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RECYCLABILITY AND ENVIRONMENTAL IMPACT OF TYPICAL SOLID WASTE MATERIALS (RUBBER, RAP, SS) IN ASPHALT MIXTURES: A STATE-OF-THE-ART REVIEW

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Abstract. The utilization of solid waste material (SWM) in sustainable asphalt pavement is one of the key paths to achieving carbon peaking and neutrality. It is imperative to seek a balance between service performance and environmental impacts of sustainable asphalt pavement. This paper makes a state-of-the-art review on recyclability and life cycle assessment of SWM in sustainable asphalt pavements based on recent five-year literatures. According to scientometric analysis results, three typical SWM, crumb rubber (CR), reclaimed asphalt pavement (RAP) and steel slag (SS), are selected to be mainly discussed over the service performance and environmental impacts via life cycle assessment. Especially, influences of material properties or production design of SWM are critically highlighted, including the CR particle size and treatment methods, strategies of RAP to mitigate performance deterioration, and enhancement mechanisms of SS in asphalt mixtures. Further, the current major research gaps and application limitations associated with SWM utilization are concluded, including the trade-offs between the environmental impacts of CR production and the service performances, the uncertainties in binder blending and rejuvenation efficiency of RAP, and the volume expansion and heavy metal leaching of SS asphalt mixtures.

Keywords: solid waste material, rubber, RAP, steel slag, asphalt pavement, life cycle assessment.

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1. Introduction

Since the Paris Agreement, the target of global average temperature rise was set to be below 2 °C relative to the pre-industrial levels, and the absolute carbon emissions must be reduced by between 40% and 70% by 2050 compared to the 2010 levels and to achieve a net zero emissions of CO2 and other greenhouse gases (GHGs) before 2100 (United Nations Framework Convention on Climate Change [UNFCCC], 2015). However, the situation of global carbon emission control is not as effective as expected. It is reported that only 35% of sustainable development goals (SDGs) were achieved as scheduled, while nearly half of SDGs were falling behind and 18% of SDGs were even regressed (Sachs et al., 2025). The United Nation Environment Programme [UNEP] has warned that the target set by the Paris Agreement would fail if the carbon emission by 2030 is failed to be reduced by 42% (for the 1.5 °C target) and 28% (for the 2 °C target) compared to carbon emissions in 2019 (UNEP, 2024). To urgently chase the SDGs, some major productive countries like China have proposed their own proactive strategies and measures for carbon peaking and carbon neutrality. It is reported that material production is responsible for about 23% of the total GHG emissions, predominantly by construction materials (International Resource Panel, 2020). Therefore, recycling materials such as end-of-life tire rubbers or reclaimed asphalt pavement (RAP) as much as possible in engineering constructions is one of the key paths to achieving carbon peaking and carbon neutrality. Solid waste materials (SWM) is one of major recyclable materials in construction engineering, in which industrial SWM takes proportion of 83.34%, while municipal and agricultural SWM took proportions of 9.9% and 6.27%, respectively (Kanwal et al., 2021).

Asphalt pavement is the core components of modern transportation infrastructure system, which demands significant amounts of construction materials including natural aggregates and asphalt. The construction, maintenance and operation of traditional pavements could, however, lead to substantial environmental consequences (Garraín & Lechón, 2019). Hence, the recyclability of SWM, especially industrial SWM in asphalt pavement engineering can not only reduce the natural resource consumption but also significantly reduce the environmental impact. With decades of technological development, some major SWM have been utilized as replacements or additives in sustainable asphalt pavement, and the service performances of sustainable asphalt pavement were enhanced. For example, as products from end-of-life tyres, crumb rubber (CR) were found to be positive on improving the rheological performances (Ren et al., 2021; Zhou et al., 2024), storage ability (Lei et al., 2021; Guo et al., 2024a), cracking resistance (Qian et al., 2020), fatigue resistance (Jamal et al., 2021), and low- and high-temperature performances (Liu et al., 2021b). Steel slag (SS), a by-product derived from the steelmaking industry, is utilized as aggregates in asphalt mixtures. Experimental assessments proved that steel slag asphalt mixture (SSAM) exhibited improvement in permanent deformation resistance (Chen & Wei, 2016; Kim et al., 2018), skid resistance (Cui et al., 2023; Yang et al., 2022a), as well as thermal performance (Cui et al., 2021b; He et al., 2024). RAP is another typical SWM from urbanization. Experimental investigations demonstrated the RAP modified asphalt mixtures could have equivalent or better performances including fatigue performances (Riccardi et al., 2016), moisture resistance (Abdel-Jaber et al., 2022), and rutting resistance (Jahanbakhsh et al., 2020). Although there have been plenty of literatures investigating the performance improvements of SWM asphalt mixtures, the service performance of SWM asphalt mixtures is sensitive to multiple factors such as material properties, treatment methods, production design and parameters, and storage conditions. The efficiency of SWM utilization in sustainable asphalt pavement still needs to be improved to seek the optimal performance.

Environmental impact is another important issue in the performance assessment of SWM asphalt pavement, which is mostly quantitatively evaluated by life cycle assessment (LCA) theory on whole material life from material production, construction to maintenance (Anastasiou et al., 2015; Fanijo et al., 2023). For utilization of SWM, a balance must be sought between the service performances and environmental impacts of asphalt mixtures. Despite significant research attempts have been made in this area, there still exists some research gaps in balancing the service performance and environmental impacts of SWM. Therefore, it is imperative that both the material properties of SWMs and the production design are carefully chosen for the optimal design of SWM asphalt pavements.

This paper provides a state-of-the-art review about recycling SWM in sustainable asphalt mixtures and the environmental impact assessment, starting with a scientometric approach focusing on the quantitative study of high-quality articles, producing more objective and unbiased results and discovering systematic literature-related findings. Three typical SWM (CR, RAP, and SS) in recent five-year literatures (2020–2025) are discussed in terms of service performances and environmental impacts, which is selected based on the scientometric analysis results. The effects of material properties and content of SWMs on the physical, mechanical, microstructure, and durability performance of asphalt pavements are discussed in detail. Additionally, the review highlights the environmental impacts of recycling SWMs in concrete pavements.

2. Methodological approach and scientometric analysis

To achieve the objectives of this state-of-the-art review, searching engine from the database of Web of Science Core Collection was utilized. The acquired literature records were thoroughly assessed and scientometric analysis was conducted in VOSviewer (version 1.6.20). A scientometric analysis is necessary for obtaining more objective and unbiased results than subjective analysis in comprehensive bodies of literature, immune to the influences of individual perspectives. The scientometric analysis from VOSviewer includes the network visualization map, overlay visualization map, and density visualization map, which can reflect the occurrence and distribution, the evolution over period, and the weight of selected topics, respectively. The selected topics come from the literature information, covering the keywords, co-authorships, publications, affiliations and countries. With these scientometric analyses, it holds potential to discover the literature-related research hotspots and prospectives that may have been overseen in manual review methods.

To investigate the research hotspots in solid wasted material modified asphalt pavement in recent years, a preliminary search was conducted with keywords *SOLID WASTE* and *ASPHALT* over the past ten years (publication year between 2015–2025). With this searching condition, 467 documents were acquired from Web of Science Core Collection and imported into VOSviewer for scientometric analysis.

2.1. Co-occurrence analysis of SWMs in sustainable asphalt pavements

The SWMs can be obtained from keywords. Keywords is one of the major indexes of publications in database and can significantly reflect the research topics and themes. With importing the acquired documents from preliminary search into VOSviewer, the keywords could be retrieved automatically. Data screening was applied by combining similar keywords such as "rubber", "waste tyre", and "crumb rubber". It should be noted that the only the keywords within the category of SWMs and the least occurrence number of 10 were selected.

Figures 1a–1c illustrate the network visualization, overlay visualization, and density visualization of the co-occurring keywords, respectively. Network visualization (Figure 1a) focuses more on the weights and relatedness among the items. Larger label and larger circle denoted higher weight of the item. Smaller distance denoted stronger relations. The colour of items indicates the cluster that items belong to. Overlay visualization (Figure 1b) indicates the research impact of items varying with time. According to the spectrum in overlay visualization, the colour indicates the corresponding average time of occurrence of the keywords. Item density visualization (Figure 1c) is similar to network visualization. The rainbow colour around the item indicated the weight of item, while the distance between items indicated the relation between the items.

It could be concluded from Figure 1a that rubber, fly ash, SS, RAP, PET, municipal solid-waste, and red mud are the major keywords that meet the selected threshold, indicating that above materials are the major SWMs in asphalt modification. The size of the nodes indicated *rubber*, *fly ash*, and *steel slag* were the top research hotspots. The overlay visualization in Figure 1b indicated that the research interests in asphalt modification mainly transferred from *rubber* and *fly ash* to *RAP* and *PET*, while *steel slag* seems to be the newest one. Density visualization in Figure 1c offered a more direct illustration about the weights of above keywords.

However, it should be noted that the preliminary searching condition (*SOLID WASTE* and *ASPHALT*) may not fully reflect the literature of all SWMs employed in asphalt modifications, because i) a considerable number of publications may not include the keyword *SOLID WASTE*; ii) municipal solid-waste is a collection of several different waste materials, and their keywords may not include *SOLID WASTE* as well. Hence, based on the output of preliminary search as shown in Figure 1, another round of searching with several types of SWMs combined with *ASPHALT* was conducted. According to the literature, municipal sol-

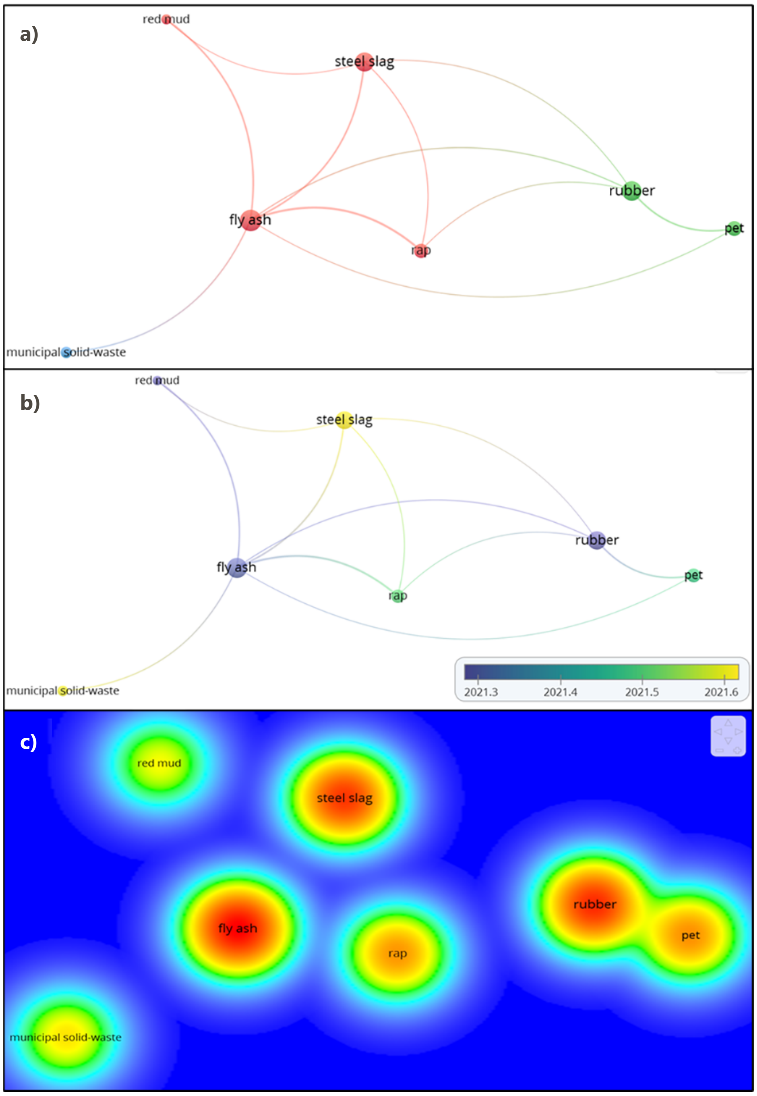


Figure 1. Mapping of scientometric analysis of SWMs in sustainable asphalt pavements: a – Network visualization; b – Overlay visualization; c – Item density visualization

id-waste materials covered recycled materials from urban life and constructions such as brick, ceramic, used medical mask, polyurethane, and RCA. The number of publications regarding to above SWMs is summarized in Figure 2. It is indicated that rubber, RAP, and SS are the three most employed waste materials in asphalt modification, and the number of their publications have broken 1000 in past ten years. Therefore, the utilization of rubber, RAP, and SS in asphalt modification will be mainly analysed in this state-of-the-art review.

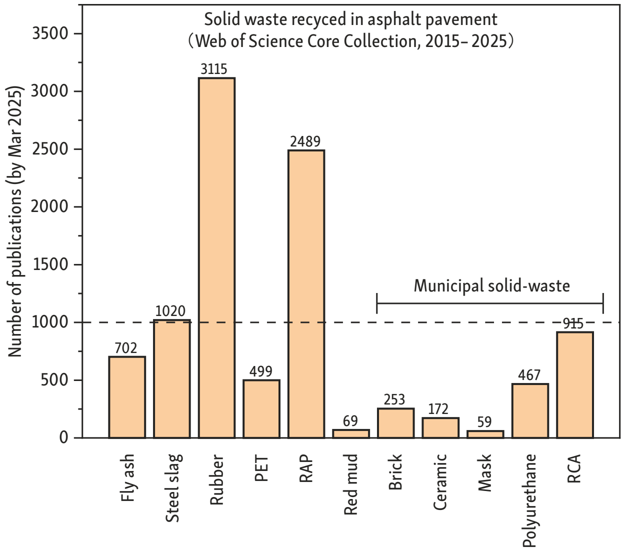


Figure 2. Number of publications in Web of Science Core Collection in past ten years, regarding to selected SWMs

2.2. Mapping of leading countries with research in sustainable asphalt pavements

Based on the 467 documents were acquired from Web of Science Core Collection, the minimum number of documents of a country was set as 5, and 29 of the 67 countries meet the threshold. Figure 3 illustrates the scientometric analysis of the selected countries in sustainable asphalt pavements. In the network visualization map (shown in Figure 3a), China (including regions of Hong Kong, Macau, and Taiwan) is the leading country that published more papers than others in the past ten years. It is followed by the USA and Italy as the second and third research impact contributor. In Figure 3b, overlay visualization map clearly indicates the research impact development in countries with time. Countries such as USA and Canada were first ones to carry out solid waste employment in asphalt mixtures, then followed by countries such as China and Pakistan. Australia and Switzerland also joined in the research impact recently. Density visualization map in Figure 3c have summarized the contribution of the leading countries. This graphical visualization and statistics of active countries will aid future research collaborations, exchange of knowledge, resources and developing innovative solutions to the existing problems.

3. Employment of recyclable SWMs in sustainable asphalt pavement

3.1. Rubber

3.1.1. Materials and pre-treatment

The rubbers employed in sustainable asphalt pavement are usually derived from waste tyres, which has become a concerning issue since the automotive industry was developed (Xu et al., 2021b). Compared to traditional disposal methods of such as landfill or combustion, the employment of waste tyres in asphalt mixtures can obviously reduce the environment impact and improve the economic efficiency (Riekstins et al., 2024). On the other hand, although the elasticity and durability of the waste tyres were compromised to some degrees, the resilient elasticity of waste tyres can still improve the long-term mechanical performance of asphalt mixtures, such as the cracking resistance, rutting resistance, anti-fatigue, and high temperature stability (Radeef et al., 2021; Pan & Pang, 2022; Hu et al., 2024; Ziari & Abdipour, 2024).

Before rubbers were utilized in asphalt pavements, some treatments on the rubbers were necessary to guarantee the well service performances of rubberized asphalt mixtures (Zhang et al., 2024a). Since most of rubbers were derived from waste tyres, physical grinding was usually the first step. To ensure the purity of rubbers, physical grinding included the washing, crushing, and screening processes, during which substances such as dirt and metal debris would be eliminated, and the waste tyres would be grinded into rubber particles with designed diameter (Li et al., 2021a). Hence, in the literature, the waste tyre derived rubbers were also usually referred as "crumb rubber" (CR). Although the CR could be directly utilized in the asphalt mixture preparation, it is found that the asphalt pavement modified by CR showed better service performance such as anti-cracking if some chemical modifications or physical treatments were included (Wang et al., 2017; Zhou et al., 2020).

1) Chemical treatments

Chemical treatment of crumb rubber aims at improving the compatibility of rubber in asphalt and enhancing the interfacial connection strength, mainly by employing desulphurization method and surface activation method. Desulphurization method could break the sulphur crosslinking bonds in rubber particles, while surface activation method aimed at modifying the chemical characteristics of rubber particle surface. Li et al. (2021a) summarized the practical surface activation methods to improve the compatibility of rubberized asphalt, and classified into five categories: pre-reaction, oxidization, grafting, polymer coating, and solution soaking. Pre-reaction of rubbers was usually achieved by mixing some agents full of aromatic fractions, which could be roughly categorized as petroleum by-products (e.g., waste engine oil) and bio-oils. Oxidization method focused on breaking the C-C and C=C bonds on the rubber surface and generate new groups by employing some

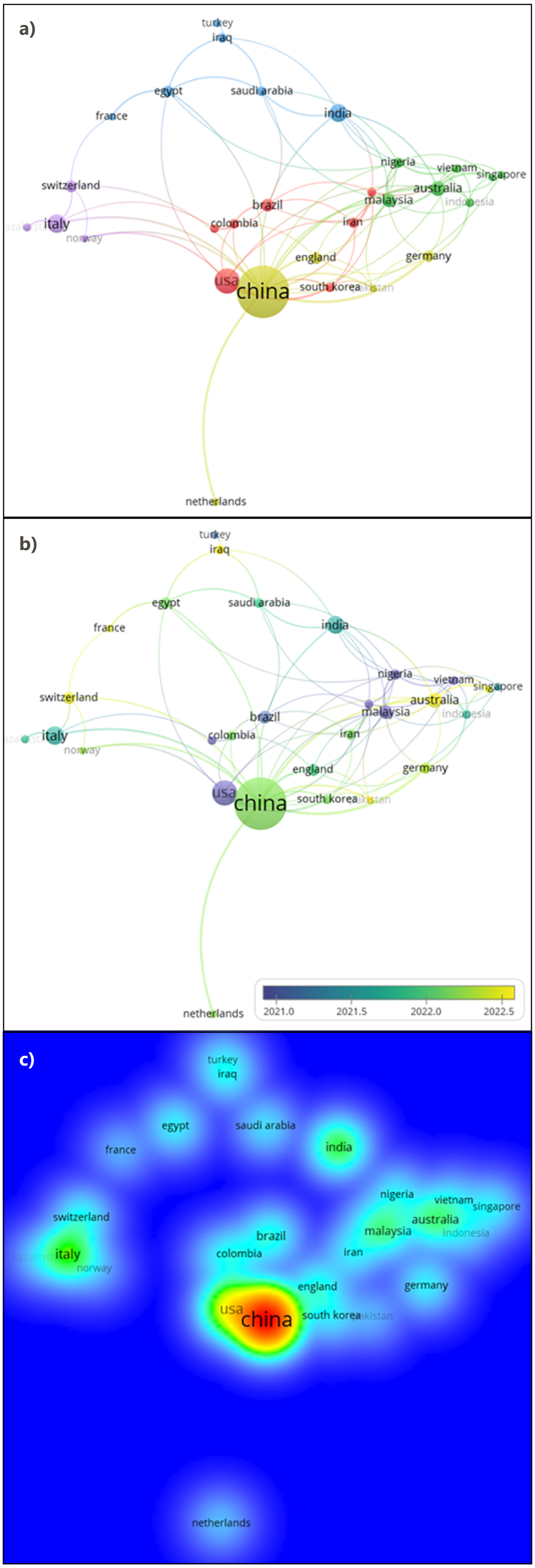


Figure 3. Mapping of scientometric analysis of countries in sustainable asphalt pavements: a – Network visualization; b – Overlay visualization; c – Density visualization

strong oxidants, in which the hydrogen peroxide (H_2O_2) was one of the most favourable in practice. Grafting method is also known as copolymerization reaction, in which the main chain of polymer was connected to the branched chain of one or several monomers. At present, there are several methods of the conversion monomers into polymers, and classified as bulk polymerization, solution polymerization, emulsion polymerization, and radiation grafting. Polymer coating method utilized some polymers as compatibilizers to cover the rubber particles and enhanced the cohesion with asphalt matrix. Solution soaking was easy to operate, with objective to remove or dissolve the adverse impurities on the rubber surfaces. The details of chemical treatment methods are tabulated in Table 1, as well as their improvement on service performances.

