DOI: https://doi.org/10.14256/JCE.4274.2025

Građevinar 10/2025

Primljen / Received: 5.3.2025.
Ispravljen / Corrected: 4.7.2025.
Prihvaćen / Accepted: 12.8.2025.
Dostupno online / Available online: 10.11.2025.

A comprehensive review of recycled materials in eco-friendly pavement construction

Author:

Associate Senior Engineer **Yuanxin Li**, CE
Gansu HATG Road Industry Co. Ltd, China
liyuanxianhatg@gmail.com
Corresponding author

Subject review

Yuanxin Li

A comprehensive review of recycled materials in eco-friendly pavement construction

The integration of recycled materials into pavement construction is a vital strategy for promoting sustainable urban infrastructure. Recycled concrete aggregate, reclaimed asphalt pavement, and crumb rubber have demonstrated significant potential to reduce environmental impacts by minimising resource consumption and construction waste generation. Technical evaluations revealed that these materials can deliver performance comparable to or exceeding that of conventional pavements. Although issues related to quality variability and lack of standardisation persist, economic analyses have identified significant cost savings. This review underscores the need for continued technological innovation and regulatory interventions to facilitate broader adoption, support circular economy objectives in pavement construction, and contribute to long-term sustainability targets.

Key words:

pavement construction, sustainable pavements, recycled materials, circular economy

Pregledni rad

Yuanxin Li

Sveobuhvatan pregled primjene recikliranih materijala u ekološki prihvatljivoj gradnji kolnika

Integracija recikliranih materijala pri izgradnji kolničkih konstrukcija ključni je segment strategije promicanja održive cestogradnje. Reciklirani betonski agregat, reciklirani asfaltirani kolnik i gumeni granulat mogu znatno doprinijeti smanjenju negativnog utjecaja cestogradnje na okoliš tako da se potrošnja neobnovljivih prirodnih resursa i nastajanje građevnog otpada svedu na najmanju moguću mjeru. Tehnička vrednovanja pokazala su da ti materijali mogu osigurati svojstva usporediva s tradicionalnima ili ih čak nadmašiti. Iako i dalje postoje problemi povezani s heterogenosti u svojstvima i nedostatkom standardizacije, ekonomske analize upućuju na mogućnost znatne uštede. Ovo istraživanje ističe potrebu za kontinuiranim tehnološkim inovacijama i uvođenjem regulatornih mjera kako bi se omogućila šira primjena recikliranih materijala, ostvarili ciljevi kružnoga gospodarstva u izgradnji kolnika te doprinijelo dugoročnoj održivosti cestogradnje.

Ključne riječi:

kolnička konstrukcija, održivi kolnici, reciklirani materijali, kružno gospodarstvo

1. Introduction

The construction industry, particularly the pavement engineering sector, encounters a critical challenge in balancing the demand for durable and high-performance infrastructure with the imperative of ecological sustainability [1, 2]. Conventional pavement materials such as concrete and asphalt are well-established in terms of performance and cost-effectiveness; however, they exhibit significant environmental detriments, including substantial greenhouse gas emissions and the depletion of finite natural resources [3, 4]. Concurrently, the escalating global waste accumulation crisis, characterised by an increasing volume of non-biodegradable waste streams, such as plastics, rubber, and construction debris, presents a formidable environmental challenge [5].

The intersection of these pressing issues has catalysed an emergent paradigm shift towards the development of sustainable alternatives for pavement material compositions. Among these alternatives, the incorporation of recycled materials has emerged as a promising solution, offering the dual advantage of mitigating the environmental footprint of pavement construction and contributing to effective waste management [6]. This transition towards the utilisation of recycled materials in pavement construction represents a broader movement toward the adoption of circular economy principles within the construction sector [7-11]. By repurposing waste materials as functional components of new pavement structures, this approach facilitates the closed-loop cycling of materials and fosters a more sustainable model for infrastructure development.

The objective of this review is to provide a comprehensive examination of recycled material integration in pavement construction. It evaluates their potential environmental benefits, technical performance characteristics, associated challenges, and implementation opportunities, thereby providing a comprehensive overview of their prospective roles in fostering a more environmentally conscious and resilient paradigm for pavement engineering practices.

2. Bibliometric analysis materials in pavement construction

The increasing commitment to sustainability has driven substantial academic interest in the application of recycled materials in pavement engineering over the past quarter-century. This trend is evident in the publication and citation data presented in Figure 1. The number of publications has increased steadily from approximately 10 in 2000 to over 400 in 2024, indicating growing research interest and focus on this sustainability-oriented topic. Notably, the number of citations has increased exponentially, from a few hundred in the early 2000s to over 14,000 by 2024. This trend suggests that research in this domain has achieved a significant impact and recognition within the scientific community. The rapid acceleration in citations beginning around 2015 further underscores the increasing relevance of this field, coinciding with a broader shift toward sustainable pavement solutions in response to environmental concerns and resource constraints. Overall, the data trends reflect the substantial progress and rapidly expanding knowledge base centred on the utilisation of recycled materials, such as crumb rubber, in the construction and maintenance of environmentally sustainable pavement systems.

The co-occurrence network map generated from the Web of Science (WoS) database analysis, shown in Figure 2, provides a comprehensive visualisation of the key topics, relationships, and interconnections within the research domain of recycled materials in pavement applications. The central and dominant cluster revolves around the term "asphalt mixture", which is closely associated with various sub-topics such as "hot mix asphalt", "recycled asphalt mixture", "binder grade", "blending agent", and "complex modulus". Therefore, the primary focus of this research area is the composition, properties, and performance of asphalt mixtures, particularly those that incorporate recycled materials. Several other prominent clusters surrounding the asphalt-centric cluster highlighted the diverse aspects of this research field. One such cluster is the "concrete"

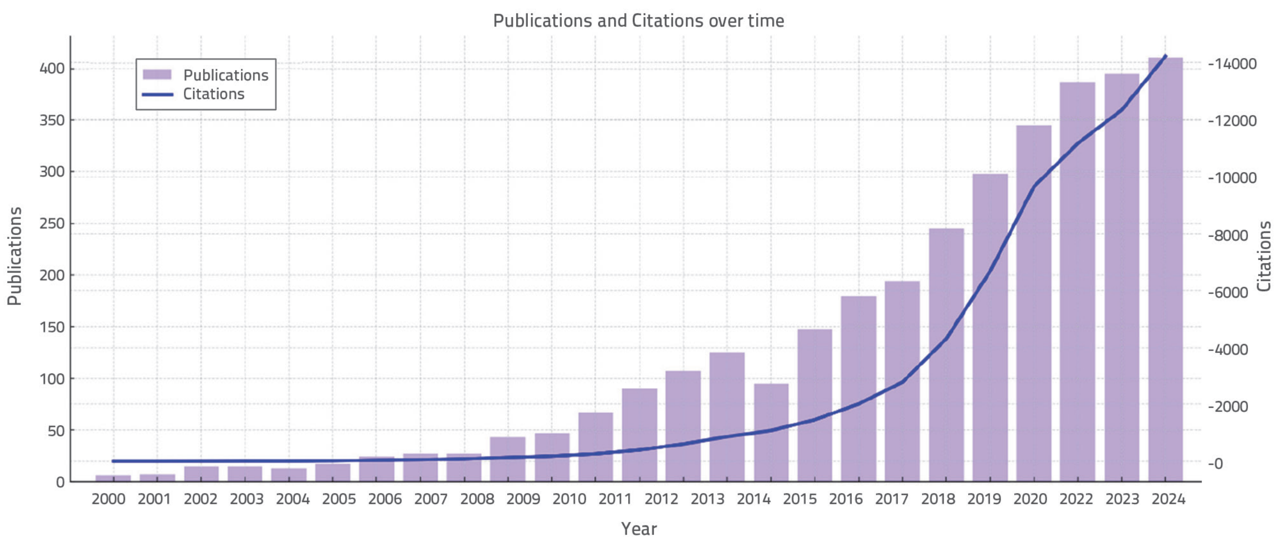

Figure 1. Annual prediction and citation trends from the Web of Science (WoS) database for the topic search terms "recycle", "materials" and "pavement" (2000–2024)

