost is moderate, and its availability is limited.

- Industrial byproducts: This material has been demonstrated to be highly effective in terms of environmental impact and frequently exhibits superior performance when utilized in concrete applications. It has also been shown to lead to cost savings. However, when employed in asphalt (e.g., slag), proper handling is imperative to ensure optimal outcomes.

- Rubber and plastics are materials that are of interest in this study. The objective is to resolve waste management issues and generally improve or maintain performance, with a focus on mitigating rutting and noise in rubber components. The cost implications of these measures are subject to variation. Additionally, it is imperative to address any ancillary issues, such as microplastics or fume control, that may arise.

In essence, a one-size-fits-all solution does not exist; however, a comparative analysis reveals that a well-chosen sustainable material or combination can yield a pavement that is environmentally friendlier, economically sensible, and technically sound. This fulfills the "triple bottom line" of sustainability (environment, economy, society).

Conclusion

The concept of sustainability in pavement engineering has evolved from a niche topic to a central consideration, as communities worldwide endeavor to mitigate environmental impacts and enhance infrastructure resource efficiency. This review has explored a broad spectrum of sustainable pavement materials, ranging from recycled aggregates and reclaimed asphalt to warm-mix technologies, bio-binders, industrial waste utilization, and other green innovations. The primary focus of this analysis is on the environmental, mechanical, and economic performance of these materials, as reported in studies up to the year 2022. A number of overarching conclusions emerge from this analysis.

- The utilization of sustainable pavement materials, when meticulously designed and implemented, has demonstrated their capacity to not only meet but also, in certain instances, surpass the performance of conventional materials. Recycled aggregates (e.g., RCA) can be utilized in bases and even new concrete with minimal strength reduction; RAP can be employed in new asphalt mixtures without compromising rutting performance and with manageable effects on cracking; warm-mix asphalt provides equivalent paving results to hot-mix while reducing production temperature by tens of degrees. Strategies such as the use of rejuvenators and anti-stripping agents have been employed to address challenges associated with RAP stiffness and WMA moisture susceptibility. A comprehensive review of the extant literature reveals a preponderance of evidence supporting the technical viability of incorporating these materials, a assertion that is further substantiated by numerous field projects and extant long-term performance data.

- It has been demonstrated that the implementation of sustainable material strategies is an effective method of reducing the environmental impact of pavements. Life-cycle assessments consistently indicate reductions in energy use and emissions. For instance, substituting a portion of Portland cement with fly ash or slag results in substantial CO_2 reductions in concrete; the incorporation of RAP and WMA in asphalt can lead to a significant decrease in greenhouse gas emissions and air pollution associated with pavement construction. Furthermore, the recycling of materials diverts these materials from being disposed of in landfills, thereby reducing the demand for virgin resources. This, in turn, fosters the development of a circular economy within the road industry. The cumulative impact of these practices is significant. If these practices were to be widely adopted, they could potentially result in millions of tons of CO_2 being saved and millions of tons of waste being repurposed on a global scale each year. Consequently, sustainable pavements are congruent with overarching objectives pertaining to climate change mitigation and resource conservation.

- From an economic perspective, the utilization of sustainable materials frequently demonstrates cost-effectiveness when assessing the complete life cycle. A significant number of these initiatives entail direct cost savings, which can be achieved by utilizing more economical recycled materials in place of new resources or by reducing energy and fuel expenditures during the manufacturing process. Notwithstanding the potential for elevated initial costs, attributable to certain additives or processing requirements, the ensuing service life prolongation and diminished maintenance needs frequently result in a reduction of life-cycle costs. For instance, the enhanced durability of rubberized asphalt or high-volume fly ash concrete has the potential to postpone rehabilitation expenditures. A societal economic benefit is also realized through the reduction of waste management costs and environmental damage. The findings of the review encourage highway agencies to adopt life-cycle cost analysis in project evaluation, as it often favors the more sustainable option.

- Despite the considerable progress that has been achieved, it is imperative to acknowledge the necessity for continued efforts to integrate these sustainable practices into the mainstream. The review underscored the necessity for revised standards, enhanced quality control mechanisms, and continuous research and development to address the residual challenges, including variability in recycled materials and the optimization of high-percentage use of recyclables. The trajectory of this field is encouraging, as it is progressing in a positive direction. Specifications are evolving to allow for higher allowable RAP contents, standards for WMA, and recycling. Additionally, new technologies are emerging, such as bio-derived additives, improved rejuvenators, and advanced recycling techniques. A multitude of opportunities exist, including the integration of diverse approaches (e.g., WMA + high RAP + bio-rejuvenators) to optimize sustainability, and the utilization of novel materials (e.g., waste plastics, nano-materials) as our understanding evolves. The field of public policy has seen a marked shift towards greater support for sustainable infrastructure, with numerous authorities establishing recycling mandates or carbon reduction targets that paveements are required to adhere to.

The ongoing and increasing focus on sustainable pavements is expected to continue, and future research and field experience will aim to address the current limitations in this area. By fostering collaboration among researchers, industry practitioners, and policymakers, the implementation challenges can be overcome. As this review illustrates, the knowledge and tools are largely in place—it is now a matter of scaling up adoption. By incorporating sustainable materials and technologies, pavement engineering can play a pivotal role in advancing sustainable infrastructure and combating global environmental challenges, while maintaining the performance and reliability that society expects from its transportation networks.

Declarations

Author Contribution

A.B: Conceptualization, Investigation, Writing of the original draft.

W.AD: Conceptualization, Writing of the original draft.

W.AA: Methodology, Investigation, Supervision.

R.A: Methodology, Writing – review & editing, visualization, Supervision.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Declaration on the Use of Generative AI and AI-Assisted Technologies

No generative AI or AI-assisted technologies were used in the preparation of this manuscript.

Data Availability

No new data was generated or analyzed in this study.

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Ethics

This study did not involve human participants or animals; hence, no ethical approval was required.

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