2) Physical treatments

In addition to the chemical methods, the rubber surfaces could be activated by some physical methods as well, such as plasma treatment and gamma radiation. Known as the fourth fundamental state of matter after solid, liquid and gas, plasma was an electrically neutral medium of unbound positive and negative particles, possessing an energy that was higher than the energy of most chemical bonds while much lower than the energy of high-frequency rays (Cheng et al., 2017). Therefore, the plasma treatment could only modify the top few nanometres of the material surface, without affecting the bulk properties. Gamma ray was another physical approach to activate rubber surfaces, including the microwave, X-rays, infrared radiation, ultraviolet radiation, and radio waves. Elnaggar's research group firstly employed gamma rays to modify CR surfaces in asphalt preparation (Elnaggar et al., 2019; Fathy et al., 2018, 2019; Ibrahim et al., 2015), and concluded the main effects of gamma rays on polymer were the grafting, cross-linking, and degradation, as the further evolution of the generated free radicals by gamma radiation on the polymer surface. The details of physical treatment methods are tabulated in Table 2, as well as their improvement on service performances.

In some practice cases, multiple chemical and physical treatments were simultaneously employed to improve the compatibility of rubbers in asphalt (Xu et al., 2023), such as the combination of microwave activation and chemical additives like waste engine oils. Xu et al. (2021a) desulfurized the CRs with the combination of waste engine oils and microwave activation, which enhanced the low-temperature flexibility and storage stability and improved the rubber solubility by 40%. Chen et al. (2024b) reported similar conclusions, noting that waste engine oil reduced rubber aggregate binding energy and promoting homogeneity. Similarly, Li et al. (2023) highlighted the combination of diesel pre-swelling and microwave activation was effective to disrupt rubber crosslinking, resulting in viscosity reduction and deformation resistance improvement.

Table 1. Categories, methods, mechanism, and performances of chemical treatment for rubber particles

Categories and methods		Materials	Mechanism	Influenced performance	References
Desulphurization method		▪ Coal tar ▪ NaOH	Break the sulphur crosslinking bonds in rubber particles	▪ Reducing crosslink density ▪ Improving high- and low-temperature performance ▪ Reducing viscosity	Song et al. (2023) Liu et al. (2021a)
Surface activation method:					
Pre-reaction		Petroleum by-products	Similar to the oil components of asphalt matrix to increase the cohesion between rubber and asphalt	▪ Reducing the viscosity, phase separation ▪ Improving storage stability, elasticity	Chen et al. (2024b) Xu et al. (2021a)
		Bio-oils		▪ Doubling elastic recovery (from 13% to 24%) ▪ Reducing rubber-bitumen separation by 82%, viscosity ▪ Enhancing ductility by 85% and toughness by 75.6%	Kabir et al. (2020) Zhang et al. (2024a) Dong et al. (2012)
Oxidization		Hydrogen peroxide (H_2O_2)	Breaking the C-C and C=C bonds on the rubber surface and generate new groups	▪ Enhancing the rheological performance ▪ Reducing pore size in CR ▪ Reducing viscosity, elasticity, and rutting resistance	Shatanawi et al. (2013) Li et al. (2019)
Grafting:	▪ Bulk polymerization ▪ Solution polymerization ▪ Emulsion polymerization ▪ Radiation grafting	▪ Styrene ▪ Maleic anhydride ▪ Methyl methacrylate	Copolymerization reaction, the main chain of polymer was connected to the branched chain of one or several monomers.	▪ Improving roughness of rubber particle surface, and creating network structure ▪ Improving rheological performance and durability ▪ Improving thermal stability and storage ability	Kocevski et al. (2012) Li et al. (2021a) Mahida et al. (2022) Liu et al. (2020c)
Polymer coating:	▪ Melting method ▪ Spraying method ▪ Solvent method	▪ KH-550 ▪ Polyamide	Utilized as compatibilizers to cover the rubber particles and enhance the cohesion with asphalt matrix	▪ Enhancing high-temperature creep resistance ▪ Improving rheological properties and storage stability	Xiang et al. (2020) Xie et al. (2020) Tan and Wang (2020)
Solution soaking		NaOH	Removing adverse impurities on the rubber surfaces such as zinc stearate and carboxyl groups	▪ Reducing viscosity ▪ Enhancing storage stability and low- and high-temperature performance	Liu et al. (2021a)

Table 2. Categories, methods, mechanism, and performances of physical treatment for rubber particles

Categories and methods		Mechanism	Influenced performance	References
Plasma treatment		Plasma treatment could only modify the top few nanometres of the material surface, without affecting the bulk properties	▪ Improving high-temperature performance ▪ Reducing penetration ▪ Increased softening point ▪ Improving rutting resistance and non-linear viscoelastic behaviour	Xiao et al. (2020) Li et al. (2020c) Li et al. (2020a) Li et al. (2020b, 2022)
Gamma ray treatment				
	▪ Microwave ▪ X-rays ▪ Infrared radiation ▪ Ultraviolet radiation ▪ Radio waves	Main effects of gamma rays on polymer were the grafting, cross-linking, and degradation	▪ Increasing surface area and porosity ▪ Improving aging resistance of fatigue life ▪ Reducing carbonyl indices ▪ Improving swelling efficiency, high-temperature performance ▪ Reducing toxic gas emissions during pyrolysis	Li et al. (2020d) Zhu et al. (2024) Yang et al. (2020)

3.1.2. Producing technologies and performances of rubberized asphalt

From the view of literatures, there were three main technologies employed to use the rubber in producing asphalt mixtures, namely the wet process, the dry process and the terminal blend process. The wet process refers to mix the rubber particles in asphalt under high temperatures (170~190 °C) to guarantee the swelling of rubbers, with the aim of increasing the durability, adhesion and mechanical properties of asphalt mixtures. The dry process refers to employ the rubber particles as replacement of partial fine aggregates in asphalt mixtures, in which the rubbers were directly mixed with aggregates and asphalt binders. The terminal blend process refers to mix the rubber particles in asphalt with high speed of shearing under high temperature, to guarantee the fully digestion and degradation of rubbers in asphalt, and thereby significantly decrease the viscosity of asphalt binder. However, it should be noted that the distinction between the wet process and terminal blend process was not that clear in recent years. Lo Presti et al. (2013) and Bressi et al. (2019), for instance, considered the terminal blend as a specific case of wet process.

1) Wet process

The wet process of rubber could be viewed as a modification of asphalt binders, where the viscosity of asphalt binders would be influenced by the interaction mechanisms between the rubber and asphalt matrix. Ren et al. (2021) made clear explanation about the physical and chemical interactions between the rubber and asphalt matrix. Generally speaking, with the agitation energy input, the rubber particles in asphalt matrix mainly endured two processes consequently: the swelling process and the degradation process.

When rubbers were mixed with asphalt under high temperature, the rubber particles would absorb the light component in asphalt matrix, resulting in the volume expansion and formation of porous structures. Such process was described as swelling process, in which the apparent viscosity of asphalt would increase, and the elasticity and anti-fatigue performance would be improved. For a certain combination of agitating temperature and speed, the apparent viscosity of asphalt binders would reach a peak value and stable afterwards, which was denoted as "swelling equilibrium state" (Ren et al., 2021). If the agitation energy was increased continuedly, thermal-oxidative degradation process was initiated, which will be discussed later in terminal blend process.

The period of swelling process could be influenced by multiple factors involving rubber particle size and ratio, agitating temperature, and shearing speed. It is proved that increasing the agitating temperature and the level of agitation allowed a considerable reduction of both peak viscosity and time of reaching swelling equilibrium (Neto et al., 2006). However, it should be noted that the agitating temperature, shearing speed and agitating period varied in different research (Ge et al., 2024). Figure 4 statistically analysed the agitating time, agitating temperature, and shearing speed collected from 122 wet process cases of rubberized asphalt from literature. The agitating time mostly ranged from 30 to 90 min, in which 60 min was mostly used in agitating period. The agitating temperature concentrated between 170~200 °C, in which 180 °C was mostly used. The shearing speed was relatively scattered, distributing between 1000~5000 r/min. In wet process, longer agitating time was equivalent to larger shearing speed, but agitating temperature played a more important role. Only when agitating temperature reached a critical value, could the shearing speed and agitating time effectively promote the interaction between rubbers and asphalt matrix. Based on the literature, the wet process in laboratory was suggested to be conducted under the agitating temperature ranging from 170~190 °C, with a shearing speed ranging from 1000~4500 r/min, and for a period of 45~60 min.

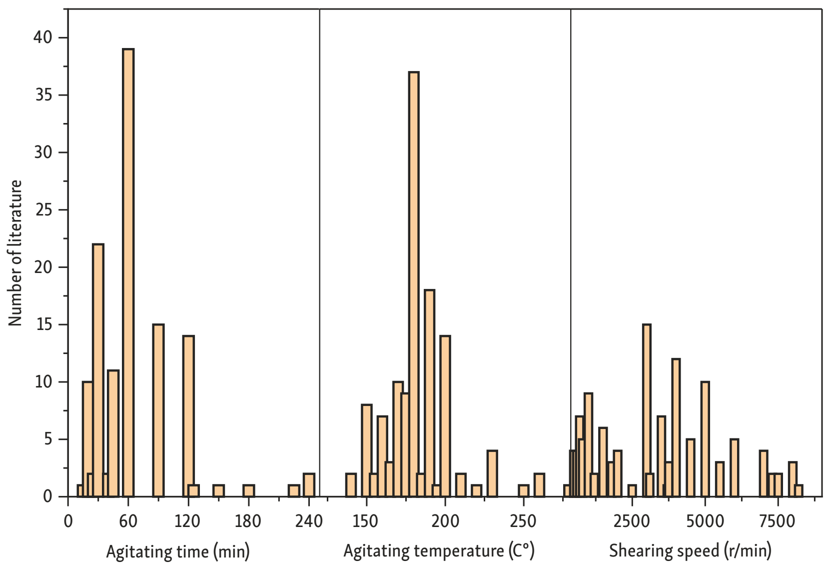


Figure 4. Preparation parameters of rubber-modified asphalt in wet process (Reproduced from Ge et al., 2024)

It is widely proved that the rubber modification in wet process could improve the service performances of asphalt mixtures including the rutting resistance, fatigue cracking resistance, low temperature performance and noise reduction. The chemical and physical interactions between rubber and asphalt in wet process enhanced the viscoelasticity and resilient modulus of asphalt binders. The higher viscosity of asphalt binders allowed stronger cohesions between asphalt binders and aggregates, resulting in good resistance to permanent deformation of asphalt mixtures, especially in high service temperature (Faccin et al., 2022; Vamsikrishna & Singh, 2023). Fatigue cracking resistance was another most perceived performance of rubberized asphalt. Venudharan et al. (2017) summarized the application cases of rubberized asphalt and confirmed the enhanced performance in terms of cracking resistance of rubberized asphalt in pavements built in different geographic locations and different traffic and climate conditions. The superior performances of rubber on elastic recovery and fatigue life of asphalt modification were also demonstrated by viscoelastic continuum damage (VECD) theory by Lee et al. (2024). In addition to the fatigue cracking, the rubber modified asphalt mixtures showed improvement on the low temperature crack resistance. As reported by Razmi and Mirsavar (2018), the rubber in asphalt could effectively enhance the low temperature flexibility and fracture resistance, which was critical for pavement longevity in cold climates. Wang et al. (2017) concluded that the anti-cracking performance of rubber in asphalt could be further improved if some chemical and physical pre-treatment methods were included. Benefitting from the elasticity of rubber particles, the transmission of acoustic wave in air could be weakened, and the noise of asphalt mixtures could be reduced. Obviously, the noise reduction effect would be more significant in open-graded mixtures. Li et al. (2020e) reported that rubberized asphalt mixtures with open gradation reduced noise by 1.6 dB and improved skid resistance. Similarly, a significant noise reduction (3.6–8.6 dB) was achieved by Wang et al. (2021), who produced a friction course by utilizing crumb rubber modified asphalt (CRMA) and open-graded aggregates.

Although there were abovementioned advantages of modifying asphalt with rubber, it should be noted that inappropriate employment of rubber in asphalt could lead to negative effects. Saberi et al. (2017) concluded that CR tended to improve the cohesion of the mixture; however, rubber particles absorbed light components of asphalt, and thus increased the viscosity of asphalt, making the coating of the aggregates difficult.

2) Dry process

The dry process directly employed rubber particles as a replacement of the fine aggregates in asphalt mixtures, indicating the application of dry process was more appropriate for gap-graded aggregates. Compared to the wet process, dry process of rubber modification could be conducted by conventional mixing equipment with smaller shear speed and lower temperature (160~180 °C).

However, many works in recent years have proved that rubberized asphalt mixtures from dry process could possess mechanical responses equivalent to the mixtures from wet process by employing modified asphalt or special additives. Liang et al. (2022, 2023) employed pretreatment methods such as high-temperature pre-swelling and microwave radiation to activate CRs before the dry process, and concluded that activated CRs could enhanced low temperature cracking resistance and moisture ability of asphalt mixtures. Their microscopic analyses also revealed improved homogeneity and interaction between rubber and asphalt. Rath et al. (2021) evaluated chemically engineered dry-process ground tire rubber in field and laboratory settings, and demonstrated improved high-temperature performance, rut resistance, and fracture energy, though conventional cracking tests sometimes underrated the field performances of dry-process ground tire rubber mixtures. Yucel et al. (2021) employed warm mixing additives during the dry process of CR modified asphalt mixtures, and concluded that warm mixing additives could reduce segregation in CR mixtures, though there might slightly decreased the contact length and contact points between particles. Despite this trade-off, both control and WMA mixtures demonstrated comparable performance when compaction is adjusted for lower temperatures or reduced effort. The study highlights the environmental and logistical advantages of WMA, including reduced energy consumption, extended hauling distances, and lower fume exposure.

3) Terminal blend process

As stated in the wet process, rubber particles would swell and absorb light components from asphalt matrix during the early agitation and reached the swelling equilibrium state. With continuous input of agitation energy (for example, increasing the temperature to 200 °C), thermal-oxidative degradation process was initiated, which is described as terminal blend (TB) process.

Compared to the wet process, TB process was usually conducted under higher temperature and longer agitating period. During this process, depolymerization and dissolution reactions were mainly triggered, in which the main chain and crosslinking bonds were fractured by the oxygen. This oxidation reaction produced low molecular substances such as free radicals, ketones, and carboxylic acids, which were easy to dissolve in asphalt matrix, and influenced the rheological property of asphalt. The degradation process was positive on the ductility performance of asphalt binders in low temperature, but at a cost of part of elasticity.

TB rubberized asphalt mixtures have gained reputation of good storage stability and low-temperature performance due to the full digestion of CR into the asphalt binder. Wen et al. (2020) emphasized the storage stability assessment methods for TB rubberized asphalt binders with various testing approaches such as softening point difference, separation index, and degradation ratios. The conclusion came to that CR content positively influenced the storage ability, and the reliable indicators of storage stability were suggested to be the high-temperature degradation ratio and percentage of separation. In addition to the storage ability, some other performances of TB rubberized asphalt were also investigated. Obaid et al. (2020) made comparisons among four pavement sections including a styrene-butadiene-styrene (SBS) polymer-modified binder and three rubber-modified asphalt binders (cryogenic rubber, cryogenic rubber with anti-settling agent, and ambient rubber) to assess the fatigue cracking, low-temperature cracking, moisture damage and rutting resistance. The comparison strongly proves that rubberized mixtures exhibited comparable performance to the polymer-modified control, with superior rutting resistance.

Although possessing good storage ability and low-temperature performance, TB rubberized asphalt gained these advantages with risking on the high-temperature performances. Sun et al. (2021) investigated the potential of utilizing waste non-tire rubber particles in TB rubberized asphalt binders, and highlighted the improvement of the thermal stability and fatigue resistance of TB rubberized asphalt. However, although pretreated by microwave and engine oils, the viscosity and high-temperature performance of TB rubberized asphalt were reduced, especially with fine rubber particles.

3.1.3. Rubber particle size

Since the development of rubberized asphalt mixtures is mainly induced by the recyclability of waste tyres, increasing the usage of CR in asphalt mixtures to the maximum extent is positive on this target. However, due to rubber particles absorbed light components from asphalt matrix, excessive rubber content would increase the viscosity of asphalt binders and make it difficult for the coating of aggregates, resulting in deterioration of mechanical performance of asphalt mixtures (Saberi et al., 2017). Summarized from the pre-treatment methods and producing technologies as stated above, the interaction between rubber and asphalt played a crucial role in the mechanical performance of asphalt mixtures. Therefore, there should seek a balance between the recyclability of CR to the maximum usage and the enhancement of rubber-asphalt interaction, which on one hand, was influenced by additives or treatment methods; on the other hand, was influenced by the geometric features of rubber particles such as content and size.

1) In wet process and terminal blend process

Current specifications or standards mainly focused on the performances of rubberized asphalt mixtures, neglecting the requirements on particle size of CRs, which left enough room for researchers to choose the size of CRs, only if the performances of final products satisfied the requirements. However, recent investigations have demonstrated complicated responses of rubberized asphalt mixtures influenced by different particle sizes. The responses could be broadly categorized into the following four groups.

- **Rheological Properties and Thermal Stability**

Several researchers investigated the influence of CR size on the rheological behaviour of asphalt under thermal conditions. Zhou et al. (2024) found that larger rubber particles (larger than 40 mesh) slowed the swelling rates and enhanced elasticity, improving rutting resistance, whereas smaller particles (larger than 60 mesh) degraded faster, negatively affecting performance but improving fatigue resistance. Similarly, Ren et al. (2021) demonstrated that finer – rubber particles (70–100 mesh) accelerated swelling-degradation, increasing viscosity and reducing workability, while coarser particles (30–40 mesh) improved high-temperature stability. Guo et al. (2024b) highlighted that composite CR ratios (80 mesh:60 mesh:40 mesh = 6:2:2) enhanced both high- and low-temperature performance in SBS-modified asphalt.

- **Storage Stability**

Despite of above-mentioned additives or treatment methods, the storage stability of rubberized asphalt mixture could be influenced by the rubber particle size to some extent. Lei et al. (2021) and Guo et al. (2024b) emphasized bio-oil pretreatment as a method to mitigate aging and improved compatibility in rubberized asphalt, particularly with finer CR particles (60–80 mesh). Vigneswaran et al. (2023) concluded that smaller CR particles (less than 0.5 mm) reduced phase separation, improving storage stability.

- **Mechanical Performance and Durability**

Multiple studies evaluated rubber-modified asphalt's resistance to cracking, moisture damage, and aging. Bilema et al. (2021) found that larger rubber particles (0.3 mm) improved indirect tensile strength (ITS), while finer particles (0.075 mm) enhanced moisture resistance. Qian et al. (2020) showed that larger rubber particles (0.60–0.75 mm) improved rutting resistance but reduce low-temperature flexibility. Some works explored sustainability aspects, such as reducing natural resource dependence (Almusawi et al., 2020) and optimizing rubber size for cost-effectiveness (Qian et al., 2020). Jamal et al. (2021) noted that coarser CR (30 mesh) improved ultraviolet (UV) resistance.

Figure 5 summarizes abovementioned literatures and illustrates the effect of rubber particle size on the performances of asphalt mixtures. Generally, there existed contradictions in rubber particle size regarding to the performances of asphalt mixtures. For wet process, in which swelling behaviour was mainly observed, larger rubber particles improved the high-temperature performance, elasticity, and resistance for ultraviolet radiation and plastic deformation, while smaller rubber particles were positive on viscosity and resistance for moisture and fatigue. For terminal blend process, in which degradation behaviour was mainly observed, smaller rubber particles in asphalt mixture could improve the storage ability and low temperature performances such as cracking resistance and flexibility. This also indicated that only for smaller rubber particles could terminal blend process demonstrate the advantages on storage stability or low temperature performances.