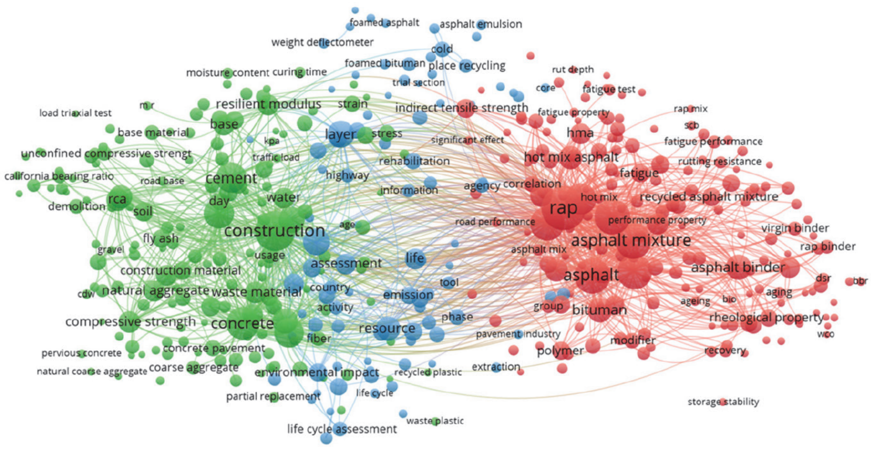

Figure 2. Co-occurrence map of keywords based on total link strength (Search criteria: Topic= "recycled", "materials", and "pavement"; all keywords; minimum number of occurrence of a keyword = 30; 446 keywords met the threshold)

group, which includes terms such as "compressive strength", "flexural strength", "recycled concrete aggregate", "subgrade stabilization", and "concrete waste". This indicates a parallel focus of the utilisation of recycled concrete and other concrete-related materials in pavement construction. Additional clusters address broader environmental and sustainability considerations. Terms such as "environmental impact", "waste plastic", "fly ash", and "life cycle assessment" reflect the growing emphasis on incorporating recycled and environmentally friendly materials into pavement construction, driven by the need for more sustainable infrastructure solutions. Other notable clusters include those related to material properties and performance, such as "rheological properties", "moisture content", "curing time", and "permanent strain", as well as terms associated with various testing and evaluation methods, such as "trial section", "monitoring", and "influence factor". Collectively, these clusters highlight the multifaceted nature of this study, encompassing both material characteristics and assessment techniques.

3. Types of recycled materials in pavement construction

The co-occurrence network map provides a comprehensive overview of key topics, interconnections, and areas of focus within the broader field of recycled materials for pavement applications, underscoring the interdisciplinary and sustainability-driven nature of this research domain. To ensure a comprehensive and analytically robust review, the literature included in this section was selected based on the following criteria: (a) publication year from 2005 to the present to reflect contemporary research developments; (b) citation frequency exceeding 10, indicating scholarly impact; (c) direct relevance to the application of recycled materials in pavement construction; and (d) methodological rigor, including experimental validation and publication in peer-reviewed journals. This section reviews different types of recycled materials successfully incorporated into pavement construction. Each material originates from distinct waste streams and exhibits unique characteristics; however, they all contribute to the overarching objective of promoting sustainable and environmentally responsible infrastructure development.

3.1 Recycled concrete aggregate (RCA)

Recycled concrete aggregate (RCA) is a granular material produced by processing hardened concrete recovered from construction and demolition wastes. It typically comprises natural aggregate particles coated with remnants of cement paste and mortar from the original concrete matrix. RCA has gained traction as a sustainable alternative to natural aggregates (NA) in pavement engineering owing to its environmental and economic advantages, including the conservation of virgin resources, reduction of construction waste, and lower embodied energy associated with aggregate production [12-15]. RCA is characterised by the presence of adhered mortar from the original concrete, which imparts distinctive physical and mechanical properties compared to conventional natural aggregates (NCA). Specifically, RCA typically exhibits a higher porosity, increased water absorption, and reduced density and strength, predominantly owing to the porous and microcracked nature of the residual mortar [16, 17]. These intrinsic characteristics can adversely impact the durability and long-term mechanical performance of concrete and the stabilised layers in which RCA is incorporated.

Despite these limitations, RCA has been successfully utilised in various pavement applications, particularly in unbound base and subbase layers, as well as in cement-treated and lean concrete mixtures. In structural concrete pavements, their applications remain limited and are often restricted to partial replacement levels owing to concerns regarding variability and performance (Figure 3). To address these challenges, significant research has focused on improving RCA quality employing pretreatment methods that either remove or reinforce the adhered mortar [18-20].

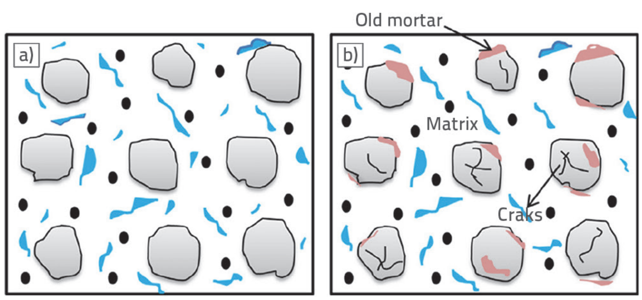

Figure 3. Schematic comparison of physical properties between: a) NCA; b) RCA [19]

Two primary strategies have been explored: mortar removal and mortar reinforcement. Mechanical techniques such as grinding can effectively detach adhered mortar; however, they may introduce microcracks and excessive fines [21-23]. Chemical treatments, including water and acid immersion, have demonstrated varying degrees of success. Although water immersion helps clean the RCA and reduce contamination levels, it may leave a layer of weakened, partially hydrated mortar. Conversely, acidic solutions can dissolve hydration products more effectively, thereby enhancing RCA quality, albeit at higher processing costs and environmental concerns [24, 25].

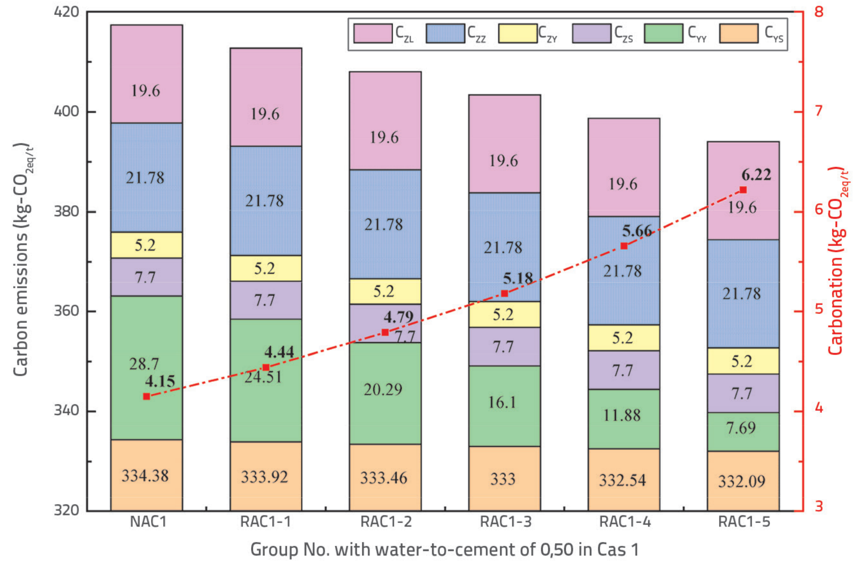

Figure 4. Life cycle carbon emissions across different recycled fine aggregate replacement ratios, with constant water-to-cement ratio [35]

Reinforcing the mortar attached to the RCA involves either sealing the pores or coating the RCA to repel water. Owing to their sticky nature, polymers can coat the RCA, thereby reducing its water absorption capacity [26]. The use of pozzolanic substances, such as silica fume, can also benefit RCA by filling the gaps in the mortar and refining the microstructure at the transition zones where the aggregate interfaces with the concrete [27].

Shaban et al. demonstrated that treating RCA with pozzolan slurries, comprising 40 % fly ash and cement in conjunction with 3 % nano-silica, 4 h resulted in over 50–55 % reduction in water absorption and 10–11 % increase in particle density. Additionally, these treatments have improved abrasion resistance by 31–35 % and yielded a more uniform microstructure with a lower calcium-to-silicon ratio, correlating with enhanced mechanical strength and durability of the aggregates [28]. Furthermore, approaches such as the biological deposition of calcium carbonate and application of a sodium silicate solution have been explored for their effectiveness in plugging microvoids and promoting in situ formation of cementitious compounds via reactions with residual calcium hydroxide in the RCA [29].

Researchers have also shown considerable interest in the durability of RCA-based concrete, particularly the ability of concrete to resist various types of damage and to maintain its structural integrity during its service life under diverse environmental conditions. This aspect is a critical determinant for the practical implementation of RCA in construction applications [30, 31]. A comprehensive review by Zhang et al. emphasized the durability of RCA concrete, particularly its resistance to aggressive environmental conditions such as chloride penetration, carbonation, sulphate attack, and freeze-thaw cycles [32]. This body of work indicates that RCA concrete can achieve durability comparable to that of conventional concrete when the water-cement ratio is controlled properly and adequate curing conditions are ensured.

Poon et al. revealed that using carbonated RCAs in recycled aggregate concrete reduces water absorption and improves impermeability, achieving over 42.4 % reductions in bulk electrical conductivity, chloride ion penetration, and gas permeability. Moreover, the carbonation of RCAs exerts a more pronounced positive effect on the durability than on the mechanical characteristics of recycled aggregate concrete (RAC), suggesting that the water absorption rates could serve as reliable indicators of RAC's overall durability [33].

In addition to its mechanical and durability properties, the structural behaviour and performance of RCA concrete have been explored across various applications. Tabsh et al. examined the influence of varying the RCA replacement levels on the shear behaviour and strength of reinforced concrete beams [34]. They observed that beams made with 50 % recycled coarse aggregate exhibited 27 % lower shear strength than natural aggregate beams at a lower shear span-to-depth ratio, while performing comparably at higher ratios. Beams with 100 % recycled aggregate consistently exhibited a 5 % lower shear strength than their natural aggregate counterparts, irrespective of the shear span-to-depth ratio. Existing theoretical models, such as the ACI 318 code and strut-and-tie method remained effective in predicting the shear strength of RAC beams.

As shown in Figure 4, Li et al. [35] evaluated the environmental impact of different RAC mixes with a water-to-cement ratio of 0.50, emphasising the carbon emissions and carbonation potential across five RAC configurations and natural aggregate concrete (NAC) control. As illustrated in Figure 4, although total carbon emissions for RAC mixtures remained comparable to NAC, the embedded CO_2 contributions from various life cycle stages (C_1–C_6) exhibited notable variations. In particular, RAC-5 exhibited the highest carbonation uptake (6.22 kg-CO_2eq/t), indicating enhanced CO_2 sequestration potential in more

porous recycled concretes. These findings underscore the dual environmental benefits of RCA use, not only in reducing the demand for virgin materials but also in contributing to carbon neutrality via higher carbonation capacity.
Recognising the potential for further performance enhancement, recent studies have investigated the synergistic effects of combining RCA with other recycled materials. Raza et al. investigated the incorporation of microcarbon fibres into RCA-based concrete and demonstrated significant improvements in the mechanical strength, microstructural integrity, and overall durability of the composite material [36]. This approach provides a solution for managing concrete waste and valorises recycled carbon fibre, highlighting the potential for innovative multi-recycled material systems in sustainable construction. Such research underscores the ongoing efforts to optimise RCA performance via advanced material engineering strategies, thereby broadening the applicability of recycled aggregates in high-performance infrastructure [37].
In summary, RCA presents both opportunities and challenges in pavement engineering, offering environmental and structural benefits when properly treated and incorporated, while ongoing innovations in pretreatment and mix design continue to enhance its performance and sustainability.

3.2. Reclaimed asphalt pavement (RAP)

Reclaimed asphalt pavement (RAP) is a recycled material generated via milling or by removing existing asphalt pavement layers during road maintenance or resurfacing. It primarily comprises aged asphalt binder and aggregates recovered from previously used pavements, which are subsequently processed via crushing and screening to meet specific gradation requirements for reuse. RAP has gained significant attention as a valuable and sustainable component in asphalt mixtures owing to its environmental and economic advantages, including the conservation of virgin aggregates, reduction of greenhouse gas emissions, and substantial cost savings in pavement construction and rehabilitation projects [38-42].
Numerous studies have highlighted the benefits of RAP incorporation across the environmental, economic, and mechanical performance domains. For instance, Zaumanis et al. reported that substituting 50 % of virgin aggregate with RAP in hot-mix asphalt (HMA) mixtures can reduce the overall carbon footprint by over 38 % [43]. This significant reduction in emissions stems is primarily attributed to the decreased energy consumption and material processing associated with virgin aggregate and binder production. Peng et al. developed a life cycle carbon emission model for asphalt pavement construction and observed that adopting energy-saving strategies such as warm mix technologies and optimised RAP use can reduce greenhouse gas emissions by 35.93 % and construction costs by 18.58 % [44, 45]. These studies collectively demonstrate that RAP utilisation aligns with global sustainability targets by mitigating climate impacts and promoting resource conservation.

From an economic perspective, Copeland reported that RAP incorporation can yield up to 34 % cost savings compared with conventional HMA mixtures [46]. These savings result from reductions in virgin aggregate and binder consumption, lower transportation requirements, and decreased landfill disposal fees. The economic advantages are particularly pronounced in large-scale paving and rehabilitation projects, where material volumes and associated costs are substantial.
Mechanically, the integration of RAP into asphalt mixtures significantly influences the structural behaviour of the resulting pavement. As shown in Figure 5, recent research by Ma et al. demonstrated that incorporating RAP in the range of 20 %–60 %, particularly when combined with high-modulus agents, leads to a substantial enhancement in the dynamic modulus and rutting resistance, which are critical parameters for performance under traffic loading [47]. However, the presence of aged binder in RAP can increase its stiffness, potentially reducing its resistance to thermal and fatigue cracking. These adverse effects can be mitigated via the use of a higher binder content and appropriate additives in these high-modulus mixes by improving moisture resistance and extending service life.

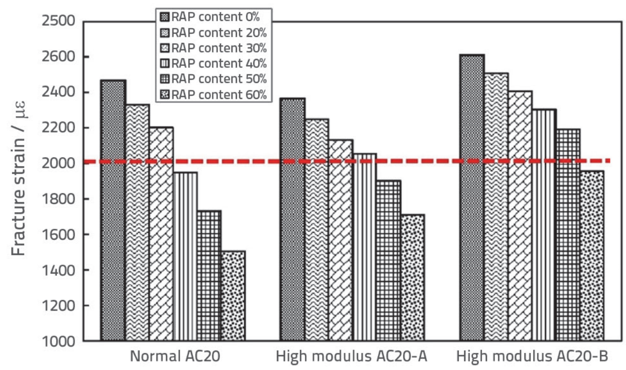

Figure 5. Test results for thermal cracking resistance evaluation [47]

Furthermore, Issmael et al. investigated cold recycled mixtures with RAP contents as high as 90 %, revealing minimal negative impacts on mechanical properties, such as strength and durability, while maintaining substantial environmental and economic gains [48]. This finding underscores the flexibility and robustness of RAP as a material that can be effectively tailored to suit various recycling technologies and performance requirements.
Collectively, these findings validates that RAP not only contributes to the reduction of environmental burden and construction costs but also offers considerable potential for engineering applications when its mechanical behaviour is properly incorporated in the mix design.

3.3. Crumb rubber

Crumb rubber, a recycled material obtained from ground scrap tires, has garnered increasing attention in pavement engineering owing to its potential to improve asphalt mixture performance while addressing the environmental challenges posed by endof-life tires [49]. Typically, crumb rubber is incorporated into asphalt binders via either wet or dry processes and is primarily applied to the surface and base course layers of flexible pavements. It is particularly effective in HMA, where it enhances mechanical properties, prolongs service life, and reduces noise emissions, making it particularly suitable for urban roadways and high-traffic pavements.

From an environmental perspective, the utilisation of crumb rubber contributes to waste tire management by diverting a substantial volume of nonbiodegradable material from landfills and incineration. Moreover, rubberised asphalt mixtures exhibit longer service lives and reduced maintenance requirements, leading to indirect reductions in the life-cycle energy consumption and greenhouse gas emissions [50, 51]. This approach aligns with circular economy principles and provides a means to reduce dependence on virgin polymer modifiers. Economic advantages have also been reported; extended pavement longevity and lower maintenance frequencies can yield long-term cost savings despite the higher initial production costs associated with rubber modification [52].

Numerous studies have investigated the mechanical behaviour of crumb rubber-modified asphalt (CRMA). Liang et al. [53] examined the effects of various activation treatments (high temperature, pre-swelling, and microwave irradiation) on the CRMA performance. Their results demonstrated significant improvements in viscosity, high-temperature stability, and rutting resistance. The treated rubber enhanced the dynamic stability of the asphalt mixtures and improved the compatibility between the rubber and asphalt binder, as validated by the more homogeneous microstructures observed via microscopic analysis. These enhancements are critical for resisting deformation under heavy traffic and elevated temperatures.