2) In dry process

All abovementioned works about rubber modified asphalt mixtures were categorized as wet process and terminal blend process, in which the swelling-degradation behaviour of rubber particles was the main factor of performance of asphalt mixtures. In dry process, due to the direct mixing of rubber particles in asphalt mixtures, the swelling and degradation processes were less completed, in which case, the rubber particle size effect on performances of asphalt mixtures was different from the wet and terminal blend modifications.

One of the aspects that all the researchers agreed is that higher rubber–asphalt interaction could be obtained with the use of fine rubber size and high asphalt content in dry process. López-Moro et al. (2013) made comparing investigations about rubber-asphalt interactions among different rubber size less than 0.5 mm, and concluded rubber particles with less than 0.2 mm showed strong interactions. Farouk et al. (2017) observed higher rubber-asphalt interaction with finer rubber particles (1.18 mm) in dry process, and concluded that finer rubberized mixtures were easier to be compacted and showed 30% higher resilient modulus than coarse (5 mm) rubberized mixtures. Díaz and Sandoval (2023) demonstrated that finer rubber-enhanced (0.425–0.075 mm) mixtures exhibited better fatigue life and plastic deformation resistance than conventional asphalt. Feiteira Dias et al. (2014) employed dry process to mix the fine rubber particles (maximum size of 0.6 mm) with aggregates and asphalt and concluded the mixtures showed a satisfactory stability under high temperature (above 30 °C). Da Silva et al. (2018) produced asphalt mixtures modified with rubber particles of less than 1 mm by the dry process (20% by weight of asphalt in the mixture) and claimed that the resistances for fatigue, permanent deformation and reflection cracking under high temperature (40 °C) were improved significantly. Moreno et al. (2013) made comparisons between rubberized (0.6 mm) mixtures produced by wet process and dry process, and concluded that resistance for permanent deformation was equally improved regardless of the producing process, and dry process showed better efficiency of utilizing rubbers and generally higher stiffness compared to wet process.

Figure 6 summarizes abovementioned literatures and illustrates the effect of rubber particle size on the performances of asphalt mixtures in dry process. Compared to wet process, the average size of rubber in dry process was generally larger. However, all the study cases indicated better rubber-asphalt interaction could be observed

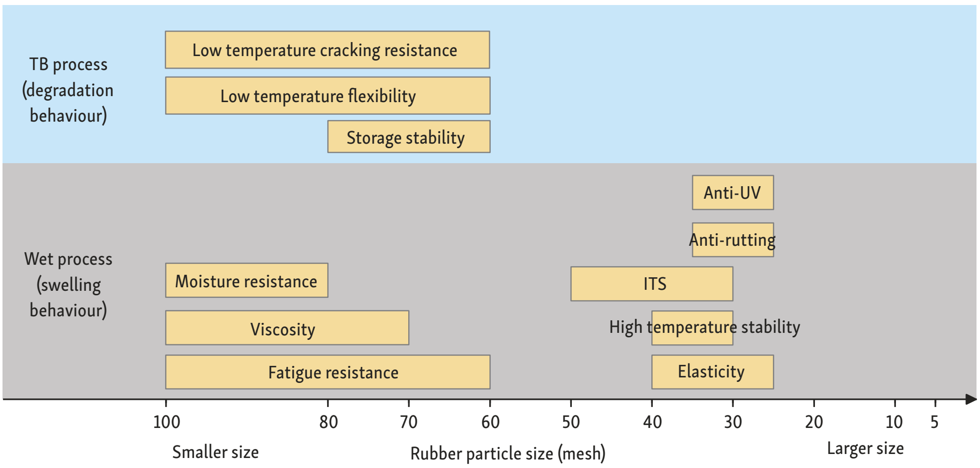


Figure 5. Performance of asphalt mixtures distributed on rubber particle size in wet and terminal blend process

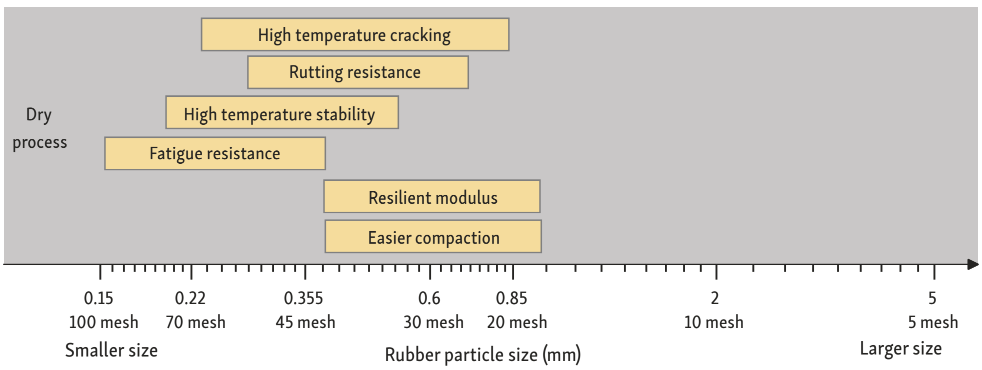


Figure 6. Performance of asphalt mixtures distributed on rubber particle size in dry process

with smaller rubber particle size. Currently, the rubber size was smaller than 1 mm in the most of dry process cases. With smaller rubber particle size, it is inferred that performances of dry process rubberized asphalt mixtures could be improved further.

It should be noted that there were conflicting findings in the literature regarding the performance improvement effect of crumb rubbers in asphalt mixtures, especially in the comparisons of wet and dry processes of rubberized asphalt mixtures. This review makes effort to organize asphalt mixture performance in terms of rubber particle size, in which the reasons leading to the conflicting findings were various and out of scope. Therefore, in Figures 5 and 6, the conflicting findings were filtered according to the simplified statistics analysis of literatures.

3.2. RAP

3.2.1. Evolution of RAP in asphalt modification

Asphalt pavement is prone to multiple deterioration mechanisms during its service life (Li et al., 2021b), including oxidation, thermal cracking, fatigue cracking, UV degradation and stripping. In the asphalt pavement rehabilitation process, milling and full-depth pavement removal generate a large amount of RAP, which is composed of high-quality aggregates coated with aged asphalt. It serves as a valuable reclaimed resource and can be effectively used for a variety of construction and rehabilitation scenarios, contributing to conserving raw materials and reducing carbon footprint. The actual RAP particle and its possible internal structure configurations are shown in Figure 7. RAP recycling methods can be classified into four primary categories based on processing temperature and location: hot in-place, cold in-place, hot central plant, and cold central plant recycling (Xing et al., 2023). Hot in-place and hot central plant are used for pavements needing quick restoration and high quality, while cold in-place and cold central plant recycling are suited for cost-effective, environmentally friendly projects. Hot central plant, renowned for its excellent performance and lower equipment investment, has become the most widely adopted reclamation technology in pavement engineering (Zhu et al., 2020).

Research and literature surveys (Karthikeyan et al., 2023; Tsakoumaki & Plati, 2024; Panda & Biswal, 2025) have highlighted the substantial global production and widespread application of RAP, with an estimated annual output exceeding 500 million tons. Encouragingly, RAP

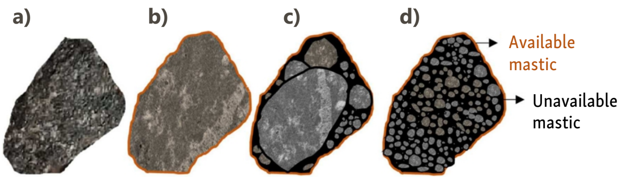


Figure 7. Illustration of RAP particles: a – Photo of a RAP particle; b – RAP particle with a single core aggregate; c – RAP particle containing a coarse aggregate particle; d – RAP particle with agglomerated fine aggregates (Fonseca da Costa et al., 2024)

utilization rates are particularly high in North America and Europe. In 2020, the United States produced approximately 85 million tons of RAP, with nearly 93% being reclaimed for asphalt layers (Williams et al., 2020). 17 European nations collectively produced around 36 million tons of RAP, with 76% successfully reincorporated into asphalt mixtures (European Asphalt Pavement Association, 2022). Countries such as the Netherlands, Belgium, Germany, and Denmark have demonstrated longstanding leadership in adopting RAP across all pavement layers (Akker, 2022; European Asphalt Pavement Association, 2022). Across Asia and Oceania, RAP recycling has also gained considerable attention. Japan stands out with an impressive 99% recycling rate, ensuring that nearly all reclaimed asphalt is reused in new road pavements (Akatsu et al., 2022). In rapidly developing countries with extensive road construction projects, RAP presents significant potential for sustainable infrastructure. For instance, China produces approximately 220 million tons of RAP annually, with a recycling rate of 30% (Ministry of Transport, 2019). With an estimated annual RAP production of 5 million tons, India possesses a vast and extensive road infrastructure network. Notably, countries such as South Korea, Singapore, Thailand, Malaysia, Saudi Arabia, Australia, and New Zealand have implemented technical guidelines to regulate RAP utilization in asphalt mixtures (Tsakoumaki & Plati, 2024). Despite its global expansion, RAP utilization remains relatively underdeveloped in certain regions, particularly Africa. For instance, Egypt produces approximately 4 million tons of RAP annually, and South Africa approximately 3.5 million tons, with an estimated 10% currently being recycled (Mousa et al., 2021; Southern African Bitumen Association, 2021). Expanding RAP recycling initiatives in these regions could substantially enhance sustainability efforts. As illustrated in Figure 8, 26 countries have implemented national regulations for RAP utilization, signifying a growing global commitment to sustainable road construction and circular economy principles.

Growing environmental concerns and a push for sustainability have led to increased research and industry interest in RAP as an alternative to virgin asphalt. The global warming potential (GWP) of RAP is 16.1 kg CO_2-eq per ton, which is lower than that of natural coarse aggregate production (21.1 kg CO_2-eq per ton) (Panda & Biswal, 2025). For the construction of a 10 km single-lane roadway, a RAP replacement rate of 40% could reduce carbon emissions by approximately 16.7 tons of CO_2-eq, equivalent to the carbon sequestration of approximately 830 trees (assuming an average annual absorption of 20 kg CO_2 per tree). Higher RAP proportions would further enhance these benefits, highlighting RAP's potential to significantly reduce carbon emissions in pavement construction. Ongoing research continues to improve RAP mixture performance, construction methods, and longevity. Future development will focus on enhancing RAP recycling efficiency, optimizing design strategies, and adopting low-carbon pavement practices.

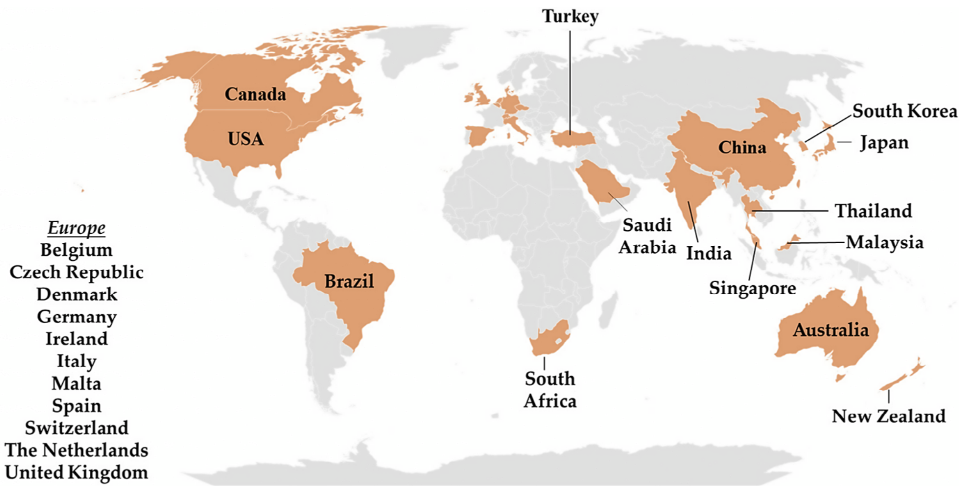


Figure 8. Countries with national specifications (Tsakoumaki & Plati, 2024)

3.2.2. Materials

1) Optimal dosage of RAP

Numerous studies have been undertaken to investigate the optimal RAP content in different types of asphalt mixtures to balance mechanical performance, durability, and environmental benefits. In the case of hot mix asphalt (HMA), Wang et al. (2022a) employed the discrete element method (DEM) to investigate the impact of different RAP contents on the mechanical properties of recycled asphalt mixtures (RAM). Using compressive strength as the sole evaluation criterion, the theoretically optimal RAP content in RAM was determined to be 28%. Furthermore, several studies have indicated that RAP contents of up to 50% can be incorporated into HMA without significant deterioration in performance, provided that proper binder blending strategies and mix design modifications are implemented. However, when RAP content exceeds 50%, aging-related issues become prominent. Imaninasab et al. (2022) modified the gradation of 100% RAP using the Bailey method's coarse dense-graded (CDG) and fine dense-graded (FDG) concepts, resulting in mixtures containing 73%, 65% CDG, and 57% FDG RAP. They developed a performance-based ranking system integrating rutting, cracking, aging, and moisture resistance. The findings demonstrated that balanced performance was achieved in rejuvenated mixtures containing 65–73% RAP. In contrast, mixtures with 100% RAP exhibited higher air voids and diminished durability. For Warm Mix Asphalt (WMA), which allows lower production temperatures, studies suggest that 40–50% RAP can be used effectively, especially when additives or rejuvenators are applied to enhance blending and restore aged binder properties. Obaid et al. (2026) conducted a response surface methodology (RSM) analysis to evaluate the effects of varying RAP contents (25–50%), WMA additive types, and dosages (1.5–4%) on the rutting resistance and moisture stability of asphalt mixtures. Through multi-objective numerical optimization, the optimal mixture was identified as containing 50% RAP and 1.5% WMA-type A. Wang et al. (2022b) evaluated the high-temperature, low-temperature, fatigue, and moisture resistance performance of recycled warm-mix asphalt (RWMA) mixtures containing 50% and 70% RAP. The results showed that WMA additive (wax R and surfactant M) effectively mitigated the negative effects associated with high RAP content. Moreover, an appropriate dosage of these additives can enhance rutting resistance and fatigue performance. The experimental results underscore the WMA additive type as a principal determinant influencing the moisture resistance behaviour of asphalt mixtures. In Stone Mastic Asphalt (SMA), due to its high binder content and reliance on stone-on-stone contact, the recommended RAP content is typically limited to 20–30%, as excessive RAP may affect mixture stability and binder film thickness. Devulapalli et al. (2020) designed four RAP gradations and evaluated 29 different SMA mixture combinations to investigate the influence of RAP content on mixture performance. A statistical analysis was conducted using a three-way analysis of variance (ANOVA) and main effect plots. The analysis identified 20–30% RAP as the optimal range for achieving balanced performance in SMA mix design. Barazi Jomoor et al. (2019) investigated the effect of increasing RAP content (0–50%) on the rutting resistance of SMA mixtures. Their results demonstrated that an RAP content of 30% yields a structurally sound and performance-consistent mixture design. Porous Asphalt (PA), designed for enhanced permeability and noise reduction, typically permits only low RAP contents (≤ 20%) to maintain its interconnected air void structure and drainage functionality (De Pascale et al., 2023). However, when the RAP content increases to 30%, reductions in air void ratio and fatigue resistance have been observed (Mousavi Rad et al., 2022). Moreover, recent field-based studies emphasize that optimal RAP dosage should also consider pavement type, traffic loading, and environmental conditions (Nian et al., 2024; Zhang et al., 2022). For example, Liu et al. (2024) demonstrated that the combined effects of climate change and traffic growth substantially accelerate pavement deterioration, leading to more frequent maintenance needs and higher carbon emissions. These findings highlight that external service conditions critically influence the long-term performance of RAP mixtures and must be factored into mixture design and RAP content optimization. Overall, the optimal RAP content is inherently dependent not only on the asphalt mixture type but also on service conditions, necessitating a tailored design approach that accounts for structural, rheological, durability, and environmental attributes.

2) RAP processing strategies

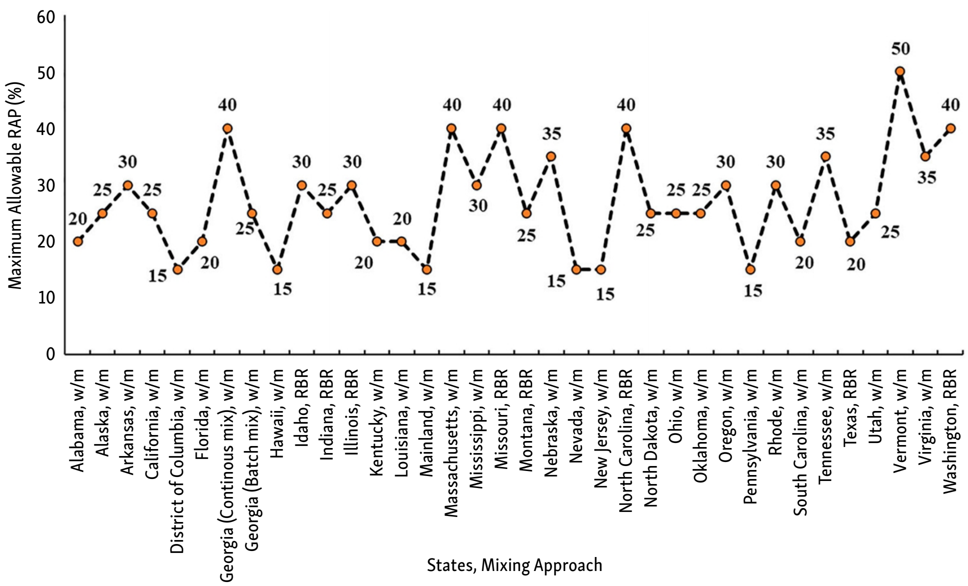
Proper fractionation and pre-treatment of RAP are beneficial for enhancing the performance of recycled asphalt mixtures. Fractionation and screening technologies enable the separation of RAP materials by controlling aggregate size and binder content. Fonseca da Costa et al. (2024) demonstrated a practical sieve analysis method to estimate recycled binder availability (RBA), simplifying previous approaches. Pre-treatment strategies such as rejuvenation and foaming restore the rheological properties of aged asphalt binders. Rejuvenators (e.g., bio-oils, aromatic extracts, polymers) replenish light fractions lost during aging, improving binder ductility and reducing brittleness. The incorporation of rejuvenators rebalances the ratio between maltenes and asphaltenes, thereby enhancing the viscoelastic properties and workability of the aged binder (Al-Saffar et al., 2021). However, the effectiveness of rejuvenators varies depending on their dosage, chemical compatibility, and mode of interaction with aged binders. Insufficient dosing may result in incomplete recovery of viscoelastic behavior, while excessive amounts can compromise mixture stiffness. Furthermore, the long-term reversibility of aging in rejuvenated binders remains uncertain, as most mechanisms of binder rejuvenation are based on restoring physical balance rather than chemically reversing oxidation. These challenges suggest the need for careful optimization of rejuvenator type and dosage, alongside more comprehensive performance evaluation over extended aging cycles. Moreover, foaming techniques, especially water-induced foaming of virgin binders, temporarily reduce binder viscosity, enhancing the coating of RAP aggregates and allowing lower production temperatures, which aligns with the principles of WMA technology (Zhao et al., 2016).