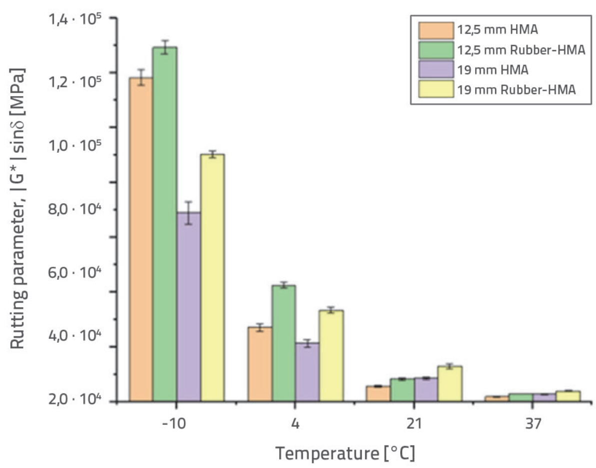

Figure 6. Rutting parameter (|G*|/sinδ) at 10 Hz of various types of HMA [54]

Further investigation by You et al. [54] revealed that dry-processed rubberised mixtures significantly outperformed conventional HMA. As shown in Figure 6, the rubberised mixtures exhibited 29–50 % higher fracture energy and up to 19 % improvement in the dynamic modulus, resulting in superior resistance to cracking and rutting across a range of temperatures. In addition to mechanical performance, rubberised mixtures demonstrated a 2–3 dB reduction in noise levels under vehicular traffic, suggesting ancillary benefits in urban environments. Mechanistic-empirical pavement design simulations indicated improved long-term performance indicators, including a reduced international roughness index (IRI), rutting, and fatigue cracking.

Life-cycle assessments have further validated the sustainability potential of CRMA. Riekstins et al. [55] concluded that for crumb rubber pavements to achieve superior environmental outcomes over traditional asphalt types, they must offer a service life extension of 2–4 years per cycle. Similarly, Xiao et al. [56] highlighted the long-term energy savings and emissions benefits of using crumb rubber, particularly when combined with warm mix asphalt technology. Although rubberised asphalt production may initially require higher mixing temperatures, the reduction in fuel consumption and emissions during maintenance compensates for this energy input [57-60].

Overall, the incorporation of crumb rubber in asphalt mixtures presents a viable strategy for improving mechanical performance, reducing environmental burden, and enhancing economic efficiency. Nevertheless, further research is warranted to optimise rubber-asphalt interactions, mitigate high processing costs, and validate long-term field performance under diverse climatic and traffic conditions.

3.4. Recycled plastics

Recycled plastics are polymeric materials recovered from post-consumer or post-industrial waste streams and repurposed for pavement construction. The incorporation of recycled plastics into asphalt mixtures represents a promising advancement toward sustainable infrastructure, addressing both the surging global plastic waste crisis and the increasing demand for performance-enhancing materials in road construction. The ESEM micrographs in Figure 7 illustrate the morphological differences between the asphalt mixtures modified with various plastics, such as polypropylene (PP), PS, HDPE, and LDPE, highlighting their influence on the homogeneity and texture of the asphalt matrix [61]. These materials are primarily used in the surface and base courses of flexible pavements and are introduced either as asphalt binder modifiers or aggregate substitutes [62-64].

Recycled plastic integration can be achieved via two primary processes [65]. The wet process involves melting plastics and blending them with bitumen at high temperatures to create a modified binder before mixing with the aggregate. This requires specific equipment to handle and mix the materials properly. By contrast, the dry process directly adds recycled plastics to the asphalt mix as modifiers or substitutes for aggregates. This approach is particularly energy efficient and can be employed with various types of plastics to enhance the physical properties of the final product. Although the wet process is suitable for plastics with lower melting points, such as polyethylene, the dry process can accommodate materials with higher melting points, such as polyethylene terephthalate (PET) and polystyrene (PS). These processes not only reflect a commitment to sustainability but also indicate an innovative step in the materials engineering domain, highlighting the versatility and adaptability of recycled plastics when applied in pavement construction.

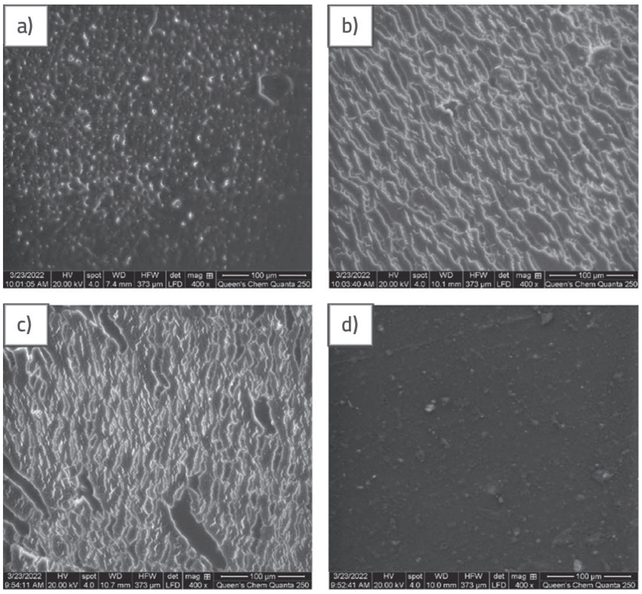

Figure 7. ESEM picture of the four plastic modified asphalts: a) 5 % PP; b) 5 % PS; c) 5 % HDPE; d) 5 % LDPE [61]

In terms of mechanical performance, numerous studies have demonstrated that plastic-modified asphalt exhibits enhanced durability, flexibility, and resistance to deformation [66]. For example, Sabina et al. conducted a comparative evaluation of bituminous concrete mixes modified with 8 % and 15 % waste PP by weight of bitumen and reported significant improvements in the Marshall stability, indirect tensile strength, and rutting resistance relative to conventional mixes. These enhancements were primarily attributed to enhanced adhesion between the PP-coated aggregates and bitumen, which improved the overall strength, durability, and moisture resistance [67]. More broadly, the inclusion of plastics in asphalt mixtures increases flexibility, thereby mitigating cracking and rutting under repeated traffic loading [68].

Shin et al. [69] evaluated the performance of asphalt mixtures reinforced with different plastic-derived fibres, including PP, polyester (PE), carbon, and nylon. Nylon at a 1.0 % volume fraction was identified as the optimal additive, delivering superior improvements in the tensile strength, moisture resistance, and fatigue life across multiple test conditions. Silva et al. [44] also noted that specific plastics significantly improved the viscosity and stiffness of the binder, particularly at elevated temperatures, contributing to enhanced rutting resistance and structural performance under climatic variations. These improvements are vital for high-performance pavements that are subjected to extreme environmental and traffic conditions.

From environmental and economic perspectives, the use of recycled plastics in pavements offers significant advantages. This practice reduces environmental pollution and promotes resource circulation by diverting plastic waste from landfills for incineration. Furthermore, it enables material savings by partially replacing virgin bitumen or aggregates, resulting in lower production costs and extended pavement service life. Leng et al. [70] conducted a life cycle analysis combining PET-modified asphalt and reclaimed asphalt pavement (RAP) and reported a 26.2 % reduction in the life cycle cost and 29.0 % reduction in greenhouse gas emissions in road rehabilitation projects. These benefits are particularly pronounced in urban areas with limited material supply, underscoring the potential for recycled plastic use in resource-constrained regions.

Despite these promising results, several challenges hinder large-scale implementation. These include the heterogeneity of plastic waste sources, compatibility issues with asphalt binders, and concerns over long-term durability and environmental safety such as potential microplastic release. The absence of standardised testing protocols and design guidelines complicates consistent performance evaluation.

To address these limitations, ongoing research efforts are focused on optimising the plastic type and dosage, enhancing the binder compatibility via pretreatment or chemical additives, and performing field-scale studies to validate laboratory findings. The development of energy-efficient production methods and comprehensive life-cycle assessments is essential for establishing the feasibility and environmental soundness of these systems.

In summary, the use of recycled plastics in asphalt pavements offers substantial environmental and economic benefits while simultaneously improving key performance metrics. Continued investigation of the material behaviour, processing methods, and field validation is critical for unlocking the full potential of recycled plastics in sustainable pavement engineering.

3.5. Steel slag

Steel slag, a byproduct of steel manufacturing processes such as basic oxygen and electric arc furnace operations, has gained traction as a valuable material in pavement construction. Instead of being discarded as industrial waste, steel slag can be repurposed as an aggregate in asphalt mixtures, thereby offering both performance and sustainability benefits. Owing to its high hardness, angularity, and rough surface texture, steel slag aggregate (SSA) is particularly suitable for surface and base courses in flexible pavements where resistance to rutting and mechanical durability are critical [71-73].

Beyond its technical properties, the environmental appeal of SSA lies in its ability to reduce the extraction of natural aggregates and divert substantial volumes of steelmaking byproducts from landfills. This reuse aligns with circular economy principles by lowering the overall carbon footprint of pavement materials while conserving nonrenewable resources. Moreover, the local availability of slag near urban centres and industrial hubs can help minimise transportation emissions and costs, further enhancing its environmental and economic value [74-76].

Several studies have explored the performance of SSA in HMA, consistently demonstrating improved mechanical behaviour [77, 78]. Mixtures incorporating 20–35 % SSA demonstrated higher stiffness, improved resistance to permanent deformation, and extended fatigue life than conventional HMA. These enhancements are primarily attributed to the superior interlocking and load distribution properties provided by the rough and angular surfaces of the SSA. Additionally, its mineral composition contributes to increased moisture resistance, which is essential for long-term pavement performance under wet or freeze–thaw conditions [16].

When used in porous asphalt, the SSA shows promise. Although its use can marginally reduce permeability owing to the dense packing of slag particles, it simultaneously improves rutting resistance and resilient modulus, which are key parameters for high-performance permeable pavements [79]. Asphalt mixtures containing SSA outperformed those with natural aggregates in several mechanical metrics, confirming their suitability for both conventional and specialty pavement applications [80].

Despite these advantages, some challenges must be addressed before SSA can be widely adopted. The presence of unstable components, such as free lime (CaO) and periclase (MgO), in untreated slag can lead to long-term expansion and cracking. Consequently, pretreatment techniques such as weathering, aging, and chemical stabilisation are often necessary to ensure volumetric stability. Furthermore, the chemical and physical variability of slags sourced from different steel plants requires consistent quality control to maintain reliable pavement performance.

To unlock the full potential of SSA in pavement engineering, further research is required to standardise processing methods, evaluate their long-term field behaviour, and explore their performance in combination with other recycled materials. Field trials under various climatic conditions and traffic loads are particularly valuable for validating laboratory findings and building confidence among infrastructure agencies.

In summary, steel slag presents a compelling opportunity to transform industrial waste into high-performance pavement materials. Its beneficial mechanical characteristics coupled with its environmental and economic advantages make it a promising alternative to traditional aggregates, contributing meaningfully to the development of more sustainable and resilient road networks.

3.6. Construction and demolition waste

Construction and demolition waste (CDW) comprises a heterogeneous mixture of materials such as concrete, brick, ceramic, mortar, wood, and asphalt fragments generated from the construction, renovation, and demolition of buildings and infrastructure. When appropriately processed, CDW can be transformed into recycled aggregates (RA), which offers a sustainable alternative to natural aggregates in pavement applications. These recycled aggregates are commonly applied in embankments, subgrades, and increasingly in the base and subbase layers, contributing to the circular economy by diverting waste from landfills and reducing dependence on virgin materials [81-85].

The primary environmental benefit of CDW reuse is the substantial reduction in construction waste disposal and raw material extraction. From an economic perspective, using local recycled aggregates can decrease material costs and transportation requirements, particularly in urban areas facing resource scarcity. However, CDW aggregates are often characterised by higher heterogeneity and water absorption than natural aggregates, presenting challenges for consistent mechanical performance.

In 2011, Bernucci developed a laboratory program for evaluating the feasibility of using recycled CDW aggregates in pavement application [86]. Their results indicated that water absorption varied significantly depending on material composition, with highly porous ceramics exhibiting increased absorption. Additionally, the grain shape can be inferred from the composition, with cementitious materials having predominantly cubic grains and less porous ceramics featuring flat grains. In addition, compaction altered the grain size distribution and shape, with increased energy, resulting in greater breakage and a higher percentage of cubic grains. The recycled CDW aggregate showed resilient modulus behaviour similar to that of well-graded crushed stone, with a higher compactive effort reducing the resilient displacement by 10–20 %.

Ossa et al.. conducted a comprehensive evaluation of recycled CDW aggregates in hot asphalt mixtures for urban roads, focusing on environmental sustainability and practical implementation[87]. Series of experimental tests, including evaluations of moisture damage susceptibility and plastic deformation, revealed that up to 20 % CDW aggregates can be incorporated into asphalt mixtures without significantly undermining their structural integrity or performance. These experiments utilised varying percentages of CDW aggregates (10 %–40 %), and the asphalt concrete specimens were assessed under controlled conditions to determine their volumetric properties and resistance to different stressors according to Superpave standards. The particle size distributions of the CDW aggregates, which significantly influence their mechanical behaviour in pavement applications, are illustrated in Figure 8. The figure compares different gradations (CDW1, CDW2, and CDW3) against a reference grading curve (Grading A), highlighting the variability in particle sizes and the need for careful gradation control when incorporating CDW into pavement layers. These results are promising for sustainable construction efforts, underscoring the potential for reducing waste disposal issues and the demand for virgin materials. However, the findings also indicate the necessity for further adjustments or additives when using higher percentages of CDW aggregates, particularly to maintain performance in high-traffic scenarios. This study highlights the importance of refining the use of recycled materials in pavement construction to extend the use of sustainable resources in urban infrastructure.

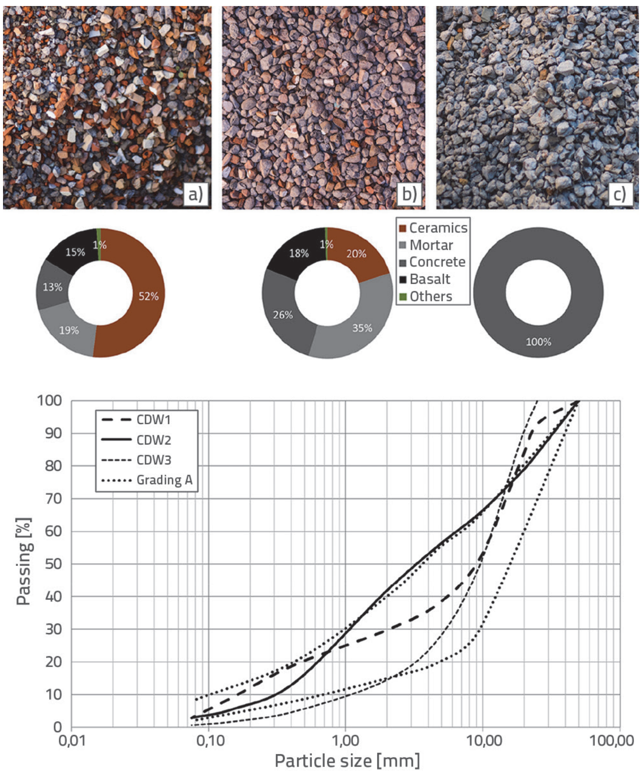

Figure 8. Composition of CDW1, CDW2, and CD3 in conjunction with corresponding grain size distribution curves and "grading A" limits [87]

Despite growing research support, several challenges must be addressed before CDW can be widely adopted as a mainstream pavement material. These include variability in material properties depending on the demolition source, contamination risk, and the need for pretreatment processes such as sorting, crushing, and screening. Furthermore, the lack of uniform technical standards across regions impedes the broader application of CDW-derived aggregates.

Future research must prioritise optimising stabilisation techniques (e.g. cement, fly ash, or polymer additives), evaluating long-term field behaviour under different climatic and traffic conditions, and integrating life-cycle assessment (LCA) tools to quantify environmental and cost savings. Overall, the CDW presents a compelling opportunity to develop more sustainable pavements, provided that its distinctive material characteristics are carefully managed through rigorous design methodologies and construction practices.

4. Discussion

The integration of recycled materials in pavement construction is a critical strategy for advancing sustainable infrastructure. A diverse range of materials, including RCA, RAP, crumb rubber, recycled plastics, steel slag, and CDW, have been investigated for their feasibility in replacing conventional aggregates and binders. These materials offer diverse benefits aligned with circular economy principles; however, each presents unique limitations that must be addressed to support broader implementation.

RCA, which is primarily sourced from demolished concrete, offers significant environmental benefits by diverting construction waste from landfills and reducing reliance on virgin aggregates. Its compatibility with both the bound and unbound pavement layers makes it a versatile material. However, its porous structure and the presence of residual mortar often result in increased water absorption and decreased mechanical strength, limiting its use in high-performance applications, unless appropriate treatments are applied. In addition, the variability in source quality can complicate performance prediction and quality control.