3) Recent advances in high-RAP content

To maximize the environmental benefits of RAP, researchers have explored a wide range of strategies to enhance the performance of asphalt mixtures incorporating high proportions of RAP. Given the inherent limitations of aged binders and recycled aggregates, various modifiers and technologies have been proposed to restore or even improve the mechanical and durability properties of these mixtures. Buritatum et al. (2023) investigated the use of natural hemp fiber (HF) as a functional additive and found that, despite reductions in Marshall stability associated with 100% RAP, the incorporation of HF significantly improved structural integrity and rutting resistance. Laomuad et al. (2024) evaluated the mechanical behavior and failure modes of asphalt concrete incorporating 100% RAP aggregate, modified with varying dosages of polyethylene terephthalate (PET, 0% to 1.0% by aggregate weight). The results revealed that PET enhanced binder–aggregate adhesion and increased air void content, leading to notable improvements in tensile strength and rutting performance, with an optimal PET dosage of 0.6% yielding the most favorable performance. As a thermosetting material, epoxy resin undergoes a chemical reaction with a curing agent to form a crosslinked polymer network, which enables strong bonding with RAP aggregates and compensates for the poor adhesion of aged asphalt. To further address the challenges of binder aging, Fan et al. (2024) employed epoxy asphalt as a binder to facilitate the full utilization of the RAP. Their study confirmed that increasing epoxy content significantly extended the fatigue life of RAP mixtures. In another approach, Song et al. (2024) combined epoxy asphalt with SS aggregate, leveraging the high surface roughness and alkaline nature of SS to improve both moisture resistance and fatigue performance. Besides, Jahanbakhsh et al. (2020) reported that waste engine oil and a supplementary binder modified with CR effectively restored RAP functionality and produced mixtures with comparable or superior mechanical and durability characteristics relative to conventional asphalt. A summary of the strategies reviewed for enhancing the performance of mixtures with high proportions of RAP is presented in Table 3.

Table 3. Key strategies for enhancing the performance of RAM with high proportions of RAP

Strategy	Testing content	Main findings	Authors
HF	lengths of 20, 22, and 24 mm; 0, 0.05, 0.1, and 0.25% by dry weight of the total aggregate	0.05% HF (24 mm length) was the optimal ingredient for enhancing rutting resistance	Buritatum et al. (2023)
PET	0%, 0.2%, 0.4%, 0.6%, 0.8%, and 1.0% relative to the total weight of RAP	Optimal PET dosage of 0.6% improved tensile strength and rutting resistance	Laomuad et al. (2024)
Epoxy-recycling technology	/	Epoxy content significantly extended fatigue life of RAP mixtures	Fan et al. (2024)
Epoxy asphalt and SS	SRAM-40 (40 %RAP, 60 % SS), RAM-80 (80 %RAP, 20 % SS), and SRAM-100 (100 %RAP)	Epoxy asphalt and SS improved moisture resistance and fatigue performance	Song et al. (2024)
Waste engine oil and CR	Waste engine oil: 10–12% (wt% RAP binder); rubber: 10% of the weight of the supplementary binder	CR modification restored RAP functionality and enhanced mechanical properties	Jahanbakhsh et al. (2020)



Note: w/m and RBR denote by weight of mix and rap binder replacement, respectively.

Figure 9. The maximum allowable of RAP percentage in the surface course for different areas of the United States (Sukhija & Coleri, 2025)

While the widespread application of 100% RAP mixtures remains in the research phase, Zaumanis et al. (2020) showed that, with appropriate techniques such as material fractionation, binder rejuvenation, and gradation control, their implementation in base and subbase layers is technically feasible, offering a promising pathway toward fully recycled and sustainable pavement systems. However, it is worth noting that the usage of RAP must comply with local regulations. Taking the United States as an example, the maximum RAP percentage allowed in different regions is shown in Figure 9.

3.2.3. Performances of RAP modifications

1) Effect of RAP on asphalt performance

The incorporation of RAP has been shown to improve or maintain key mechanical properties of asphalt mixtures when applied within a suitable content range. In porous asphalt, RAP serves as a suitable substitute for virgin materials, offering comparable performance with reduced environmental impacts. For example, Riccardi et al. (2016) reported no observable difference in the fatigue behavior of stone mastic asphalt (SMA) mixtures containing 23% RAP compared to virgin mixtures. In HMA, the addition of up to 40% RAP has been associated with improved moisture resistance, primarily due to the presence of aged binder coating the aggregates, which reduces moisture susceptibility (Abdel-Jaber et al., 2022). Notably, permanent deformation is widely recognized as a major distress mechanism in asphalt pavements, particularly in the form of rutting under repeated traffic loading. Increasing the RAP content in asphalt mixtures has been shown to reduce permanent deformation, which directly translates into enhanced rutting resistance. This effect is largely attributed to the increased stiffness introduced by the aged binder. Previous studies (Jahanbakhsh et al., 2020) have also shown that mixtures incorporating less than 30% RAP exhibit mechanical performance comparable to virgin mixtures, particularly in terms of fatigue cracking resistance, rutting resistance, and tensile strength ratio. However, extensive research has revealed potential drawbacks at higher RAP contents, particularly regarding cracking resistance and low-temperature performance. A high proportion of RAP increases the brittleness of the aged binder, thereby compromising the mixture's resistance to low-temperature cracking (Yu et al., 2024). Yan et al. (2017) evaluated 14 RAP mixtures with polymer-modified asphalt binders and found that RAP gradation strongly influenced fracture behavior by controlling binder distribution and blending. They observed that higher RAP contents increased tensile strength but reduced ductility, as indicated by lower failure strain and fracture energy, and therefore recommended limiting RAP usage to 40%. Similarly, Li et al. (2025) reported that the brittleness of aged RAP asphalt heightens susceptibility to low-temperature cracking, while insufficient bonding between virgin and aged binders reduces toughness and overall mixture strength. Hoon Moon et al. (2017) further assessed the effect of RAP content using DSR and BBR tests, demonstrating that when RAP incorporation exceeds 25%, mixtures display inferior low-temperature performance compared with conventional hot-mix asphalt. Collectively, these findings indicate that while RAP can be advantageous at moderate levels, excessive incorporation may adversely affect cracking resistance unless appropriate rejuvenation strategies are employed.

2) Mechanisms underlying RAP's impact on binder properties

The performance of RAM is strongly influenced by the intrinsic properties of RAP, which is a heterogeneous material composed of aged binder and reclaimed aggregates. Research has shown that incorporating RAP can improve the modulus and rutting resistance of asphalt mixtures, particularly when the content is optimized (Ye et al., 2024). This enhancement is largely attributed to the increased stiffness provided by the aged binder, which contributes to greater resistance to deformation under repeated traffic loading, especially at elevated temperatures. However, the effectiveness of RAP integration depends on several critical factors, including the RAP content, the degree of binder aging, and the blending efficiency with virgin asphalt. Depending on the severity of aging, RAP can behave either as an inert material, commonly referred to as "black rock", where the aged binder exhibits minimal interaction with the virgin binder, or as a partially active component that contributes to the blending and bonding process (Sukhija & Coleri, 2025). In cases where the RAP binder remains chemically active, it can reduce the overall demand for virgin binder by participating in the formation of a unified binder phase. Nevertheless, RAP undergoes oxidative aging over time due to exposure to environmental conditions, heat, and traffic loads. This process involves the volatilization of light fractions, such as saturates and aromatics, and the transformation of maltenes into high-molecular-weight asphaltenes. These chemical changes are accompanied by the formation of carbonyl (C=O) and sulfoxide (S=O) functional groups, which are indicative of binder hardening (Omairey et al., 2019). Consequently, the aged binder becomes increasingly stiff and brittle, leading to reduced penetration, lower ductility, higher softening point, and elevated viscosity. These rheological changes significantly alter the viscoelastic behavior of the binder, resulting in RAM with higher stiffness modulus and lower phase angles. While this can be beneficial for rutting resistance, it often comes at the expense of fatigue performance and cracking resistance. As RAP content increases, these negative effects tend to become more pronounced, particularly when the blending between aged and virgin binders is incomplete. An excessive proportion of RAP can negatively impact the performance of the asphalt mixture, ultimately reducing the overall effectiveness of asphalt pavements (Laomuad et al., 2024). Some studies (Wang et al., 2022c) indicate that the aged asphalt in RAP may adversely affect RAM's performance. High proportions of aged asphalt often exhibit lower adhesion, leading to greater susceptibility to cracking due to increased brittleness. This adversely affects the overall crack resistance and fatigue performance of the mixture. In addition to binder aging, the surface properties of RAP aggregates also play a decisive role in mixture performance. The presence of aged binder films on RAP aggregates can reduce surface free energy and weaken adhesion with virgin binder. Luo et al. (2024) used molecular dynamics simulations to study moisture-induced damage in aged RAP binder. They showed that oxidative aging increases oxygen content and hydrophilicity, promoting moisture infiltration and partial asphalt detachment at the aggregate interface. Aging also raises intermolecular friction and reduces binder flexibility, compromising coating quality. Recent experimental studies (Zhang et al., 2025b) have further demonstrated that the fine separation and treatment of RAP, such as the use of finely separated RAP (FRAP), can substantially improve surface properties and interfacial bonding. The reduction of aged asphalt zones and formation of thinner, more uniform asphalt films enhances blending with virgin binder, increasing cohesion and water stability of recycled mixtures. As RAP proportion increases, the challenge of achieving effective coating and bonding between virgin and aged binders becomes more significant (Majidifard et al., 2019). Moreover, achieving a uniform blend between aged and virgin asphalt remains challenging due to the heterogeneous surfaces of RAP aggregates. Inadequate mixing can reduce workability and structural integrity, making placement and compaction more difficult. Lower workability may also weaken the mixture's self-healing ability, accelerating pavement deterioration.

3) Approaches to alleviate performance degradation

To counteract the performance degradation associated with high RAP contents, a range of mitigation strategies has been developed. The use of rejuvenators is considered one of the most effective methods, as they can replenish the lost maltenes in aged binders, restoring ductility, flexibility, and viscoelastic recovery (Elkashef et al., 2018; Jahanbakhsh et al., 2020). In addition, the application of soft binders with lower performance grades has been found to reduce overall mixture stiffness and enhance low-temperature cracking resistance (Soleimani Golsefidi & Ali Sahaf, 2022). WMA additives are another recommended strategy for enhancing the performance of high-RAP mixtures. WMA technologies significantly contribute to this improvement by lowering production and compaction temperatures, promoting better blending between aged and virgin binders, and enhancing the overall workability of the mixture (El Sharkawy et al., 2016). Furthermore, advanced production methods, including staged mixing, double-drum techniques, and the use of FRAP, have been demonstrated to improve binder distribution, reduce air voids, and enhance the mechanical integrity of recycled asphalt mixtures. The FRAP process, achieved through refined separation techniques, effectively reduces the agglomeration of RAP and the variability in both aggregate gradation and asphalt content (Wang et al., 2024c). Consequently, it enables higher proportions of RAP to be incorporated into recycled asphalt mixtures while simultaneously enhancing mixture quality, interfacial cohesion, and water stability. Beyond these approaches, polymer modification techniques, such as incorporating SBS or SBR modified emulsified asphalts, have demonstrated the potential to optimize the interfacial transition zone, thereby increasing modulus and improving resistance to stripping and moisture damage (Zhang et al., 2025b). Table 4 summarizes the main mitigation approaches, their mechanisms, and relevant references. The combined use of these strategies, including rejuvenators, soft binders, WMA additives, advanced production methods, as well as polymer modification, has proven to be effective in mitigating the aging effects of RAP materials and supporting the successful incorporation of high RAP contents without compromising mechanical performance or long-term pavement durability.

3.3. SS

3.3.1. Evolution of SS in asphalt modification

As a by-product derived from the steelmaking industry, SS is primarily categorized into three types based on the differences in smelting processes: Basic Oxygen Furnace slag (BOFS), Electric Arc Furnace slag (EAFS), and Ladle Refining slag (LFS) (Ameri et al., 2013; Cui et al., 2021b; Mahoutian et al., 2014; Yildirim & Prezzi, 2011). In the field of environmental remediation research, numerous scholars have applied SS to atmospheric improvement (Huijgen et al., 2005), wastewater treatment (Yu et al., 2022), and marine environment management (Ogawa et al., 2020). These studies have consistently demonstrated the remarkable efficacy of SS in significantly reducing airborne pollutants such as NOx and SO_2 (Sun et al., 2017; Xing et al., 2022), achieving high removal rates of heavy metals and organic contaminants in industrial wastewater (Yu et al., 2022), and effectively restoring marine ecosystems by enhancing water clarity and biodiversity (Liu et al., 2021c; Yu et al., 2021).

The research on utilizing SS as an aggregate in asphalt mixture for road construction commenced at the dawn of the 21st century (Rohde et al., 2003). Prior to this, the predominant methods of handling SS were stacking and landfilling. However, these approaches not only occupy substantial space and squander land resources but also exacerbate the potential leaching of heavy metal elements from the SS, posing a threat to the natural environment (Nakase et al., 2013; Nunes & Borges, 2021). Consequently, these methods are deemed unsustainable. Currently, developed nations represented by the United States and Japan, along with multiple European countries, have achieved large-scale application of SS materials in road engineering. In stark contrast, despite being the world's largest steel producer, China demonstrates significantly lower utilization rates of SS resources. At present, domestic engineering practices employing SS as aggregate in asphalt mixtures are primarily concentrated in provinces such as Jiangsu and Hubei (Nunes & Borges, 2021). The primary reasons for this disparity lie in the insufficient emphasis on the reuse of SS and the lack of in-depth and comprehensive research in this field. Therefore, this paper focuses on the research of steel slag asphalt mixture (SSAM) in road infrastructure construction, systematically reviewing and summarizing the latest research findings in this field, with the aim of providing theoretical support and practical insights for the efficient utilization of SS in road engineering.

3.3.2. Materials

SS is primarily composed of a variety of minerals, including CaO, Fe_2O_3, and SiO_2. Research indicates that SS produced by different processes exhibit significant variations in the content of their mineral compositions, yet there is no substantial distinction in the types of constituents present, as shown in Table 5.

The Los Angeles Abrasion rate, Apparent Specific Gravity, and Water Absorption rate are pivotal metrics for evaluating the physical properties of aggregates. These indi-

Table 4. Strategies to mitigate performance degradation in high-RAP asphalt mixtures

Strategy	Mechanism	Performance Improvement	References
Rejuvenators	Replenish lost maltenes in aged binder	Restores ductility, flexibility, and viscoelastic recovery	Jahanbakhsh et al. (2020)
Soft binders	Reduce overall mixture stiffness	Enhance low-temperature cracking resistance	Soleimani Golsefidi and Ali Sahaf (2022)
WMA additives	Lower compaction temperatures, promote better blending	Improve workability and binder distribution	El Sharkawy et al. (2016)
Advanced production methods	Staged mixing, double-drum techniques, and FRAP	Reduce air voids, improve binder distribution, enhance mechanical integrity, increase maximum RAP blending ratio, improve mixture cohesion and water stability	Wang et al. (2024c)
Polymer modification	Optimize interfacial transition zone, enhance binder elasticity	Increase modulus, improve stripping resistance and water damage resistance	Zhang et al. (2025b)

Table 5. The elemental composition of SS

Reference	SS type	Oxide composition (%)						
		CaO	Fe_2O_3	SiO_2	MgO	MnO	Al_2O_3	P_2O_5
Ameri et al. (2013)	EAFS	25.58	35.16	18.72	7.50	0.304	2.75	–
Fakhri and Ahmadi (2017)	EAFS	40	27	16	5	1	5	2
Swathi et al. (2021)	BOFS	52.27	22.87	14.69	2.75	0.83	2.80	2.21
Chen et al. (2024b)	BOFS	31.49	16.28	14.6	13.83	–	5.71	0.3
Uibu et al. (2011)	LFS	42.22	0.79	15.02	14.99	–	22.34	–

cators comprehensively characterize critical attributes of aggregates, including abrasion resistance, durability, water absorption, and porosity (Chen et al., 2024a, 2022b; Song et al., 2024). They provide a robust scientific foundation for assessing the performance of aggregates in engineering applications, ensuring the reliability and longevity of construction materials. SS exhibits outstanding physical properties, characterized by high strength and substantial density, which endow it with excellent wear resistance, remarkable stability and high density (Nunes & Borges, 2021; Swathi et al., 2021). However, the water absorption rate of SS is significantly higher compared to conventional aggregates, which not only leads to volume expansion in SSAM but also increases the potential for leaching of heavy metal ions. Furthermore, SS exhibits a multi-angular morphology with a rough surface texture and an abundance of pores, demonstrating a distinct porous structural characteristic (Chai et al., 2020; Gao et al., 2024). The distinctive physical properties of SS play a decisive role in the superior pavement performance of SSAM. Moreover, in-depth research into the reinforcement mechanisms of SS in mixtures not only facilitates the optimization of material design and enhances road durability but also holds significant theoretical and practical value for promoting the resource utilization of SS.

Currently, the reinforcement mechanisms of SSAM primarily encompass two aspects: the interfacial enhancement between SS and the asphalt, and the structural enhancement effect of the skeleton within SSAM itself. The mainstream approach involves categorizing the morphological characteristics of SS aggregates into macro, meso, and micro scales, and systematically investigating the interfacial enhancement mechanisms at these three distinct levels (Cui et al., 2018, 2022). At the mesoscopic level, the morphological features of aggregates are predominantly characterized by Texture, which encapsulates the degree of surface roughness. Collectively, Angularity, Sphericity, and Texture constitute the geometric characteristics of aggregates, with their dimensional representations illustrated in the accompanying figure. Research has demonstrated that SS, owing to its pronounced angularity, low sphericity, and high surface texture characteristics, exhibits superior bonding performance with asphalt. This conclusion has been substantiated through both direct and indirect experimental evidence (Cui et al., 2018; Yang et al., 2022a). Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) are sophisticated techniques employed for the characterization of the microscopic morphology of aggregates, which can be utilized to observe the microporous structures on the surface of SS. With the assistance of such techniques, the porous honeycomb-like structure on the surface of SS has been directly observed. These pores significantly increase the specific surface area of the SS, thereby providing an anchoring effect for the asphalt and further enhancing the interfacial adhesion between the SS and the asphalt (Chai et al., 2020; Yang et al., 2022a). Furthermore, due to the presence of various alkaline oxides in SS, its alkaline nature readily facilitates chemical reactions with acidic asphalt, forming chemical bonds that enhance the interfacial properties between the two (Liu et al., 2019, 2020d). However, physical adsorption between the SS and asphalt remains the predominant mechanism (Liu et al., 2020b).

In the asphalt mixture, the aggregates interlock to form a skeleton structure, which plays an important role in bearing and distributing external loads. However, attributing these enhancement of the SSAM skeleton structure to the morphological characteristics of SS, such as its angularity and rough texture, is considered overly simplistic (Wang et al., 2024a). Therefore, characterizing the skeleton structure of SSAM and investigating its reinforcement mechanisms hold significant academic value and practical importance for enhancing material performance and advancing the relevant theoretical framework. Contact points, contact length, and contact orientation are commonly utilized metrics for quantifying the skeleton structure of SSAM. As contact point represents the relatively weaker locations within the stress transmission path of the aggregate skeleton under vehicular loading, they play a critical role in determining the structural stability of the aggregate framework (Wan et al., 2024). From the aforementioned research perspective, numerous studies have demonstrated that the incorporation of SS significantly enhanced the skeleton structure of SSAM (Cui et al., 2021b; Wang et al., 2024a; Xu et al., 2024). Cui et al. (2021b) demonstrated that, compared to conventional asphalt mixtures, SSAM exhibits superior skeletal structure integrity and enhanced damage resistance. Wang et al. (2024a) pioneered the concept of the Horizontal Overall Contact Index (HCI), an integrated parameter for evaluating the contact characteristics and skeletal structure quality of mixtures by incorporating aggregate property metrics. Research revealed that as the SS content increased, the HCI value exhibited a corresponding rise. This indicates that incorporating SS as an aggregate enhances the overall skeletal quality of the mixture, attributable to its pronounced angularity and rough surface texture working synergistically.

The porous surface, rough texture, and intricate angularity of SS endow it with significantly superior bonding performance with asphalt compared to conventional aggregates. Through interparticle interlocking and dense packing within the mixture, SS forms a highly stable skeletal structure with enhanced mechanical integrity, which critically governs the pavement performance improvement of SSAM.

3.3.3. Performance

Compared to conventional asphalt mixtures, the incorporation of SS significantly enhances the interfacial properties and skeleton structure of SSAM. This improvement is most directly reflected in the superior pavement performance exhibited by SSAM. Pavement performance refers to the comprehensive capability of road surfaces to withstand vehicle loads, environmental factors, and the effects of time, serving as a critical indicator for evaluating road quality and service life. Common pavement performance metrics include resistance to permanent deformation, skid resistance, and self-healing properties. This chapter provides a systematic review of the pavement performance of SSAM and summarizes the key limiting factors hindering the large-scale application of SS.

1) Mechanical properties

The mechanical properties of pavement refer to its response and performance under the influence of vehicular loads and environmental factors, which directly impact the service life, safety, and comfort of the road. Key performance characteristics include resistance to permanent deformation, fatigue resistance, and the ability to withstand cracking under varying temperature conditions. Rutting is a visible manifestation of permanent deformation in asphalt pavement, representing an irreversible alteration in its structure (Pasetto et al., 2022). Currently, research on the permanent deformation resistance of SSAM is relatively comprehensive. Chen and Wei (2016), Kim et al. (2018) conducted tests on the permanent deformation resistance of SSAM using the wheel track test, revealing that SSAM exhibited varying degrees of improvement in permanent deformation resistance compared to conventional asphalt mixtures. Furthermore, Marshall stability serves as a critical indicator for evaluating the deformation resistance of asphalt mixtures under traffic loads. Numerous scholars conducted in-depth experimental studies on the Marshall stability and flow characteristics of asphalt mixtures, demonstrating that the incorporation of SS significantly enhanced the resistance to permanent deformation under traffic loading conditions (Ahmedzade & Sengoz, 2009; Ziaee & Behnia, 2020). In flexible asphalt pavements, fatigue cracking represents a critical failure mechanism. Studies showed that the incorporation of SS significantly improved the fatigue resistance of asphalt mixtures, thereby effectively mitigating the occurrence of fatigue cracking and extending the pavement's service life (Pasetto et al., 2017; Yang et al., 2022a). Alnadish et al. (2021) revealed that asphalt mixtures incorporating SS coarse aggregates exhibit markedly enhanced fatigue resistance compared to those utilizing conventional granite aggregates. As illustrated in Table 6, studies on the mechanical behavior of SSAM demonstrate that the inclusion of SS markedly improves the mechanical properties of asphalt mixtures, with the optimal SS dosage being 75% for maximum performance enhancement. Numerous studies demonstrated that the use of SS as an aggregate in asphalt mixtures significantly enhanced the mechanical properties of SSAM, showcasing its potential to replace conventional natural aggregates.

2) Skid resistance

From the perspective of vehicular safety, skid resistance constitutes a critical factor influencing road traffic safety (Pang et al., 2023). Consequently, in-depth research on the skid resistance performance of asphalt mixtures is of paramount significance for enhancing road safety standards and exploring their engineering application value. It is noteworthy that the incorporation of SS significantly enhances the micro-roughness of aggregate surfaces and increases the proportion of positive texture, thereby exerting a substantial positive influence on the improvement of anti-skid performance in SSAM (Cui et al., 2023; Yang et al., 2022a). To comprehensively evaluate the skid resistance performance of SSAM, Cui et al. (2020) employed two complementary testing methodologies to validate the superior skid resistance performance of SSAM: the research team initially conducted assessments using the British Pendulum Test (BPT), while innovatively incorporating advanced laser scanning technology to achieve precise capture and quantitative analysis of the intricate surface texture characteristics of the SSAM. Furthermore, conducting wear tests to simulate the degradation process of skid resistance performance holds significant research value, which is determined by the characteristic that the skid resistance performance of road surfaces gradually diminishes over time. Wang et al. (2024b) investigated the time-dependent characteristics of the skid resistance performance of SSAM, revealing that compared to natural aggregates, SS maintains superior macro-texture angles, more pronounced surface texture roughness, and more durable skid resistance properties even after prolonged wear. Systematic analysis based on extensive experimental data and research findings demonstrates that SSAM exhibits remarkable superiority in terms of skid resistance. As shown in Table 7, the incorporation of SS enhances the skid resistance of asphalt mixtures, with the optimal skid resistance of SSAM achieved at an SS content of 50–60%. These research discoveries not only establish a solid theoretical foundation for the practical application of SSAM in engineering projects but also provide essential guidance for their widespread implementation.

Table 6. Research on the mechanical properties of SS

References	SS type	Control mix	Mechanical properties	Particle size used (mm)	Percentage used (%)	Optimal content (%)
Yang et al. (2024)	–	diabase	increase	5–15	0, 25, 50, 75, 100	75
Goli (2022)	–	limestone	increase	–	0, 25, 50, 75	75
Ziaee and Behnia (2020)	EAFS	limestone	increase	0–15	0, 25, 50, 75	75
Pasetto and Baldo (2011)	EAFS	limestone	increase	0-10	0, 30, 60, 90	90
Pattanaik et al. (2021)	EAFS	–	increase	0–15	0, 25, 50, 75, 100	75

Table 7. Research on the skid resistance of SS

References	SS type	Control mix	Skid resistance	Particle size used (mm)	Percentage used (%)	Optimal content (%)
Ji et al. (2023a)	BOFS	limestone	increase	2.35–9.5	0, 25, 50, 75, 100	50
Yang et al. (2022a)	BOFS	basalt	increase	2.36–16	30, 40, 50	50
Song et al. (2024)	BOFS	–	increase	4.75–16	0, 20, 60	60
Zhang et al. (2024c)	–	limestone	increase	2.36–13.2	0, 25, 50, 75	50
Ji et al. (2023b)	–	limestone	increase	2.36–9.5	0, 25, 50, 75, 100	50

3) Thermal performance

The thermal performance, as one of the critical characteristics of SSAM, has also garnered widespread attention. The utilization of thermal properties for asphalt mixture has been demonstrated as an effective pavement maintenance methodology, particularly in addressing prevalent distresses such as cracking and spalling in asphalt pavements. Currently, electromagnetic induction heating and microwave heating are two leading pavement repair methods. They work by heating metal particles in the mixture, which improves asphalt binder flow through heat transfer, enabling pavement self-healing. Notably, SS contains metal oxides like Al_2O_3, CaO, Fe_2O_3, and Fe_3O_4, giving it excellent heating properties and high energy efficiency (Cui et al., 2021a; He et al., 2024). Through systematic experimental investigations, Yang et al. (2022b) have demonstrated that the incorporation of SS significantly enhances the self-healing properties of asphalt mixtures compared to conventional ones. Benefiting from the superior self-healing properties of SSAM, its application as a pavement material significantly reduces maintenance costs (Liu et al., 2023). Notably, the self-healing capacity of SSAM may exhibit a strong correlation with both the particle size composition of aggregates and the number of thermal cycling treatments (Liu et al., 2022; Yang et al., 2022b). As summarized in Table 8, research on the thermal characteristics of SSAM indicates that the combination of 60% SS content and a particle size distribution of 4.75–9.5 mm yields the most favourable thermal performance.

4) Limitation

Despite demonstrating superior performance across multiple technical metrics, the widespread adoption of SSAM remains constrained by several practical limitations. Chief among these is the propensity of oxide-rich components in SS to undergo hydration reactions, resulting in volumetric expansion – a characteristic that has been identified as a critical driver of pavement structural degradation (Santamaria et al., 2018; Sun et al., 2024, 2025). Currently, the modification of SS primarily involves pretreatment techniques, including natural aging, surface modification treatments, and chemical solution immersion methods (Sun et al., 2023, 2024). Sun et al. (2024) investigated various pretreatment methods for SS and evaluated their modification effects through comparative experiments. The research findings demonstrate that pretreatment techniques can significantly improve the volume expansion characteristics of SSAM, with surface treatment exhibiting the most optimal modification efficacy. Although these treatment methods have been proven effective in controlling the volume expansion of SS, the associated increase in economic costs and reduction in time efficiency remain unresolved issues. Moreover, the leaching potential of heavy metal contaminants (Cu, As, Zn, etc.) from SS under hydrological conditions (e.g., precipitation events) presents non-negligible ecotoxicological risks, including bioaccumulation hazards and ecosystem disruption (Barišić et al., 2017; Francisca & Glatstein, 2020). This persistent environmental concern constitutes a major technological barrier to the widespread implementation of SSAM in civil infrastructure applications. Gan et al. (2022) conducted a systematic investigation into the leaching mechanisms of heavy metals SS, revealing that Cu exhibits the highest migration potential and ecological risk. Further studies demonstrated that the leaching behavior of heavy metals in mixtures is predominantly governed by aggregate gradation types. These findings provide critical theoretical foundations for controlling heavy metal contamination during the application of SSAM. In contrast to open-air stockpiling disposal methods, the resource utilization of SS in road construction demonstrates significantly enhanced environmental benefits. Research confirms that the encapsulation effect of asphalt binder effectively immobilizes heavy metals within SS, thereby substantially mitigating potential risks to surrounding ecosystems (Cui et al., 2021a; Liu et al., 2020a). Through systematic experimental investigation, Sorlini et al. (2012) conclusively demon-

Table 8. Research on the thermal performance of SS

References	SS type	Control mix	Thermal performance	Percentage used (%)	Optimal content (%)	Optimal sizes (mm)
Lou et al. (2020)	BOFS	limestone	increase	0, 20, 40, 60, 80,100	60	4.75–9.5
Liu et al. (2021c)	BOFS	limestone	increase	0, 25, 50, 75, 100	–	4.75–9.5
Chen et al. (2022a)	–	basalt	increase	0, 50, 100	50	4.75–13.2
Zhang et al. (2024d)	BOFS	limestone	increase	0, 25, 50,75, 100	50	–
Luo et al. (2022)	–	limestone	increase	0, 20, 40, 60, 80, 100	60	4.75–9.5

strated that SS encapsulated with asphalt binder exhibits significantly reduced heavy metal leaching concentrations compared to untreated SS. This pivotal finding not only verifies the immobilization effect of asphalt encapsulation on heavy metals in SS, but more importantly, provides critical environmental safety and technical feasibility support for large-scale engineering applications of SSAM.

4. Sustainability performance of recyclable SWMs in asphalt pavement

4.1. Employment of life cycle assessment (LCA) analysis

As a systematic evaluation technology, LCA theory is widely employed to quantify the environmental impact of sustainable asphalt pavement from material production, construction, maintenance and even end-of-life (Anastasiou et al., 2015; Fanijo et al., 2023). It is widely accepted that the good sustainability and environmental impact reduction are the main advantages of recycling SWM in asphalt pavement. As representatives of climate change in LCA category, greenhouse gases (GHG) or global warming potential (GWP) is the most representative index. The quantified GHG reduction of three typical materials in asphalt mixtures is tabulated in Table 9.

LCA was mostly performed and interpreted on software platforms such as SimaPro, OpenLCA, CMLCA, and GaBi (Medina et al., 2023). Most of LCA analysis followed the international standard ISO 14040:2006 (International Organization for Standardization, 2006) and comprised four sequent analysis steps including the definition of goal and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation (Cao et al., 2025), which varied with analysed material types and applications. Especially, LCIA covers multiple impact categories including but not limited to the climate change, fossil depletion, freshwater ecotoxicity, freshwater eutrophication, human toxicity, marine ecotoxicity, marine eutrophication, particulate matter formation, terrestrial acidification, ozone depletion, terrestrial ecotoxicity and water depletion (Bressi et al., 2021).

4.2. LCA analysis on rubberized asphalt pavement

Table 9 tabulated two sort of common system boundaries in LCA of rubberized asphalt pavement: cradle-to-gate and cradle-to-grave. The difference between these two boundaries focused on whether the maintenance and end-of-life of rubberized pavement was considered. It is obvious that cradle-to-grave could lead to more reduction of GHG emissions than cradle-to-gate. The CR employed in asphalt pavement was generally derived from the waste tires, which initiated the sustainable process of recycling of waste tires. Therefore, a 'cut-off' approach was mostly adopted for the evaluation of the burdens and benefits associated with the use of CRs, in which the process of tire production was not considered. According to this approach, the production process of rubberized asphalt pavement included shredding and granulating, pretreatment (if there's any), asphalt production, aggregate production, asphalt mixtures production and layer construction, and transportation materials.

Figure 10 illustrates an example of relative contribution of different life cycle phases for environmental impacts due to the use of CR in asphalt mixture. It is obvious that "Bitumen production" phase and "Asphalt mixture production and layer construction" phase were the main phases that contributed to the environmental impacts. Additionally, the "Ambient grinding" phase was directly influenced by the recyclability of CRs. It should be noted that the CR in the case of Figure 10 was mixed with asphalt without any treatment. If the CR was pretreated or mixed in dry process, the environmental impacts of crumb rubberized asphalt mixtures would be different (Bressi et al., 2021).

Table 9. Quantification of LCA in sustainable asphalt mixtures

Materials	Sources	System boundaries	Quantification of GHG reduction
Crumb rubber	Ibrahim et al. (2024)	Cradle-to-Grave	83%, terminal blend vs. neat bitumen 63%, terminal blend vs. polymer-modified bitumen
	Xin et al. (2024)	Cradle-to-Gate	36–45%, vs. conventional bitumen
	Cao et al. (2025)	Cradle-to-Gate Cradle-to-Grave	44.6%, terminal blend vs. dry process 7%, terminal blend vs. wet process
RAP	Gruber and Hofko (2023)	Raw material-Transportation-Production-Construction-Process-End-of-life	17%, major in production stage
	Tushar et al. (2025)	Raw materials-Manufacturing-Mixing & construction-Maintenance-Operation	28.81%, major in maintenance stage
	De Pascale et al. (2023)	Raw materials-Production-Transportation-Recycling	25%, major in transportation stage
SS	Zhong et al. (2024)	Material production-Transportation-Construction	1.1%–8.6%, major in material production stage
	Liu et al. (2023)	Raw materials-Transportation-Mixing, & construction-Maintenance	20%–28%, major in maintenance stage
	Zhang et al. (2025a)	Materials-Recycling-Production-Distribution-Construction-End-of-life	29.55%–53.95%, major in recycling stage

1) Influence of treatment methods on environmental impacts of recycling CR

As mentioned in Section 3.1.1, chemical or physical treatment methods has been proved to be effective on increasing the compatibility between the CR particles and asphalt matrix. Although the service performances of crumb rubberized asphalt mixtures could be enhanced, the treatment methods inevitably increase the energy consumption and potential environmental impacts. As a comparison to the rubberized asphalt mixtures without treatments in Figure 10, Bressi et al. (2021) conducted LCA on rubberized asphalt mixtures with devulcanization of CR, in which plasticisers (pine tar and rosin) were employed under a temperature of 230 °C and a pressure of 2.2 MPa. Figure 11 illustrates the environmental impact of rubberized asphalt mixtures considering devulcanization and refining process. It could be concluded from Figure 11 that the devulcanization of CR significantly contributed to all categories of environmental impacts except for fossil depletion and marine ecotoxicity.

Similar conclusions were drawn by other researchers. Rajagopal et al. (2024) investigated CR modification on concrete, and conducted LCA considering the chemical treatment on CR. Their findings supported that the usage of NaOH solution for pretreatment of CR marginally increased the environmental impacts in comparison to the

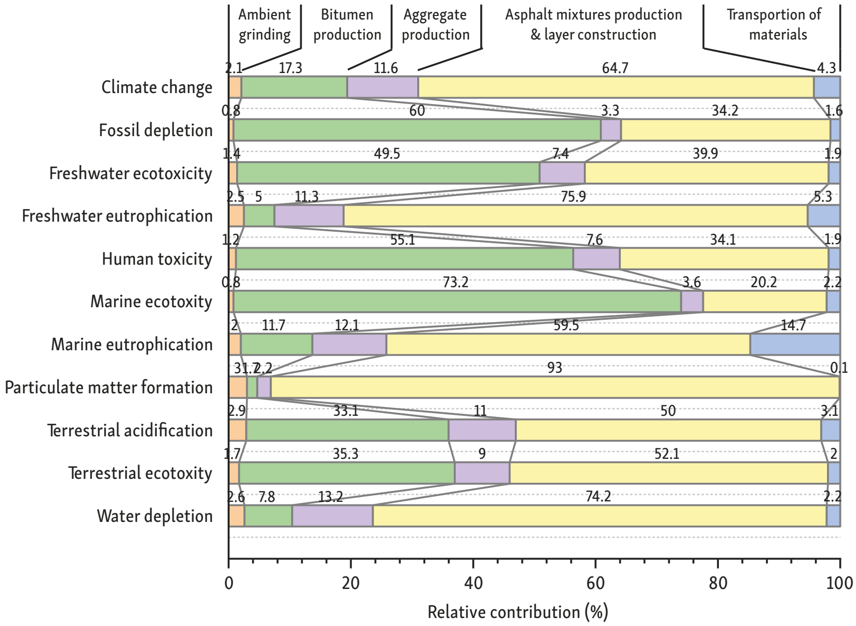


Figure 10. Relative contribution of the different life cycle phases and subphases for environmental impacts due to the use of asphalt mixture with vulcanised CR (Reproduced from Bressi et al., 2021)

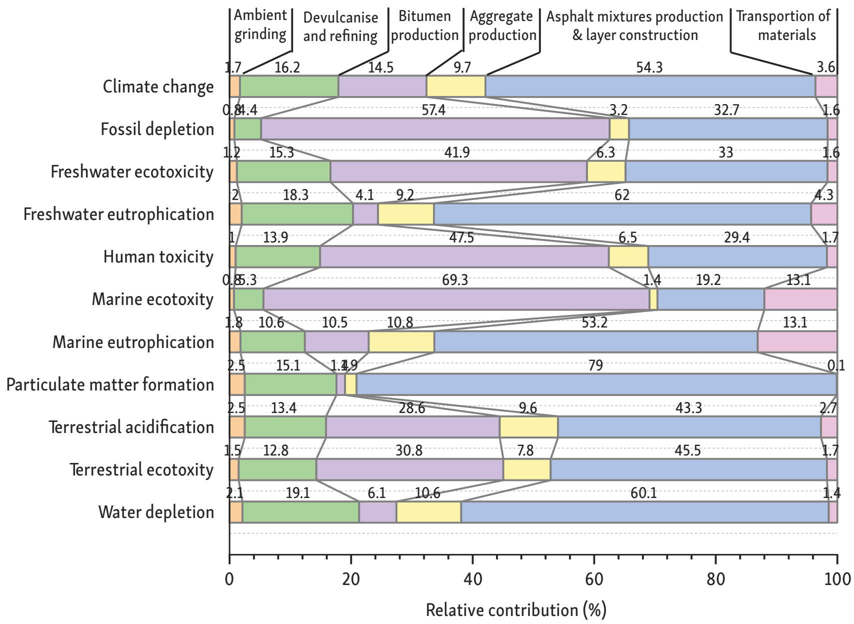


Figure 11. Relative contribution of the different life cycle phases and subphases for environmental impacts due to the use of asphalt mixture with devulcanized CR (Reproduced from Bressi et al., 2021)

untreated modifications. Although the pretreatment on CR increased the environmental impact to some degrees, such increment in environmental impacts could be compensated by proper design of recyclable materials. Bressi et al. (2018) conducted a comparative LCA of asphalt mixtures containing CR and RAP for railway sub-ballast applications. It is reported that while CRMA had higher environmental impacts due to rubber treatment and increased bitumen usage, RAP-based mixtures showed significant environmental improvements, especially with full binder blending. Currently, only few literatures focused on the LCA of treatment methods of CRs in asphalt modification. The research on the optimal design of recyclable sustainable materials to reach minimum environmental impact is still needed.

2) Influence of CR particle size on environmental impacts

In many LCA cases that adopted "cut-off" strategy, the LCA phases usually started with the end-of-life tires, i.e. CRs. However, the CR particle size was mostly ignored although it's been proved that particle size showed significant influences on service performances of crumb rubberized asphalt mixtures (as stated in Section 3.1.3). Liang et al. (2020) reported that the production of fine CR (0.5~2 mm) might increase energy consumption by 15–20% compared to coarse particles (5~10 mm), which potentially offset environmental benefits. Similarly, Patrisia et al. (2025) concluded that CR concrete with coarse particles demonstrated lower resource depletion and toxicity impacts compared to finer alternatives. Meanwhile, coarser rubber reduced reliance on virgin aggregates in construction, aligning with circular economy principles and lowering global warming potential by 8–9% in cradle-to-gate scenarios.

The above descriptions both support the conclusion that production of finer rubber particles increased energy consumption, toxicity impacts and emissions. However, the acknowledged advantages of finer rubber particles on improvements of storage stability and durability could not be ignored in LCA categories. Liang et al. (2020) also reported that finer rubber particles only contributed marginally higher CO_2 emissions (e.g., 0.33–3.05% variance) due to processing, but their improved performance in applications like asphalt can offset these impacts over the product lifecycle.