The RAP is among the most direct pathways to resource conservation in asphalt pavement recycling, enabling the reuse of both aggregate and aged binders. This reduces the energy demand and greenhouse gas emissions while offering potential economic advantages. Nevertheless, the aging of bitumen within RAP can lead to increased stiffness and brittleness in recycled mixtures, potentially compromising the fatigue resistance unless modification or rejuvenation strategies are implemented. Furthermore, a lack of consensus on optimal RAP content thresholds for maintaining balanced performance continues to challenge RAP implementation across varying climates and traffic conditions [88].

Crumb rubber, derived from scrap tires, introduces elasticity and damping characteristics that enhance the resistance to rutting and cracking. It also provides noise-reduction benefits and supports waste tire management. Despite these advantages, challenges include higher production temperatures, potential phase separation in wet-process mixtures, and inconsistencies in rubber-asphalt compatibility. These factors can adversely impact the mixture homogeneity and long-term durability if not carefully managed.

Recycled plastics employed in dry or wet processes offer mechanical reinforcement to asphalt mixtures and significantly reduce plastic waste. They can improve the stiffness, deformation resistance, and aging properties of binders. However, concerns remain regarding the compatibility of different plastic types, potential microplastic release, and the long-term recyclability of plastic-modified pavements. In addition, the lack of standardised processing methods and performance criteria hinders consistent implementation.

Steel slag, a by-product of steel manufacturing, exhibits excellent angularity, hardness, and adhesion properties, making it suitable for use in asphalt and concrete pavements. Its high mechanical strength and skid resistance make it ideal for the surface and base layers. However, the volumetric instability caused by free lime or magnesia and potential environmental concerns related to heavy metal leaching require stringent material conditioning and testing protocols.

The CDW aggregates, which are abundant and cost-effective, are often highly heterogeneous. These materials have demonstrated suitability in lower pavement layers (e.g. embankments and subgrades); however, higher structural applications necessitate stabilisation or blending to meet the performance criteria. Durability concerns, inconsistent compositions, and elevated fines content can limit mechanical reliability; however, these can be mitigated through proper processing and mix design.

In summary, although each recycled material presents unique sustainability and engineering advantages, its limitations highlight the need for tailored material selection, processing, and design approaches. A system-level approach that incorporates life cycle performance, environmental impact, economic feasibility, and construction practices is essential for integrating these materials effectively into pavement design and policy frameworks. Future research must prioritise multimaterial synergies, long-term field validation, and standardisation to ensure that sustainability gains are realised without compromising infrastructure performance.

5. Conclusions

This comprehensive review highlights the burgeoning utilisation of various recycled materials in pavement construction, which is a testament to the commitment of the construction industry to sustainability and environmental stewardship. By reevaluating traditional practices and materials, the industry is actively seeking innovative ways to reduce its ecological footprint, while enhancing the functionality and longevity of pavement infrastructure. Recycled materials represent a viable path in the evolution of pavement construction. As the sector advances towards more sustainable practices, these materials stand out as key components in the development of environmentally friendly, economically viable, and technically robust pavements. The synergy between environmental sustainability and engineering innovation continues to drive the industry toward greener solutions, exemplifying the potential of recycled materials to revolutionise pavement construction and contribute to sustainable urban development.

REFERENCES

[1] Lee, J.C., Edil, T.B., Tinjum, J.M., Benson, C.H.: Quantitative assessment of environmental and economic benefits of recycled materials in highway construction, Transp. Res. Rec., (2010), p. 2158., https://doi.org/10.3141/2158-17.

[2] Park, K., Hwang, Y., Seo, S., Seo, H.: Quantitative assessment of environmental impacts on life cycle of highways, J. Constr. Eng. Manag., 129 (2003) 1, https://doi.org/10.1061/(asce)0733-9364(2003)129:1(25).

[3] Santero, N.J., Masanet, E., Horvath, A.: Life-cycle assessment of pavements. Part I: Critical review, 2011., https://doi.org/10.1016/j.resconrec.2011.03.010.

[4] Alaloul, W.S., Altaf, M., Musarat, M.A., Javed, M.F., Mosavi,A.: Systematic review of life cycle assessment and life cycle cost analysis for pavement and a case study, 2021., https://doi.org/10.3390/su13084377.

[5] Velvizhi, G., et al.: Biodegradable and non-biodegradable fraction of municipal solid waste for multifaceted applications through a closed loop integrated refinery platform: Paving a path towards circular economy, Science of the Total Environment, 731 (2020), https://doi.org/10.1016/j.scitotenv.2020.138049.

[6] Salehi, S., Arashpour, M., Kodikara, J., Guppy, R.: Sustainable pavement construction: A systematic literature review of environmental and economic analysis of recycled materials, 2021., https://doi.org/10.1016/j.jclepro.2021.127936.

[7] Raouf Dar, A., Singh, E.S.: Use of recycled materials in pavement construction, IJSDR2008038 International Journal of Scientific Development and Research, 2020.

[8] Al-Mosawe, H., Albayati, A., Wang, Y., Mashaan, N.S.: An Experimental study of granular material using recycled concrete waste for pavement roadbed construction, Buildings, 12 (2022) 11, https://doi.org/10.3390/buildings12111926.

[9] Pereira, P.M., Vieira, C.S.: A literature review on the use of recycled construction and demolition materials in unbound pavement applications, 2022. https://doi.org/10.3390/su142113918.

[10] Xiao, Y., Dong, Q., Chang, X., Cui, P., Liu, G.: Research hotspots and development trends on recycled construction materials in pavement engineering: A bibliometric evaluation, 2021., https://doi.org/10.3390/ma14092170.

[11] Jakhar,A., Meena, R.: Sustainable pavement construction: A Comprehensive review on the use of recycled materials and their impact on performance, Tuijin Jishu/Journal of Propulsion Technology, 44 (2023) 3, https://doi.org/10.52783/tjjpt.v44.i3.2078.

[12] Tam, V.W.Y., Soomro, M., Evangelista, A.C.J.: A review of recycled aggregate in concrete applications (2000 - 2017), Constr. Build. Mater., 172 (2018), https://doi.org/10.1016/j.conbuildmat.2018.03.240.

[13] Bu, C., et al.: The durability of recycled fine aggregate concrete: A Review, 2022., https://doi.org/10.3390/ma15031110.

[14] Ouyang, K., et al.: Influence of pre-treatment methods for recycled concrete aggregate on the performance of recycled concrete: A review, 2023., https://doi.org/10.1016/j.resconrec.2022.106717.

[15] Geçkil, T., Tanyıldızı, M.M., İnce, C.B., Investigation of Use potential of fiber added concretes as road pavement on weak soils, Građevinar, 75 (2023) 7, pp. 665–678

[16] Neves, J., Crucho, J.: Performance evaluation of steel slag asphalt mixtures for sustainable road pavement rehabilitation, Applied Sciences (Switzerland), 13 (2023) 9, https://doi.org/10.3390/app13095716.

[17] Danish, A., Mosaberpanah, M.A.: A review on recycled concrete aggregates (RCA) characteristics to promote RCA utilization in developing sustainable recycled aggregate concrete (RAC), 2022. https://doi.org/10.1080/19648189.2021.1946721.

[18] Behera, M., Bhattacharyya, S.K., Minocha, A.K., Deoliya, R., Maiti, S.: Recycled aggregate from C&D waste & its use in concrete - A breakthrough towards sustainability in construction sector: A review, 2014., https://doi.org/10.1016/j.conbuildmat.2014.07.003.

[19] Strieder, H.L., Dutra, V.F.P., Graeff, Â.G., Núñez, W.P., Merten, F.R.M.: Performance evaluation of pervious concrete pavements with recycled concrete aggregate, Constr. Build. Mater., 315 (2022), https://doi.org/10.1016/j.conbuildmat.2021.125384.

[20] Fanijo, E.O., Kolawole, J.T., Babafemi, A.J., Liu, J.: A comprehensive review on the use of recycled concrete aggregate for pavement construction: Properties, performance, and sustainability, 2023., https://doi.org/10.1016/j.clema.2023.100199.

[21] Shi, C., Li, Y., Zhang, J., Li, W., Chong, L., Xie, Z.: Performance enhancement of recycled concrete aggregate - A review, 2016., https://doi.org/10.1016/j.jclepro.2015.08.057.

[22] Mills-Beale, J., You, Z.: The mechanical properties of asphalt mixtures with recycled concrete aggregates, Constr. Build. Mater., 24 (2010) 3, https://doi.org/10.1016/j.conbuildmat.2009.08.046.