Conclusively, current research gaps involved direct LCA comparisons across different particle sizes in CR production, including the quantification of energy and emissions for specific size ranges, and the evaluations of trade-offs between the environmental impacts of CR production and the service performances.

4.3. LCA analysis on RAP modified asphalt pavement

1) Impact of RAP content on environmental sustainability

Numerous studies have shown that increasing the RAP content in asphalt mixtures can substantially reduce energy consumption and GHG emissions. For instance, Tushar et al. (2025) used SimaPro to conduct an LCA on RAP incorporation in asphalt mixtures. They found that replacing virgin materials with 60% rejuvenated RAP reduced carbon emissions by up to 31.85%. Similarly, Rout et al. (2023) observed that using RAP as a recycled aggregate in concrete pavements could reduce GHG emissions by approximately 42% over a 30-year period. These findings highlight the potential of high RAP content to mitigate environmental impacts across the pavement lifecycle. Moreover, Yu et al. (2013) developed a life cycle analysis and life cycle cost analysis (LCA-LCCA) model that optimizes pavement maintenance to reduce energy consumption, GHG emissions, and total costs. Abdalla et al. (2022) further confirmed that increasing RAP content (0%, 15%, 30%, 50%, 80%, and 100%) consistently reduces environmental impacts across multiple indicators, reinforcing the environmental value of maximizing RAP use. However, concerns remain regarding long-term durability at high RAP levels, which may lead to increased maintenance needs. This underscores the need for further research into degradation models for high-RAP mixtures and more robust performance data from the construction and service phases.

2) Environmental implications of RAP processing

Beyond material substitution benefits, the processing of RAP plays a critical role in its overall environmental impact. Tushar et al. (2025) noted that high moisture content in RAP significantly increased heating energy demand, thereby reducing the net environmental benefits of its use. Moisture management thus becomes a key factor in realizing the full sustainability potential of RAP-based mixtures. Furthermore, Zheng et al. (2019) conducted a comparative study between traditional thin hot mix asphalt layers and RAP-incorporated strategies, finding that although RAP use reduced economic costs by approximately 8.4%, the additional energy consumption required for crushing and reheating the reclaimed materials introduced notable environmental burdens. These findings underscore the need for balanced design approaches that consider both environmental performance and the energy intensity of processing operations when maximizing RAP utilization. To optimize the environmental benefits of RAP, future research should focus on enhancing the performance and durability of high-RAP mixtures, alongside the development of more energy-efficient processing techniques, ensuring that both sustainability and performance are maximized across the lifecycle.

4.4. LCA analysis on SS modified asphalt pavement

De Pascale et al. (2023) conducted a comparative LCA of three distinct asphalt mixtures, demonstrating that the incorporation of EAFS with RAP yields optimal environmental benefits, achieving a 25% reduction in environmental impact. This demonstrates that the recycling of SS and other solid wastes in road construction can generate positive ecological impacts, aligning with the principles of sustainable development. Research findings demonstrate that, compared to conventional asphalt mixtures, SS-modified asphalt mixtures exhibit significant advantages in CO_2 emissions when assessed using the LCA methodology. Specifically, SS-modified mixtures show markedly lower carbon emissions throughout their life cycle, with this reduction being particularly pronounced during the raw material production and pavement maintenance units (De Pascale et al., 2023; Liu et al., 2023; Zhang et al., 2025a).

1) Raw material production unit

When considering solely the CO_2 emissions from the raw material production unit, SS typically exhibits a higher carbon footprint compared to natural aggregates. However, when accounting for the avoided landfill disposal emissions through slag recycling within the system boundaries, its lifecycle carbon emission performance demonstrates significant improvement (Liu et al., 2023; Zhang et al., 2025). Zhang et al. (2025) revealed that SSAM exhibited considerable potential as a low-carbon construction material. The results demonstrated a significant decreasing trend in total carbon emissions with increasing SS content, primarily attributed to the emission reduction achieved through SS recycling. Distinctively, this study pioneered a comprehensive systematic evaluation integrating both environmental benefits and road performance characteristics of SSAM. The research conclusively determined that a 60% SS incorporation ratio achieves optimal comprehensive performance.

2) Pavement maintenance unit

The experimental results confirmed that SSAM exhibited remarkable self-healing capabilities, primarily owing to the superior thermal conductivity properties of SS (Liu et al., 2023; Luo et al., 2022). The findings demonstrated that the self-healing properties of SSAM could effectively eliminate the need for extensive manual repairs. Through its intrinsic thermal-activated self-restoration mechanism, SSAM significantly reduces carbon emissions associated with maintenance activities. Liu et al. (2023) systematically characterized the self-healing mechanisms and performance of SSAM, while also identifying its significant CO_2 emission reduction benefits during the maintenance phase.

5. Recommendations for future perspectives

This paper makes a general review of the mechanical performance and life cycle assessment of asphalt pavements considering the involvement of three typical SWM (rubber, RAP, and SS). As mentioned in Section 2, the three typical SWM were selected from the scientometric analysis of literature database in recent years. Although not within the scope of this review, some other SWM such as bricks, fly ash, or reclaimed concrete aggregates (RCA) played important roles in performance improvement and decarbonisation of asphalt pavement (Ahmed et al., 2025). With the industrial and technological development, the employment and impact of SWM in asphalt mixtures may furtherly evolve (Xu et al., 2021a). Therefore, the research on SWM in mechanical and environmental impact in asphalt mixtures needs updates according to technological developments.

Additionally, the employment of three typical SWM (rubber, RAP, and SS) is not limited in asphalt pavement but also in other engineering fields. For example, rubbers derived from waste tyres have shown advantages on performance enhancement of concrete and soil. The concrete containing rubber particles have better performances on sustaining freeze-thawing protection (Richardson et al., 2016) and strength improvement (Thomas & Gupta, 2016). In geotechnical application, crumb rubber was beneficial in soil stabilization (Juliana et al., 2020; Ravi et al., 2024) and seismic isolation performance (Kuvat et al., 2024; Pitilakis et al., 2024). SS was also employed in atmospheric improvement (Huijgen et al., 2005), wastewater treatment (Yu et al., 2022), and marine environment management (Ogawa et al., 2020). These studies have consistently demonstrated the remarkable efficacy of SS in significantly reducing airborne pollutants such as NOx and SO_2 (Sun et al., 2017; Xing et al., 2022), achieving high removal rates of heavy metals and organic contaminants in industrial wastewater (Yu et al., 2022), and effectively restoring marine ecosystems by enhancing water clarity and biodiversity (Liu et al., 2021c; Yu et al., 2021). Although the SWM have been widely used in other engineering fields, the improvement mechanism of these materials is mutually shared. Hence, the application and treatment of SWM in other engineering fields could be a reference in asphalt mixtures improvement.

6. Conclusions

This paper makes the state-of-the-art review on recycling of SWMs in the production of sustainable low-carbon asphalt pavements based on recent five-years (2020–2025) literatures. According to the scientometric analysis of the literature, three typical SWMs (rubber, RAP and SS) are selected to be mainly discussed over the influences on the service performance and environmental impacts of sustainable asphalt pavements. Based on this overview, the following conclusive remarks could be drawn:

1. Co-occurrence analysis showed that the most utilized SWMs in asphalt pavement is crumb rubber, followed by RAP and SS. The leading country with most publications in sustainable asphalt pavements has shifted from USA to China in the past ten years.
2. The service performance of rubberized asphalt pavement is essentially decided by the compatibility and interfacial cohesion between rubber and asphalt matrix, which could be influenced by multiple factors. Besides the pre-treatment methods (chemical or physical treatment) and producing technologies (wet, dry or terminal blend process), the particle size of rubber plays an important role as well. Literature

review concludes that rubber particles with smaller size imposed more positive influences on the service performance of asphalt pavements such as storage stability, fatigue resistance, moisture resistance and cracking resistance.

3. In terms of pretreatment method and size of rubber particles, there exists trade-offs between the environmental impacts and the service performances in production of rubberized asphalt pavements. Current research gaps involved direct LCA comparisons of different particle sizes in rubberized asphalt production, including the quantification of energy and emissions for specific size ranges, and the evaluations of mentioned trade-offs.
4. The incorporation of SS enhances the asphalt mixture's mechanical properties, skid resistance, and thermal performance to varying degrees, with the optimal comprehensive performance achieved at approximately 60% SS content.
5. Volume expansion and heavy metal leaching currently represent the primary limiting factors for large-scale application of SS in pavement infrastructure construction. However, appropriate pretreatment of SS can effectively mitigate these challenges.
6. The recycling and utilization of SS not only reduces raw material consumption but also significantly decreases CO_2 emissions associated with landfilling. Furthermore, the superior self-healing properties of SSAM contribute substantially to emission reduction during the maintenance phase.
7. The optimal RAP content varies by asphalt type, requiring adjustments based on the targeted performance. While RAP fractionation and rejuvenation techniques have improved mixture consistency and binder restoration, quantifying the effective blending degree and rejuvenation efficiency remains a technical challenge, especially for mixtures with high RAP content. Notably, full utilization of 100% RAP is still limited primarily by cracking, poor adhesion, and increased air voids. Moreover, optimal RAP content should be evaluated in the context of pavement type, traffic loading, and environmental conditions, as these factors critically influence the performance, durability, and service life of recycled asphalt mixtures.
8. The effects of RAP on asphalt mixture performance and strategies to mitigate performance degradation are explored. Moderate RAP content improves stiffness and rutting resistance, yielding mechanical properties comparable to virgin mixtures. However, at higher RAP levels, the aged binder introduces brittleness and blending challenges, compromising fatigue and cracking resistance. Although strategies such as rejuvenators and WMA additives have demonstrated the potential to restore aged binder properties and improve mixture workability, their long-term aging characteristics and durability under field conditions remain inadequately understood.
9. The integration of RAP in asphalt pavements demonstrates notable environmental benefits, particularly in terms of reducing energy consumption and greenhouse gas emissions over the pavement lifecycle. LCA highlights the sustainability advantages of high RAP content in mitigating environmental impacts during production and use. However, research gaps remain concerning long-term durability and processing energy consumption, particularly in balancing high-RAP content design with improved processing efficiency to enhance the overall environmental benefits.

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Author contributions

Yilin Wang and Guoyang Lu conceived this study and were responsible for the structure organization of this review. Zijun Xu, Yilin Wang and Zekang Sun were responsible for the data collection and analysis of RAP, Rubber, and SS in asphalt mixtures, respectively, and wrote the first draft of the article. Thomas Ng and Guoyang Lu were responsible for funding acquisition. Wisal Ahmed participated in the first draft and finished the revisions of the article.

Disclosure statement

The authors declare no conflict of interest.

References

Abdalla, A., Faheem, A. F., & Walters, E. (2022). Life cycle assessment of eco-friendly asphalt pavement involving multi-recycled materials: A comparative study. *Journal of Cleaner Production*, *362*, Article 132471. https://doi.org/10.1016/j.jclepro.2022.132471

Abdel-Jaber, M., Al-shamayleh, R. A., Ibrahim, R., Alkhrissat, T., & Alqatamin, A. (2022). Mechanical properties evaluation of asphalt mixtures with variable contents of reclaimed asphalt pavement (RAP). *Results in Engineering*, *14*, Article 100463. https://doi.org/10.1016/j.rineng.2022.100463

Ahmed, W., Lu, G., Ng, S. T., & Liu, G. (2025). Innovative valorization of solid waste materials for production of sustainable low-carbon pavement: A systematic review and scientometric analysis. *Case Studies in Construction Materials*, *22*, Article e04541. https://doi.org/10.1016/j.cscm.2025.e04541

Ahmedzade, P., & Sengoz, B. (2009). Evaluation of steel slag coarse aggregate in hot mix asphalt concrete. *Journal of Hazardous Materials*, *165*(1–3), 300–305. https://doi.org/10.1016/j.jhazmat.2008.09.105

Akatsu, K., Kanou, Y., & Akiba, S. (2022). Technical approaches to the recycling of reclaimed asphalt pavement into aggregate and binder. *Construction Materials*, *2*(2), 85–100. https://doi.org/10.3390/constrmater2020007

Akker, J. (2022). *Evaluation of material properties of hot mix asphalt mixtures with high levels of reclaimed asphalt pavement using multi-scale characterization* [Master's thesis]. Technical University of Delft.

Almusawi, A., Abdulrahman, H., Shakhan, M., & Dogaroglu, B. (2020). Effects of crumb rubber size and concentration on marshall parameters of rubberized asphalt mixture. *Pamukkale University Journal of Engineering Sciences-Pamukkale Universitesi Muhendislik Bilimleri Dergisi*, *26*(6), 1048–1052. https://doi.org/10.5505/pajes.2020.50318

Alnadish, A. M., Aman, M. Y., Katman, H. Y. B., & Ibrahim, M. R. (2021). Laboratory assessment of the performance and elastic behavior of asphalt mixtures containing steel slag aggregate and synthetic fibers. *International Journal of Pavement Research and Technology*, *14*(4), 473–481. https://doi.org/10.1007/s42947-020-1149-y

Al-Saffar, Z. H., Yaacob, H., Satar, M. K. I. M., & Jaya, R. P. (2021). Impacts of maltene on the wettability and adhesion properties of rejuvenated asphalt binder. *Arabian Journal for Science and Engineering*, *46*(11), 10557–10568. https://doi.org/10.1007/s13369-021-05413-0

Ameri, M., Hesami, S., & Goli, H. (2013). Laboratory evaluation of warm mix asphalt mixtures containing electric arc furnace (EAF) steel slag. *Construction and Building Materials*, *49*, 611–617. https://doi.org/10.1016/j.conbuildmat.2013.08.034

Anastasiou, E. K., Liapis, A., & Papayianni, I. (2015). Comparative life cycle assessment of concrete road pavements using industrial by-products as alternative materials. *Resources*, *Conservation and Recycling*, *101*, 1–8. https://doi.org/10.1016/j.resconrec.2015.05.009

Barazi Jomoor, N., Fakhri, M., & Keymanesh, M. R. (2019). Determining the optimum amount of recycled asphalt pavement (RAP) in warm stone matrix asphalt using dynamic creep test. *Construction and Building Materials*, *228*, Article 116736. https://doi.org/10.1016/j.conbuildmat.2019.116736

Barišić, I., Netinger Grubeša, I., & Hackenberger Kutuzović, B. (2017). Multidisciplinary approach to the environmental impact of steel slag reused in road construction. *Road Materials and Pavement Design*, *18*(4), 897–912. https://doi.org/10.1080/14680629.2016.1197143

Bilema, M., Aman, M., Hassan, N., Haloul, M., & Modibbo, S. (2021). Influence of crumb rubber size particles on moisture damage and strength of the hot mix asphalt. *Materials Today*: *Proceedings*, *42*, 2387–2391. https://doi.org/10.1016/j.matpr.2020.12.423

Bressi, S., Santos, J., Giunta, M., Pistonesi, L., & Lo Presti, D. (2018). A comparative life-cycle assessment of asphalt mixtures for railway sub-ballast containing alternative materials. *Resources*, *Conservation and Recycling*, *137*, 76–88. https://doi.org/10.1016/j.resconrec.2018.05.028

Bressi, S., Fiorentini, N., Huang, J., & Losa, M. (2019). Crumb rubber modifier in road asphalt pavements: State of the art and statistics. *Coatings*, *9*(6), Article 384. https://doi.org/10.3390/coatings9060384

Bressi, S., Santos, J., Oreskovic, M., & Losa, M. (2021). A comparative environmental impact analysis of asphalt mixtures containing crumb rubber and reclaimed asphalt pavement using life cycle assessment. *International Journal of Pavement Engineering*, *22*(4), 524–538. https://doi.org/10.1080/10298436.2019.1623404

Buritatum, A., Suddeepong, A., Akkharawongwhatthana, K., Horpibulsuk, S., Yaowarat, T., Hoy, M., Arulrajah, A., & Rashid, A. S. A. (2023). Hemp fiber-modified asphalt concretes with reclaimed asphalt pavement for low-traffic roads. *Sustainability*, *15*(8), Article 6860. https://doi.org/10.3390/su15086860

Cao, R., Leng, Z., Li, D., & Zou, F. (2025). Comparative life cycle assessment of three types of crumb rubber modified asphalt under different system boundaries. *Resources*, *Conservation and Recycling*, *212*, Article 107922. https://doi.org/10.1016/j.resconrec.2024.107922

Chai, C., Cheng, Y., Zhang, Y., Zhu, B., & Liu, H. (2020). Mechanical properties of crumb rubber and basalt fiber composite modified porous asphalt concrete with steel slag as aggregate. *Polymers*, *12*(11), Article 2552. https://doi.org/10.3390/polym12112552

Chen, J.-S., & Wei, S.-H. (2016). Engineering properties and performance of asphalt mixtures incorporating steel slag. *Construction and Building Materials*, *128*, 148–153. https://doi.org/10.1016/j.conbuildmat.2016.10.027

Chen, X., Wang, Y., Liu, Z., Dong, Q., & Zhao, X. (2022a). Temperature analyses of porous asphalt mixture using steel slag aggregates heated by microwave through laboratory tests and numerical simulations. *Journal of Cleaner Production*, *338*, Article 130614. https://doi.org/10.1016/j.jclepro.2022.130614

Chen, Z., Leng, Z., Jiao, Y., Xu, F., Lin, J., Wang, H., Cai, J., Zhu, L., Zhang, Y., Feng, N., Dong, Y., & Zhang, Y. (2022b). Innovative use of industrially produced steel slag powders in asphalt mixture to replace mineral fillers. *Journal of Cleaner Production*, *344*, Article 131124. https://doi.org/10.1016/j.jclepro.2022.131124

Chen, J., Wang, J., Shi, Z., Zhang, Z., & Dan, H. (2024a). Computational fracture analysis of steel slag asphalt mixture subjected to moisture damage. *Construction and Building Materials*, *433*, Article 136697. https://doi.org/10.1016/j.conbuildmat.2024.136697

Chen, Y., Hu, K., Chen, Y., Zhang, T., & Zhang, W. (2024b). Preparation and modification mechanism study of microwave-treated crumb rubber and waste engine oil-modified asphalt. *Environmental Science and Pollution Research*, *31*(8), 12483–12498. https://doi.org/10.1007/s11356-023-31144-w

Cheng, X., Huang, S., Guo, X., & Duan, W. (2017). Crumb waste tire rubber surface modification by plasma polymerization of ethanol and its application on oil-well cement. *Applied Surface Science*, *409*, 325–342. https://doi.org/10.1016/j.apsusc.2017.03.072

Cui, P., Xiao, Y., Yan, B., Li, M., & Wu, S. (2018). Morphological characteristics of aggregates and their influence on the performance of asphalt mixture. *Construction and Building Materials*, *186*, 303–312. https://doi.org/10.1016/j.conbuildmat.2018.07.124

Cui, P., Wu, S., Xiao, Y., Yang, C., & Wang, F. (2020). Enhancement mechanism of skid resistance in preventive maintenance of asphalt pavement by steel slag based on micro-surfacing. *Construction and Building Materials*, *239*, Article 117870. https://doi.org/10.1016/j.conbuildmat.2019.117870

Cui, P., Wu, S., Xiao, Y., Hu, R., & Yang, T. (2021a). Environmental performance and functional analysis of chip seals with recycled basic oxygen furnace slag as aggregate. *Journal of Hazardous Materials*, *405*, Article 124441. https://doi.org/10.1016/j.jhazmat.2020.124441

Cui, P., Wu, S., Xiao, Y., Liu, Q., & Wang, F. (2021b). Hazardous characteristics and variation in internal structure by hydrodynamic damage of BOF slag-based thin asphalt overlay. *Journal of Hazardous Materials*, *412*, Article 125344. https://doi.org/10.1016/j.jhazmat.2021.125344

Cui, P., Wu, S., Liu, Q., & Wang, F. (2022). Artificial neural network modeling for predicting surface texture and its attenuation of micro-surfacing containing steel slag aggregates. *Construction and Building Materials*, *346*, Article 128504. https://doi.org/10.1016/j.conbuildmat.2022.128504

Cui, P., Ma, T., Wu, S., Xu, G., & Wang, F. (2023). Texture characteristic and its enhancement mechanism in stone mastic asphalt incorporating steel slag. *Construction and Building Materials*, *369*, Article 130440. https://doi.org/10.1016/j.conbuildmat.2023.130440

Da Silva, L., Benta, A., & Picado-Santos, L. (2018). Asphalt rubber concrete fabricated by the dry process: Laboratory assessment of resistance against reflection cracking. *Construction and Building Materials*, *160*, 539–550. https://doi.org/10.1016/j.conbuildmat.2017.11.081

De Pascale, B., Tataranni, P., Lantieri, C., Bonoli, A., & Vignali, V. (2023). Mechanical performance and environmental assessment of porous asphalt mixtures produced with EAF steel slags and RAP aggregates. *Construction and Building Materials*, *400*, Article 132889. https://doi.org/10.1016/j.conbuildmat.2023.132889

Devulapalli, L., Kothandaraman, S., & Sarang, G. (2020). Effect of rejuvenating agents on stone matrix asphalt mixtures incorporating RAP. *Construction and Building Materials*, *254*, Article 119298. https://doi.org/10.1016/j.conbuildmat.2020.119298

Díaz, R., & Sandoval, C. (2023). Effect of the grain size of recycled rubber on the behaviour of an asphalt mix. *Revista Ingenieria De Construccion*, *38*(1), 163–175. https://doi.org/10.7764/RIC.00059.21

Dong, D., Huang, X., Li, X., & Zhang, L. (2012). Swelling process of rubber in asphalt and its effect on the structure and properties of rubber and asphalt. *Construction and Building Materials*, *29*, 316–322. https://doi.org/10.1016/j.conbuildmat.2011.10.021

European Asphalt Pavement Association. (2022). *Asphalt in figures 2022*.

El Sharkawy, S. A., Wahdan, A. H., & Galal, S. A. (2016). Utilisation of warm-mix asphalt technology to improve bituminous mixtures containing reclaimed asphalt pavement. *Road Materials and Pavement Design*, *18*(2), 477–506. https://doi.org/10.1080/14680629.2016.1162731

Elkashef, M., Williams, R. C., & Cochran, E. W. (2018). Physical and chemical characterization of rejuvenated reclaimed asphalt pavement (RAP) binders using rheology testing and pyrolysis gas chromatography-mass spectrometry. *Materials and Structures*, *51*(1), Article 12. https://doi.org/10.1617/s11527-018-1141-z

Elnaggar, M. Y., Fathy, E. S., Amdeha, E., & Hassan, M. M. (2019). Impact of gamma irradiation on virgin styrene butadiene rubber blended with ultrasonically devulcanized waste rubber. *Polymer Engineering & Science*, *59*(4), 807–813. https://doi.org/10.1002/pen.25014

Faccin, C., Specht, L., Schuster, S., Boeira, F., Bueno, L., Brondani, C., Pereira, D., & do Nascimento, L. (2022). Flow number parameter as a performance criteria for asphalt mixtures rutting: Evaluation to mixes applied in Brazil Southern region. *International Journal of Pavement Engineering*, *23*(9), 3055–3067. https://doi.org/10.1080/10298436.2021.1880580

Fakhri, M., & Ahmadi, A. (2017). Recycling of RAP and steel slag aggregates into the warm mix asphalt: A performance evaluation. *Construction and Building Materials*, *147*, 630–638. https://doi.org/10.1016/j.conbuildmat.2017.04.117

Fan, Y., Chen, H., Yi, X., Gong, M., Xu, G., Shi, C., Huang, S., Zhou, Y., Wu, Y., Yang, J., Leng, Z., & Huang, W. (2024). Fatigue performance evaluation of epoxy-recycling technology utilising 100% reclaimed asphalt pavement (RAP): Binders and mixtures. *International Journal of Pavement Engineering*, *25*(1), Article 2409902. https://doi.org/10.1080/10298436.2024.2409902

Fanijo, E. O., Kolawole, J. T., Babafemi, A. J., & Liu, J. (2023). A comprehensive review on the use of recycled concrete aggregate for pavement construction: Properties, performance, and sustainability. *Cleaner Materials*, *9*, Article 100199. https://doi.org/10.1016/j.clema.2023.100199

Farouk, A. I. B., Hassan, N. A., Mahmud, M. Z. H., Mirza, J., Jaya, R. P., Hainin, M. R., Yaacob, H., & Yusoff, N. I. Md. (2017). Effects of mixture design variables on rubber–bitumen interaction: Properties of dry mixed rubberized asphalt mixture. *Materials and Structures*, *50*(1), Article 12. https://doi.org/10.1617/s11527-016-0932-3

Fathy, E. S., Saleh, H. H., Elnaggar, M. Y., & Ali, Z. I. (2018). Gamma irradiation of (styrene butadiene rubber)/(devulcanized waste rubber) blends modified by organoclay. *Journal of Vinyl and Additive Technology*, *24*(1), 50–57. https://doi.org/10.1002/vnl.21524

Fathy, E. S., Elnaggar, M. Y., & Raslan, H. A. (2019). Thermoplastic elastomer based on waste polyethylene/waste rubber containing activated carbon black: Impact of gamma irradiation. *Journal of Vinyl and Additive Technology*, *25*(S1), E166–E173. https://doi.org/10.1002/vnl.21675

Feiteira Dias, J. L., Picado-Santos, L. G., & Capitão, S. D. (2014). Mechanical performance of dry process fine crumb rubber asphalt mixtures placed on the portuguese road network. *Construction and Building Materials*, *73*, 247–254. https://doi.org/10.1016/j.conbuildmat.2014.09.110

Fonseca da Costa, R., Aparicio Alvis, M. C., & Castorena, C. (2024). Validation of a sieve analysis procedure to quantify reclaimed asphalt pavement (RAP) binder availability. *International Journal of Pavement Engineering*, *25*(1), Article 2427269. https://doi.org/10.1080/10298436.2024.2427269

Francisca, F. M., & Glatstein, D. A. (2020). Environmental application of basic oxygen furnace slag for the removal of heavy metals from leachates. *Journal of Hazardous Materials*, *384*, Article 121294. https://doi.org/10.1016/j.jhazmat.2019.121294

Gan, Y., Li, C., Zou, J., Wang, W., & Yu, T. (2022). Evaluation of the impact factors on the leaching risk of steel slag and its asphalt mixture. *Case Studies in Construction Materials*, *16*, Article e01067. https://doi.org/10.1016/j.cscm.2022.e01067

Gao, B., Xu, H., Wu, S., Wang, H., Yang, X., & Chen, P. (2024). Research on improving moisture resistance of asphalt mixture with compounded recycled metallurgical slag powders. *Materials*, *17*(14), Article 3499. https://doi.org/10.3390/ma17143499

Garraín, D., & Lechón, Y. (2019). Environmental footprint of a road pavement rehabilitation service in Spain. *Journal of Environmental Management*, *252*, Article 109646. https://doi.org/10.1016/j.jenvman.2019.109646

Ge, D., Jiang, X., Lv, S., Zhang, H., & Song, X. (2024). Research progress of rubber-modified asphalt by wet process. *Journal of China and Foreign Highway*, *44*(6), 27–50.

Goli, A. (2022). The study of the feasibility of using recycled steel slag aggregate in hot mix asphalt. *Case Studies in Construction Materials*, *16*, Article e00861. https://doi.org/10.1016/j.cscm.2021.e00861

Gruber, M. R., & Hofko, B. (2023). Life cycle assessment of greenhouse gas emissions from recycled asphalt pavement production. *Sustainability*, *15*(5), Article 4629. https://doi.org/10.3390/su15054629

Guo, F., Shen, Z., Jiang, L., Long, Q., & Yu, Y. (2024a). Study on the performance of asphalt modified with bio-oil, SBS and the crumb rubber particle size ratio. *Polymers*, *16*(13), Article 1929. https://doi.org/10.3390/polym16131929

Guo, F., Shen, Z., Yu, Z., Jiang, L., Long, Q., & He, C. (2024b). Performance study of SBS/CRMA with different composite crumb rubber particle size ratios. *Case Studies in Construction Materials*, *20*, Article e03232. https://doi.org/10.1016/j.cscm.2024.e03232

He, Y., Xiong, K., Zhang, J., Guo, F., Li, Y., & Hu, Q. (2024). A state-of-the-art review and prospectives on the self-healing repair technology for asphalt materials. *Construction and Building Materials*, *421*, Article 135660. https://doi.org/10.1016/j.conbuildmat.2024.135660

Hoon Moon, K., Cannone Falchetto, A., Wang, D., Wistuba, M. P., & Tebaldi, G. (2017). Low-temperature performance of recycled asphalt mixtures under static and oscillatory loading. *Road Materials and Pavement Design*, *18*(2), 297–314. https://doi.org/10.1080/14680629.2016.1213500

Hu, J., Wang, L., Guo, C., & Liu, H. (2024). Quantitative study on fatigue characteristics of warm mix recycled asphalt. *Construction and Building Materials*, *431*, Article 136532. https://doi.org/10.1016/j.conbuildmat.2024.136532

Huijgen, W. J. J., Witkamp, G.-J., & Comans, R. N. J. (2005). Mineral CO_2 sequestration by steel slag carbonation. *Environmental Science & Technology*, *39*(24), 9676–9682. https://doi.org/10.1021/es050795f

Ibrahim, I. M., Fathy, E. S., El-Shafie, M., & Elnaggar, M. Y. (2015). Impact of incorporated gamma irradiated crumb rubber on the short-term aging resistance and rheological properties of asphalt binder. *Construction and Building Materials*, *81*, 42–46. https://doi.org/10.1016/j.conbuildmat.2015.01.015

Ibrahim, H., Marini, S., Farina, A., & Lanotte, M. (2024). Integrating mechanistic-empirical pavement analysis in the life cycle assessment use phase and monetization of environmental impacts to promote low carbon transportation materials. *Transportation Research Record*: *Journal of the Transportation Research Board*, *2678*(12), 1964–1978. https://doi.org/10.1177/03611981241253576

Imaninasab, R., Loria-Salazar, L., & Carter, A. (2022). Integrated performance evaluation of asphalt mixtures with very high reclaimed asphalt pavement (RAP) content. *Construction and Building Materials*, *347*, Article 128607. https://doi.org/10.1016/j.conbuildmat.2022.128607

International Resource Panel. (2020). *Resource efficiency and climate change*: *Material efficiency strategies for a low-carbon future*. United Nations Environment Programme, Nairobi, Kenya.

International Organization for Standardization. (2006). *Environmental management*: *Life cycle assessment*: *Principles and framework* (ISO Standard No. 14040:2006). https://www.iso.org/standard/37456.html

Jahanbakhsh, H., Karimi, M. M., Naseri, H., & Nejad, F. M. (2020). Sustainable asphalt concrete containing high reclaimed asphalt pavements and recycling agents: Performance assessment, cost analysis, and environmental impact. *Journal of Cleaner Production*, *244*, Article 118837. https://doi.org/10.1016/j.jclepro.2019.118837

Jamal, M., Martinez-Arguelles, G., & Giustozzi, F. (2021). Effect of waste tyre rubber size on physical, rheological and UV resistance of high-content rubber-modified bitumen. *Construction and Building Materials*, *304*, Article 124638. https://doi.org/10.1016/j.conbuildmat.2021.124638

Ji, K., Shi, C., Jiang, J., Tian, Y., Zhou, X., & Xiong, R. (2023a). Determining the long-term skid resistance of steel slag asphalt mixture based on the mineral composition of aggregates. *Polymers*, *15*(4), Article 807. https://doi.org/10.3390/polym15040807

Ji, K., Xiong, R., Jiang, J., Li, X., Tian, Y., Yan, X., & Wang, H. (2023b). Experimental analysis of long-term skid resistance of steel slag asphalt mixture based on differential wear. *International Journal of Pavement Engineering*, *24*(1), Article 2165655. https://doi.org/10.1080/10298436.2023.2165655

Juliana, I., Fatin, A. R., Rozaini, R., Masyitah, M. N., Khairul, A. H., & Nur Shafieza, A. (2020). Effectiveness of crumb rubber for subgrade soil stabilization. *IOP Conference Series*: *Materials Science and Engineering*, *849*(1), Article 12029. https://doi.org/10.1088/1757-899X/849/1/012029

Kabir, S. F., Mousavi, M., & Fini, E. H. (2020). Selective adsorption of bio-oils' molecules onto rubber surface and its effects on stability of rubberized asphalt. *Journal of Cleaner Production*, *252*, Article 119856. https://doi.org/10.1016/j.jclepro.2019.119856

Kanwal, Q., Li, J., & Zeng, X. (2021). Mapping recyclability of industrial waste for anthropogenic circularity: A circular economy approach. *ACS Sustainable Chemistry & Engineering*, *9*(35), 11927–11936. https://doi.org/10.1021/acssuschemeng.1c04139

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

Kim, K., Haeng Jo, S., Kim, N., & Kim, H. (2018). Characteristics of hot mix asphalt containing steel slag aggregate according to temperature and void percentage. *Construction & Building Materials*, *188*, 1128–1136. https://doi.org/10.1016/j.conbuildmat.2018.08.172

Kocevski, S., Yagneswaran, S., Xiao, F., Punith, V. S., Smith, D. W., & Amirkhanian, S. (2012). Surface modified ground rubber tire by grafting acrylic acid for paving applications. *Construction and Building Materials*, *34*, 83–90. https://doi.org/10.1016/j.conbuildmat.2012.02.040

Kuvat, A., Sadoglu, E., & Zardari, S. (2024). Experimental investigation of sand–rubber–bitumen mixtures as a geotechnical seismic isolation material. *International Journal of Geomechanics*, *24*(3), Article 4023293. https://doi.org/10.1061/IJGNAI.GMENG-7015

Laomuad, A., Suddeepong, A., Horpibulsuk, S., Buritatum, A., Yaowarat, T., Akkharawongwhatthana, K., Pongsri, N., Phunpeng, V., Chinkulkijniwat, A., & Arulrajah, A. (2024). Evaluating polyethylene terephthalate in asphalt concrete with reclaimed asphalt pavement for enhanced performance. *Construction and Building Materials*, *422*, Article 135749. https://doi.org/10.1016/j.conbuildmat.2024.135749

Lee, J., Lee, S., Hwang, Y., Kwon, O., & Yeon, G. (2024). Mechanistic fatigue performance evaluation of stone mastic asphalt mixtures: Effect of asphalt performance grade and elastic recovery. *Polymers*, *16*(17), Article 2414. https://doi.org/10.3390/polym16172414

Lei, Y., Wei, Z., Wang, H., You, Z., Yang, X., & Chen, Y. (2021). Effect of crumb rubber size on the performance of rubberized asphalt with bio-oil pretreatment. *Construction and Building Materials*, *285*, Article 122864. https://doi.org/10.1016/j.conbuildmat.2021.122864

Li, B., Li, H., Wei, Y., Zhang, X., Wei, D., & Li, J. (2019). Microscopic properties of hydrogen peroxide activated crumb rubber and its influence on the rheological properties of crumb rubber modified asphalt. *Materials*, *12*(9), Article 1434. https://doi.org/10.3390/ma12091434

Li, J., Xiao, F., & Amirkhanian, S. (2020a). High temperature rheological characteristics of plasma-treated crumb rubber modified binders. *Construction and Building Materials*, *236*, Article 117614. https://doi.org/10.1016/j.conbuildmat.2019.117614

Li, J., Xiao, F., & Amirkhanian, S. (2020b). Rheological and chemical characterization of plasma-treated rubberized asphalt using customized extraction method. *Fuel*, *264*, Article 116819. https://doi.org/10.1016/j.fuel.2019.116819

Li, J., Xiao, F., & Amirkhanian, S. (2020c). Viscous-elastic characteristics of plasma-treated rubberized binders and their chemical composition influences. *Journal of Materials in Civil Engineering*, *32*(11), Article 04020320. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003402

Li, B., Zhu, X., Zhang, X., Yang, X., & Su, X. (2020d). Surface area and microstructure of microwave activated crumb rubber modifier and its influence on high temperature properties of crumb rubber modifier binders. *Materials Express*, *10*(2), 272–277. https://doi.org/10.1166/mex.2020.1634

Li, W., Han, S., & Huang, Q. (2020e). Performance of noise reduction and skid resistance of durable granular ultra-thin layer asphalt pavement. *Materials*, *13*(19), Article 4260. https://doi.org/10.3390/ma13194260

Li, J., Chen, Z., Xiao, F., & Amirkhanian, S. (2021a). Surface activation of scrap tire crumb rubber to improve compatibility of rubberized asphalt. *Resources, Conservation and Recycling*, *169*, Article 105518. https://doi.org/10.1016/j.resconrec.2021.105518

Li, M., Liu, L., Xing, C., Liu, L., & Wang, H. (2021b). Influence of rejuvenator preheating temperature and recycled mixture's curing time on performance of hot recycled mixtures. *Construction and Building Materials*, *295*, Article 123616. https://doi.org/10.1016/j.conbuildmat.2021.123616

Li, J., Yao, S., Xiao, F., & Amirkhanian, S. (2022). Surface modification of ground tire rubber particles by cold plasma to improve compatibility in rubberised asphalt. *International Journal of Pavement Engineering*, *23*(3), 651–662. https://doi.org/10.1080/10298436.2020.1765242

Li, M., Xu, O., Min, Z., & Wang, Q. (2023). Engineering performance and activation mechanism of asphalt binder modified by microwave and diesel pre-processed waste crumb rubber. *Materials and Structures*, *56*(7), Article 117. https://doi.org/10.1617/s11527-023-02204-x

Li, M., Han, Z., Cheng, H., Yang, R., Yuan, J., & Jin, T. (2025). Low-temperature performance improvement strategies for high RAP content recycled asphalt mixtures: Focus on RAP gradation variability and mixing process. *Fuel*, *387*, Article 134362. https://doi.org/10.1016/j.fuel.2025.134362

Liang, M., Ren, S., Sun, C., Zhang, J., Jiang, H., & Yao, Z. (2020). Extruded tire crumb-rubber recycled polyethylene melt blend as asphalt composite additive for enhancing the performance of binder. *Journal of Materials in Civil Engineering*, *32*(3), Article 4019373. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003044

Liang, M., Qiu, Z., Luan, X., Qi, C., Guo, N., Liu, Z., Su, L., Yao, Z., & Zhang, J. (2022). The effects of activation treatments for crumb rubber on the compatibility and mechanical performance of modified asphalt binder and mixture by the dry method. *Frontiers in Materials*, *9*, Article 845718. https://doi.org/10.3389/fmats.2022.845718

Liang, M., Luan, X., Qiu, Z., Ma, C., Qi, C., Wang, B., Wang, J., Jiang, H., Yao, Z., & Guo, N. (2023). 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*(12), Article 4023433. https://doi.org/10.1061/JMCEE7.MTENG-15081

Liu, W., Li, H., Zhu, H., & Xu, P. (2019). Properties of a steel slag–permeable asphalt mixture and the reaction of the steel slag–asphalt interface. *Materials*, *12*(21), Article 3603. https://doi.org/10.3390/ma12213603

Liu, W., Li, H., Zhu, H., & Xu, P. (2020a). Effects of steel-slag components on interfacial-reaction characteristics of permeable steel-slag–bitumen mixture. *Materials*, *13*(17), Article 3885. https://doi.org/10.3390/ma13173885

Liu, W., Li, H., Zhu, H., & Xu, P. (2020b). The interfacial adhesion performance and mechanism of a modified asphalt–steel slag aggregate. *Materials*, *13*(5), Article 1180. https://doi.org/10.3390/ma13051180

Liu, B., Li, J., Han, M., Zhang, Z., & Jiang, X. (2020c). Properties of polystyrene grafted activated waste rubber powder (PS-ARP) composite SBS modified asphalt. *Construction and Building Materials*, *238*, Article 117737. https://doi.org/10.1016/j.conbuildmat.2019.117737

Liu, J., Yu, B., & Hong, Q. (2020d). Molecular dynamics simulation of distribution and adhesion of asphalt components on steel slag. *Construction and Building Materials*, *255*, Article 119332. https://doi.org/10.1016/j.conbuildmat.2020.119332

Liu, J., Wang, Z., Guo, H., & Yan, F. (2021a). Thermal transfer characteristics of asphalt mixtures containing hot poured steel slag through microwave heating. *Journal of Cleaner Production*, *308*, Article 127225. https://doi.org/10.1016/j.jclepro.2021.127225