[23] Zheng, Y., Zhang, Y., Zhang, P.: Methods for improving the durability of recycled aggregate concrete: A review, 2021., https://doi.org/10.1016/j.jmrt.2021.11.085.

[24] Katz, A.: Treatments for the improvement of recycled aggregate, Journal of Materials in Civil Engineering, 16 (2024) 6, pp. 597–603, https://doi.org/10.1061/(ASCE)0899-1561(2004)16:6(597).

[25] Tam, V.W.Y., Tam, C.M., Le, K.N.: Removal of cement mortar remains from recycled aggregate using pre-soaking approaches, Resour. Conserv. Recycl., 50 (2007) 1, pp. 82–101, https://doi.org/10.1016/J.RESCONREC.2006.05.012.

[26] Kou, S.C., Poon, C.S.: Properties of concrete prepared with PVA-impregnated recycled concrete aggregates, Cem. Concr. Compos., 32 (2010) 8, https://doi.org/10.1016/j.cemconcomp.2010.05.003.

[27] Kong, D., Lei, T., Zheng, J., Ma, C., Jiang, J., Jiang, J.: Effect and mechanism of surface-coating pozzalanics materials around aggregate on properties and ITZ microstructure of recycled aggregate concrete, Constr. Build. Mater., 24 (2010) 5, https://doi.org/10.1016/j.conbuildmat.2009.10.038.

[28] Shaban, W.M., et al.: Properties of recycled concrete aggregates strengthened by different types of pozzolan slurry, Constr. Build. Mater., 216 (2019), https://doi.org/10.1016/j.conbuildmat.2019.04.231.

[29] Wu, C.R., Zhu, Y.G., Zhang, X.T., Kou, S.C.: Improving the properties of recycled concrete aggregate with bio-deposition approach, Cem. Concr. Compos., 94 (2018), https://doi.org/10.1016/j.cemconcomp.2018.09.012.

[30] Thomas, C., Setién, J., Polanco, J.A., Alaejos, P., Sánchez De Juan, M.: Durability of recycled aggregate concrete, Constr. Build. Mater., 40 (2013), https://doi.org/10.1016/j.conbuildmat.2012.11.106.

[31] Khaoula, N., Bouyahyaoui, A., Cherradi, T.: Durability of recycled aggregate concrete, Advances in Science, Technology and Engineering Systems, 6 (2021) 1, https://doi.org/10.25046/aj060180.

[32] Guo, H., et al.: Durability of recycled aggregate concrete - A review, Cem. Concr. Compos., 89 (2018), https://doi.org/10.1016/j.cemconcomp.2018.03.008.

[33] Xuan, D., Zhan, B., Poon, C.S.: Durability of recycled aggregate concrete prepared with carbonated recycled concrete aggregates, Cem. Concr. Compos., 84 (2017), https://doi.org/10.1016/j.cemconcomp.2017.09.015.

[34] Sagheer, A.M., Tabsh, S.W.: Shear Strength of concrete beams without stirrups made with recycled coarse aggregate, Buildings, 13 (2023) 1, https://doi.org/10.3390/buildings13010075.

[35] Lei, B., Yu, L., Chen Z., Yang, W., Deng, C., Tang, Z.: Carbon emission evaluation of recycled fine aggregate concrete based on life cycle assessment, Sustainability (Switzerland), 14 (2022), p. 21, https://doi.org/10.3390/su142114448.

[36] Raza, S.S., Fahad, M., Ali, B., Amir, M.T., Alashker, Y., Elhag, A.B.: Enhancing the performance of recycled aggregate concrete using micro-carbon fiber and secondary binding material, Sustainability (Switzerland), 14 (2022), pp. 21, https://doi.org/10.3390/su142114613.

[37] Ashraf, M.J., Idrees, M., Akbar, A.: Performance of silica fume slurry treated recycled aggregate concrete reinforced with carbon fibers, Journal of Building Engineering, 66 (2023), https://doi.org/10.1016/j.jobe.2023.105892.

[38] Stojanovic, M., Radonjanin, V., Malesev, M., Milovic, T., Furgan, S.: Compressive strength of cement stabilizations containing recycled and waste materials, Građevinar, 73 (2021) 8, https://doi.org/10.14256/JCE.3161.2021.

[39] Feng, D., Cao, J., Gao, L., Yi, J.: Recent developments in asphalt-aggregate separation technology for reclaimed asphalt pavement, 2022., https://doi.org/10.1016/j.jreng.2022.07.002.

[40] Mariyappan, R., Palammal, J.S., Balu, S.: Sustainable use of reclaimed asphalt pavement (RAP) in pavement applications-a review, 2023., https://doi.org/10.1007/s11356-023-25847-3.

[41] Jahanbakhsh, H., Karimi, M.M., Naseri, H., Nejad, F.M.: Sustainable asphalt concrete containing high reclaimed asphalt pavements and recycling agents: Performance assessment, cost analysis, and environmental impact, J. Clean. Prod., 244 (2020), https://doi.org/10.1016/j.jclepro.2019.118837.

[42] Karthikeyan, K., Kothandaraman, S., Sarang, G.: Perspectives on the utilization of reclaimed asphalt pavement in concrete pavement construction: A critical review, Case Studies in Construction Materials, 19 (2023), https://doi.org/10.1016/j.cscm.2023.e02242.

[43] Zaumanis, M., Mallick, R.B., Poulikakos, L., Frank, R.: Influence of six rejuvenators on the performance properties of Reclaimed Asphalt Pavement (RAP) binder and 100 % recycled asphalt mixtures, Comput. Chem. Eng., 71 (2014), https://doi.org/10.1016/j.conbuildmat.2014.08.073.

[44] Gouveia, B.G., Donato, M., da Silva, M.A.V.: Life cycle assessment in road pavement infrastructures: A Review, Civil Engineering Journal (Iran), 8 (2022) 6, https://doi.org/10.28991/CEJ-2022-08-06-015.

[45] Peng, B., Cai, C., Yin, G., Li, W., Zhan, Y.: Evaluation system for CO2 emission of hot asphalt mixture, Journal of Traffic and Transportation Engineering (English Edition), 2 (2015) 2, https://doi.org/10.1016/j.jtte.2015.02.005.

[46] FHWA: Reclaimed asphalt pavement in asphalt mixtures: State of the practice, Report No. FHWA-HRT-11-021, 2011.

[47] Ma, T., Ding, X., Zhang, D., Huang, X., Chen, J.: Experimental study of recycled asphalt concrete modified by high-modulus agent, Constr. Build. Mater., 128 (2016), https://doi.org/10.1016/j.conbuildmat.2016.10.078.

[48] Al-Jumaili, M.A., Issmael, O.D.: Cold asphalt mixtures with high reclaimed pavement material percentages response to local traffic loading and environmental conditions, IOP Conference Series: Materials Science and Engineering, 2018., https://doi.org/10.1088/1757-899X/433/1/012013.

[49] Li, J., Saberian, M., Nguyen, B.T.: Effect of crumb rubber on the mechanical properties of crushed recycled pavement materials, J. Environ. Manage., 218 (2018), https://doi.org/10.1016/j.jenvman.2018.04.062.

[50] Liang, M., et al.: The effects of activation treatments for crumb rubber on the compatibility and mechanical performance of modified asphalt binder and mixture by the dry method, Front. Mater., 9 (2022), https://doi.org/10.3389/fmats.2022.845718.

[51] Shu, X., Huang, B.: Recycling of waste tire rubber in asphalt and portland cement concrete: An overview, Constr. Build.Mater.- PART B, 67 (2014), https://doi.org/10.1016/j.conbuildmat.2013.11.027.

[52] Lo Presti, D.: Recycled tyre rubber modified bitumens for road asphalt mixtures: A literature review, 2013., https://doi.org/10.1016/j.conbuildmat.2013.09.007.

[53] Liang, M., et al.: Microscopic analysis of activated crumb rubber and its effect on mechanical performance of asphalt mixtures using dry process, Journal of Materials in Civil Engineering, 35 (2023) 12, https://doi.org/10.1061/jmcee7.mteng-15081.

[54] Jin, D., Ge, D., Wang, J., Malburg, L., You, Z.: Reconstruction of asphalt pavements with crumb rubber modified asphalt mixture in cold region: Material characterization, construction, and performance, Materials, 16 (2023) 5, https://doi.org/10.3390/ma16051874.

[55] Riekstins, A., Haritonovs, V., Straupe, V.: Economic and environmental analysis of crumb rubber modified asphalt, Constr. Build. Mater., 335 (2022), https://doi.org/10.1016/j.conbuildmat.2022.127468.

[56] Wang, T., Xiao, F., Zhu, X., Huang, B., Wang, J., Amirkhanian, S.: Energy consumption and environmental impact of rubberized asphalt pavement, 2018., https://doi.org/10.1016/j.jclepro.2018.01.086.

[57] Mavridou, S., Kehagia, F.: Environmental noise performance of rubberized asphalt mixtures: Lamia's case study, Procedia Environ. Sci., 38 (2017), https://doi.org/10.1016/j.proenv.2017.03.165.

[59] Tehrani, F.M.: Noise abatement of rubberized hot mix asphalt: A brief review, International Journal of Pavement Research and Technology, 8 (2015) 1, https://doi.org/10.6135/ijprt.org.tw/2015.8(1).58.

[59] Wang, T., Lee, I.S., Kendall, A., Harvey, J., Lee, E.B., Kim, C.: Life cycle energy consumption and GHG emission from pavement rehabilitation with different rolling resistance, J. Clean. Prod., 33 (2012), https://doi.org/10.1016/j.jclepro.2012.05.001.

[60] Wang, T., Xiao, F., Amirkhanian, S., Huang, W., Zheng, M.: A review on low temperature performances of rubberized asphalt materials, 2017., https://doi.org/10.1016/j.conbuildmat.2017.04.031.

[61] Ma, J., Nawarathna, H.M.C., Hesp, S.A.M.: On the sustainable use of recycled plastics in flexible asphalt pavements, J. Clean. Prod., 359 (2022), https://doi.org/10.1016/j.jclepro.2022.132081.

[62] Hao, G., He, M., Lim, S.M., Ong, G.P., Zulkati, A., Kapilan, S.: Recycling of plastic waste in porous asphalt pavement: Engineering, environmental, and economic implications, J. Clean. Prod., 440 (2024), https://doi.org/10.1016/j.jclepro.2024.140865.

[63] Ma, Y., et al.: The utilization of waste plastics in asphalt pavements: A review, 2021. https://doi.org/10.1016/j.clema.2021.100031.

[64] You, L., et al.: Review of recycling waste plastics in asphalt paving materials, 2022., https://doi.org/10.1016/j.jtte.2022.07.002.

[65] Daniel, G.: Assessing the impact of the incorporation of aramid and polyolefin to hot and warm asphaltic mixture using dry and wet process: A Review, IOP Conference Series: Materials Science and Engineering, 2020. https://doi.org/10.1088/1757-899X/930/1/012062.

[66] Pacheco-Torgal, F., Khatib, J., Colangelo, F., Tuladhar, R.: Use of recycled plastics in eco-efficient concrete, 2018., https://doi.org/10.1016/B978-0-08-102676-2.01001-X.

[67] Sabina, T., Khan, A., Sangita, D., Sharma, K., Sharma, B.M.: Performance evaluation of waste plastic/polymer modified bituminous concrete mixes, J. Sci. Ind. Res., (India),68 (2009) 11, 2009.

[68] White, G.: A synthesis on the effects of two commercial recycled plastics on the properties of bitumen and asphalt, Sustainability (Switzerland), 12 (2020) 20, 2020, https://doi.org/10.3390/su12208594.

[69] Kim, M.J., Kim, S., Yoo, D.Y., Shin, H.O.: Enhancing mechanical properties of asphalt concrete using synthetic fibers, Constr. Build.Mater., 178 (2018), https://doi.org/10.1016/j.conbuildmat.2018.05.070.

[70] Yao, L., Leng, Z., Lan, J., Chen, R., Jiang, J.: Environmental and economic assessment of collective recycling waste plastic and reclaimed asphalt pavement into pavement construction: A case study in Hong Kong, J. Clean. Prod., 336 (2022), https://doi.org/10.1016/j.jclepro.2022.130405.

[71] Es-Samlali, L., El Haloui, Y., Amrani, M., Oudrhiri-Hassani, F., Tlidi, A., Bekri, A.: Potential valorisation of steel slag waste as an alternative material for pavement layers, Građevinar, 75 (2023) 2, 2023, https://doi.org/10.14256/JCE.3571.2022.

[72] Pasetto, M., Baliello, A., Giacomello, G., Pasquini, E.: The use of steel slags in asphalt pavements: A State-of-the-Art Review, 2023. https://doi.org/10.3390/su15118817.

[73] Liu, J., et al.: Towards the sustainable utilization of steel slag in asphalt pavements: A case study of moisture resistance and life cycle assessment, Case Studies in Construction Materials, 18 (2023), https://doi.org/10.1016/j.cscm.2022.e01722.

[74] Bonoli, A., Degli Esposti, A., Magrini, C.: A case study of industrial symbiosis to reduce GHG Emissions: Performance analysis and LCA of asphalt concretes made with RAP aggregates and steel slags, Front. Mater., 7 (2020), https://doi.org/10.3389/fmats.2020.572955.

[75] Li, J., Xiao, F., Zhang, L., Amirkhanian, S.N.: Life cycle assessment and life cycle cost analysis of recycled solid waste materials in highway pavement: A review, 2019., https://doi.org/10.1016/j.jclepro.2019.06.061.

[76] Geçkil, T., Tanyıldızı, M.M., İnce, C.B.: Benefit - cost relationship of using concrete with blast furnace slag as road pavement, Građevinar, 75 (2023) 1, https://doi.org/10.14256/JCE.3570.2022.

[77] Ozcanan, S., Firat, T., Ozcan, O.: Investigating the use of concrete and RCC instead of HMA in highway pavement in hot regions, Građevinar, 76 (2024), pp. 813–827, https://doi.org/10.14256/JCE.4024.2024

[78] Chen, X., Wang, L.: Temperature-water - load coupling study on stress characteristics of BFRP–CRCP pavement, Građevinar, 76 (2024) 3, pp. 247 - 256, https://doi.org/10.14256/JCE.3547.2022

[79] Loureiro, C.D.A., Moura, C.F.N., Rodrigues, M., Martinho, F.C.G., Silva, H.M.R.D., Oliveira, J.R.M.: Steel slag and recycled concrete aggregates: Replacing quarries to supply sustainable materials for the asphalt paving industry, 2022., https://doi.org/10.3390/su14095022.

[80] Dondi, G., Mazzotta, F., Lantieri, C., Cuppi, F., Vignali, V., Sangiovanni, C.: Use of steel slag as an alternative to aggregate and filler in road pavements, Materials, 14 (2021) 2, https://doi.org/10.3390/ma14020345.

[81] Barroqueiro, T., da Silva, P.R., de Brito, J.: High-performance self-compacting concrete with recycled aggregates from the precast industry: Durability assessment, Buildings, 10 (2020) 6, https://doi.org/10.3390/BUILDINGS10060113.

[82] Vieira, T., Alves, A., de Brito, J., Correia, J.R., Silva, R.V.: Durability-related performance of concrete containing fine recycled aggregates from crushed bricks and sanitary ware, Mater. Des., 90 (2016), https://doi.org/10.1016/j.matdes.2015.11.023.

[83] Alexandridou, C., Angelopoulos, G.N., Coutelieris, F.A.: Mechanical and durability performance of concrete produced with recycled aggregates from Greek construction and demolition waste plants, J.Clean. Prod., 176 (2018), https://doi.org/10.1016/j.jclepro.2017.12.081.

[84] Bravo, M., De Brito, J., Pontes, J., Evangelista, L.: Durability performance of concrete with recycled aggregates from construction and demolition waste plants, Constr. Build. Mater., 77 (2015), https://doi.org/10.1016/j.conbuildmat.2014.12.103.

[85] Dimter, S., Kuburić, G., Ević, E., Vrhovac, G.: Road building using wood ash, Građevinar, 76 (2024) 12, pp. 1077–1086, https://doi.org/10.14256/JCE.4157.2024

[86] Leite, F.D.C., Motta, R.D.S., Vasconcelos, K.L., Bernucci, L.: Laboratory evaluation of recycled construction and demolition waste for pavements, Constr. Build. Mater., 25 (2011) 6, https://doi.org/10.1016/j.conbuildmat.2010.11.105.

[87] Ossa, A., García, J.L., Botero, E.: Use of recycled construction and demolition waste (CDW) aggregates: A sustainable alternative for the pavement construction industry, J. Clean. Prod., 135 (2016) 11, pp. 379–386, https://doi.org/10.1016/J.JCLEPRO.2016.06.088.

[88] Yaro, N.S.A., et al.: A comprehensive overview of the utilization of recycled waste materials and technologies in asphalt pavements: Towards environmental and sustainable low-carbon roads, 2023., https://doi.org/10.3390/pr11072095.