Liu, L., Liu, Z., Yang, C., Huang, Y., & Li, W. (2021b). Effect of the binary compound method of TOR promoting dissolution and NaOH solution surface treatment on the performance of rubber asphalt. *Construction and Building Materials*, *305*, Article 124697. https://doi.org/10.1016/j.conbuildmat.2021.124697

Liu, T., Wang, Y., Li, J., Yu, Q., Wang, X., Gao, D., Wang, F., Cai, S., & Zeng, Y. (2021c). Effects from Fe, P, Ca, Mg, Zn and Cu in steel slag on growth and metabolite accumulation of microalgae: A review. *Applied Sciences*, *11*(14), Article 6589. https://doi.org/10.3390/app11146589

Liu, J., Zhang, T., Guo, H., Wang, Z., & Wang, X. (2022). Evaluation of self-healing properties of asphalt mixture containing steel slag under microwave heating: Mechanical, thermal transfer and voids microstructural characteristics. *Journal of Cleaner Production*, *342*, Article 130932. https://doi.org/10.1016/j.jclepro.2022.130932

Liu, J., Jing, H., Wang, Z., Wang, X., & Zhang, L. (2023). Recycling of steel slag in sustainable bituminous mixtures: Self-healing performance, mechanism, environmental and economic analyses. *Journal of Cleaner Production*, *429*, Article 139496. https://doi.org/10.1016/j.jclepro.2023.139496

Liu, T., Yang, S., Liao, B., Yang, E., & Jiang, X. (2024). Contribution of climate change and traffic load on asphalt pavement carbon emissions. *Journal of Cleaner Production*, *434*, Article 140553. https://doi.org/10.1016/j.jclepro.2023.140553

Lo Presti, D. (2013). Recycled tyre rubber modified bitumens for road asphalt mixtures: A literature review. *Construction and Building Materials*, *49*, 863–881. https://doi.org/10.1016/j.conbuildmat.2013.09.007

López-Moro, F. J., Moro, M. C., Hernández-Olivares, F., Witoszek-Schultz, B., & Alonso-Fernández, M. (2013). Microscopic analysis of the interaction between crumb rubber and bitumen in asphalt mixtures using the dry process. *Construction and Building Materials*, *48*, 691–699. https://doi.org/10.1016/j.conbuildmat.2013.07.041

Lou, B., Sha, A., Li, Y., Wang, W., Liu, Z., Jiang, W., & Cui, X. (2020). Effect of metallic-waste aggregates on microwave self-healing performances of asphalt mixtures. *Construction and Building Materials*, *246*, Article 118510. https://doi.org/10.1016/j.conbuildmat.2020.118510

Luo, W., Huang, S., Liu, Y., Peng, H., & Ye, Y. (2022). Three-dimensional mesostructure model of coupled electromagnetic and heat transfer for microwave heating on steel slag asphalt mixtures. *Construction and Building Materials*, *330*, Article 127235. https://doi.org/10.1016/j.conbuildmat.2022.127235

Luo, L., Yang, S.-H., Oeser, M., & Liu, P. (2024). Moisture damage mechanism of asphalt mixtures containing reclaimed asphalt pavement binder: A novel molecular dynamics study. *Journal of Cleaner Production*, *475*, Article 143711. https://doi.org/10.1016/j.jclepro.2024.143711

Mahida, S., Shah, Y. U., & Sharma, S. (2022). Analysis of the influence of using waste polystyrene in virgin bitumen. *International Journal of Pavement Research and Technology*, *15*(3), 626–639. https://doi.org/10.1007/s42947-021-00041-1

Mahoutian, M., Ghouleh, Z., & Shao, Y. (2014). Carbon dioxide activated ladle slag binder. *Construction and Building Materials*, *66*, 214–221. https://doi.org/10.1016/j.conbuildmat.2014.05.063

Majidifard, H., Tabatabaee, N., & Buttlar, W. (2019). Investigating short-term and long-term binder performance of high-RAP mixtures containing waste cooking oil. *Journal of Traffic and Transportation Engineering*, *6*(4), 396–406. https://doi.org/10.1016/j.jtte.2018.11.002

Medina, T., Calmon, J. L., Vieira, D., Bravo, A., & Vieira, T. (2023). Life cycle assessment of road pavements that incorporate waste reuse: A systematic review and guidelines. *Sustainability*, *15*(20), Article 14892. https://doi.org/10.3390/su152014892

Ministry of Transport. (2019). *Technical specifications for highway asphalt pavement recycling* (JTGT 5521-2019). China Communications Press.

Moreno, F., Sol, M., Martín, J., Pérez, M., & Rubio, M. C. (2013). The effect of crumb rubber modifier on the resistance of asphalt mixes to plastic deformation. *Materials* & *Design*, *47*, 274–280. https://doi.org/10.1016/j.matdes.2012.12.022

Mousa, E., El-Badawy, S., & Azam, A. (2021). Evaluation of reclaimed asphalt pavement as base/subbase material in Egypt. *Transportation Geotechnics*, *26*, Article 100414. https://doi.org/10.1016/j.trgeo.2020.100414

Mousavi Rad, S., Kamboozia, N., Anupam, K., & Saed, S. A. (2022). Experimental evaluation of the fatigue performance and self-healing behavior of nanomodified porous asphalt mixtures containing RAP materials under the aging condition and freeze–thaw cycle. *Journal of Materials in Civil Engineering*, *34*(12), Article 04022323. https://doi.org/10.1061/(ASCE)MT.1943-5533.0004488

Nakase, K., Matsui, A., Kikuchi, N., Miki, Y., Kishimoto, Y., Goto, I., & Nagasaka, T. (2013). Fundamental research on a rational steelmaking slag recycling system by phosphorus separation and collection. *Journal for Manufacturing Science and Production*, *13*(1–2), 39–45. https://doi.org/10.1515/jmsp-2012-0038

Neto, S. A. D., Farias, M. M., Pais, J. C., Pereira, P. A. A., & Sousa, J. B. (2006). Influence of crumb rubber and digestion time on the asphalt rubber binders. *Road Materials and Pavement Design*, *7*(2), 131–148. https://doi.org/10.1080/14680629.2006.9690030

Nian, T., Wang, M., Li, S., Li, P., & Song, J. (2024). Enhancing pavement structural resilience: Analyzing the impact of vehicle-induced dynamic loads on RAP-recycled cement-stabilized crushed stone pavements with tip cracks. *Materials and Structures*, *57*(7), Article 162. https://doi.org/10.1617/s11527-024-02439-2

Nunes, V. A., & Borges, P. H. R. (2021). Recent advances in the reuse of steel slags and future perspectives as binder and aggregate for alkali-activated materials. *Construction and Building Materials*, *281*, Article 122605. https://doi.org/10.1016/j.conbuildmat.2021.122605

Obaid, A., Nazzal, M., Kim, S., Abbas, A., Arefin, M., & Quasem, T. (2020). Evaluation of terminal blend GTR mixes with RAP. *Journal of Transportation Engineering Part B-Pavements*, *146*(1), Article 04019041. https://doi.org/10.1061/JPEODX.0000145

Obaid, H. A., Enieb, M., Eltwati, A., & Al-Jumaili, M. A. (2026). Prediction and optimization of asphalt mixtures performance containing reclaimed asphalt pavement materials and warm mix agents using response surface methodology. *International Journal of Pavement Research and Technology*, *19*, 381–397. https://doi.org/10.1007/s42947-024-00464-6

Ogawa, A., Tanaka, R., Hirai, N., Ochiai, T., Ohashi, R., Fujimoto, K., Akatsuka, Y., & Suzuki, M. (2020). Investigation of biofilms formed on steelmaking slags in marine environments for water depuration. *International Journal of Molecular Sciences*, *21*(18), Article 6945. https://doi.org/10.3390/ijms21186945

Omairey, E. L., Zhang, Y., Al-Malaika, S., Sheena, H., & Gu, F. (2019). Impact of anti-ageing compounds on oxidation ageing kinetics of bitumen by infrared spectroscopy analysis. *Construction and Building Materials*, *223*, 755–764. https://doi.org/10.1016/j.conbuildmat.2019.07.021

Pan, Q., & Pang, H. (2022). Durability capacity change of rubber powder composite BRA modified asphalt mixture. *Advances in Materials Science and Engineering*, *2022*, Article 5419057. https://doi.org/10.1155/2022/5419057

Panda, R., & Biswal, D. R. (2025). A systematic review of geopolymer stabilised reclaimed asphalt pavement (RAP) as a base layer of pavement. *Road Materials and Pavement Design*, *26*(2), 231–253. https://doi.org/10.1080/14680629.2024.2349021

Pang, Y., Zhu, X., Jin, Y., Yang, Z., Liu, S., Shen, L., Li, X., & Lee, C. (2023). Textile-inspired triboelectric nanogenerator as intelligent pavement energy harvester and self-powered skid resistance sensor. *Applied Energy*, *348*, Article 121515. https://doi.org/10.1016/j.apenergy.2023.121515

Pasetto, M., & Baldo, N. (2011). Mix design and performance analysis of asphalt concretes with electric arc furnace slag. *Construction and Building Materials*, *25*(8), 3458–3468. https://doi.org/10.1016/j.conbuildmat.2011.03.037

Pasetto, M., Baliello, A., Giacomello, G., & Pasquini, E. (2017). Sustainable solutions for road pavements: A multi-scale characterization of warm mix asphalts containing steel slags. *Journal of Cleaner Production*, *166*, 835–843. https://doi.org/10.1016/j.jclepro.2017.07.212

Pasetto, M., Baliello, A., Giacomello, G., & Pasquini, E. (2022). Mechanical feasibility of asphalt materials for pavement solar collectors: small-scale laboratory characterization. *Applied Sciences*, *13*(1), Article 358. https://doi.org/10.3390/app13010358

Patrisia, Y., Law, D. W., Gunasekara, C., & Setunge, S. (2025). Assessment of waste-integrated concrete products: A cradle-to-cradle perspective. *International Journal of Life Cycle Assessment*, *30*(5), 834–861. https://doi.org/10.1007/s11367-025-02443-w

Pattanaik, M. L., Choudhary, R., Kumar, B., & Kumar, A. (2021). Mechanical properties of open graded friction course mixtures with different contents of electric arc furnace steel slag as an alternative aggregate from steel industries. *Road Materials and Pavement Design*, *22*(2), 268–292. https://doi.org/10.1080/14680629.2019.1620120

Pitilakis, D., Anastasiadis, A., Vratsikidis, A., & Kapouniaris, A. (2024). Configuration of a gravel-rubber geotechnical seismic isolation system from laboratory and field tests. *Soil Dynamics and Earthquake Engineering*, *178*, Article 108463. https://doi.org/10.1016/j.soildyn.2024.108463

Qian, C., Fan, W., Yang, G., Han, L., Xing, B., & Lv, X. (2020). Influence of crumb rubber particle size and SBS structure on properties of CR/SBS composite modified asphalt. *Construction and Building Materials*, *235*, Article 117517. https://doi.org/10.1016/j.conbuildmat.2019.117517

Radeef, H., Hassan, N., Mahmud, M., Abidin, A., Ismail, C., Abbas, H., & Al-Saffar, Z. (2021). Characterisation of cracking resistance in modified hot mix asphalt under repeated loading using digital image analysis. *Theoretical and Applied Fracture Mechanics*, *116*, Article 103130. https://doi.org/10.1016/j.tafmec.2021.103130

Rajagopal, M. R., Ganta, J., & Pamu, Y. (2024). Enhancing the strength and the environmental performance of concrete with pre-treated crumb rubber and micro-silica. *Recycling*, *9*(3), Article 32. https://doi.org/10.3390/recycling9030032

Rath, P., Majidifard, H., Jahangiri, B., Chen, S., & Buttlar, W. G. (2021). Laboratory and field evaluation of pre-treated dry-process rubber-modified asphalt binders and dense-graded mixtures. *Transportation Research Record*: *Journal of the Transportation Research Board*, *2675*(10), 381–394. https://doi.org/10.1177/03611981211011480

Ravi, R., Bhat, H., Nayak, R., Phadte, P., Sawant, P., Prasanna, S., & Fondekar, K. P. (2024). Experimental study on waste rubber chips and brick powder for soil stabilization. In R. Ghai, L.-M. Chang, R. Sharma, & A. K. Chandrappa (Eds.), *Lecture notes in civil engineering*: *Vol. 441*. *Sustainable design and eco technologies for infrastructure*. *CECAR 2022* (pp. 147–155). Springer Nature Singapore. https://doi.org/10.1007/978-981-99-8465-7_11

Razmi, A., & Mirsayar, M. M. (2018). Fracture resistance of asphalt concrete modified with crumb rubber at low temperatures. *International Journal of Pavement Research and Technology*, *11*(3), 265–273. https://doi.org/10.1016/j.ijprt.2017.10.003

Ren, S., Liu, X., Lin, P., Wang, H., Fan, W., & Erkens, S. (2021). The continuous swelling-degradation behaviors and chemo-rheological properties of waste crumb rubber modified bitumen considering the effect of rubber size. *Construction and Building Materials*, *307*, Article 124966. https://doi.org/10.1016/j.conbuildmat.2021.124966

Riccardi, C., Cannone Falchetto, A., Losa, M., & Wistuba, M. (2016). Back-calculation method for determining the maximum RAP content in stone matrix asphalt mixtures with good fatigue performance based on asphalt mortar tests. *Construction and Building Materials*, *118*, 364–372. https://doi.org/10.1016/j.conbuildmat.2016.05.086

Richardson, A., Coventry, K., Edmondson, V., & Dias, E. (2016). Crumb rubber used in concrete to provide freeze–thaw protection (optimal particle size). *Journal of Cleaner Production*, *112*, 599–606. https://doi.org/10.1016/j.jclepro.2015.08.028

Riekstins, A., Haritonovs, V., Straupe, V., Izaks, R., Merijs-Meri, R., & Zicans, J. (2024). Comparative environmental and economic assessment of a road pavement containing multiple sustainable materials and technologies. *Construction and Building Materials*, *432*, Article 136522. https://doi.org/10.1016/j.conbuildmat.2024.136522

Rohde, L., Peres Núñez, W., & Augusto Pereira Ceratti, J. (2003). Electric arc furnace steel slag: base material for low-volume roads. *Transportation Research Record*: *Journal of the Transportation Research Board*, *1819*(1), 201–207. https://doi.org/10.3141/1819b-26

Rout, M. K. D., Biswas, S., Shubham, K., & Sinha, A. K. (2023). A systematic review on performance of reclaimed asphalt pavement (RAP) as sustainable material in rigid pavement construction: Current status to future perspective. *Journal of Building Engineering*, *76*, Article 107253. https://doi.org/10.1016/j.jobe.2023.107253

Saberi, K. F., Fakhri, M., & Azami, A. (2017). Evaluation of warm mix asphalt mixtures containing reclaimed asphalt pavement and crumb rubber. *Journal of Cleaner Production*, *165*, 1125–1132. https://doi.org/10.1016/j.jclepro.2017.07.079

Sachs, J. D., Lafortune, G., Fuller, G., & Iablonovski, G. (2025). *Sustainable development report 2025*. *Financing sustainable development to 2030 and mid-century*. Dublin University Press.

Santamaria, A., Faleschini, F., Giacomello, G., Brunelli, K., San José, J.-T., Pellegrino, C., & Pasetto, M. (2018). Dimensional stability of electric arc furnace slag in civil engineering applications. *Journal of Cleaner Production*, *205*, 599–609. https://doi.org/10.1016/j.jclepro.2018.09.122

Shatanawi, K. M., Biro, S., Naser, M., & Amirkhanian, S. N. (2013). Improving the rheological properties of crumb rubber modified binder using hydrogen peroxide. *Road Materials and Pavement Design*, *14*(3), 723–734. https://doi.org/10.1080/14680629.2013.812535

Soleimani Golsefidi, S., & Ali Sahaf, S. (2022). Effect of reclaimed asphalt pavement (RAP) on fracture properties of stone matrix asphalt (SMA) at low temperature. *Construction and Building Materials*, *352*, Article 128899. https://doi.org/10.1016/j.conbuildmat.2022.128899

Song, Z., Hu, Y., Han, Y., Chen, S., Zhao, X., Sun, J., Mao, Y., Wang, X., & Wang, W. (2023). Effect of swelling pretreatment by coal tar on the microwave pyrolysis of waste tires. *Journal of Environmental Chemical Engineering*, *11*(5), Article 110781. https://doi.org/10.1016/j.jece.2023.110781

Song, Y., Xu, H., Wu, S., Xie, J., Chen, A., Lv, Y., Cheng, Y., & Li, Y. (2024). High-quality utilization of reclaimed asphalt pavement (RAP) in asphalt mixture with the enhancement of steel slag and epoxy asphalt. *Construction and Building Materials*, *445*, Article 137963. https://doi.org/10.1016/j.conbuildmat.2024.137963

Sorlini, S., Sanzeni, A., & Rondi, L. (2012). Reuse of steel slag in bituminous paving mixtures. *Journal of Hazardous Materials*, *209–210*, 84–91. https://doi.org/10.1016/j.jhazmat.2011.12.066

Southern African Bitumen Association. (2021). *Use of reclaimed asphalt in the production of asphalt*. Pinelands, South Africa.

Sukhija, M., & Coleri, E. (2025). A review on the incorporation of reclaimed asphalt pavement material in asphalt pavements: Management practices and strategic techniques. *Road Materials and Pavement Design*, *26*(12), 2991–3030. https://doi.org/10.1080/14680629.2025.2470889

Sun, Y., Liu, Q., Wang, H., Zhang, Z., & Wang, X. (2017). Role of steel slags on biomass/carbon dioxide gasification integrated with recovery of high temperature heat. *Bioresource Technology*, *223*, 1–9. https://doi.org/10.1016/j.biortech.2016.10.028

Sun, L., Wen, Y., Liu, Q., Li, D., Lyu, L., Pei, J., Zhang, J., & Li, R. (2021). A laboratory investigation into the effect of waste non-tire rubber particles on the performance properties of terminal blend rubberized asphalt binders. *Construction and Building Materials*, *313*, Article 125409. https://doi.org/10.1016/j.conbuildmat.2021.125409

Sun, J., Luo, S., Wang, Y., Dong, Q., & Zhang, Z. (2023). Pre-treatment of steel slag and its applicability in asphalt mixtures for sustainable pavements. *Chemical Engineering Journal*, *476*, Article 146802. https://doi.org/10.1016/j.cej.2023.146802

Sun, J., Huang, W., Wang, X., Hu, J., Wang, Y., Zhang, Z., & Luo, S. (2024). Feasibility of pretreated steel slag for asphalt pavement application and risk assessment of hazardous substance leaching. *Chemical Engineering Journal*, *498*, Article 155497. https://doi.org/10.1016/j.cej.2024.155497

Sun, Z., Zhang, Z., Lu, G., & Luo, S. (2025). Recent advances in research on steel slag for asphalt pavements: A review. *Case Studies in Construction Materials*, *22*, Article e04698. https://doi.org/10.1016/j.cscm.2025.e04698

Swathi, M., Andiyappan, T., Guduru, G., Amarnatha Reddy, M., & Kuna, K. K. (2021). Design of asphalt mixes with steel slag aggregates using the Bailey method of gradation selection. *Construction and Building Materials*, *279*, Article 122426. https://doi.org/10.1016/j.conbuildmat.2021.122426

Tan, Z., & Wang, J. (2020). Research of the rheological modification mechanism of crumb rubber-modified asphalt containing polyamide 6 additive. *Advances in Civil Engineering*, *2020*, Article 8877487. https://doi.org/10.1155/2020/8877487

Thomas, B. S., & Gupta, R. C. (2016). A comprehensive review on the applications of waste tire rubber in cement concrete. *Renewable and Sustainable Energy Reviews*, *54*, 1323–1333. https://doi.org/10.1016/j.rser.2015.10.092

Tsakoumaki, M., & Plati, C. (2024). A critical overview of using reclaimed asphalt pavement (RAP) in road pavement construction. *Infrastructures*, *9*(8), Article 128. https://doi.org/10.3390/infrastructures9080128

Tushar, Q., Santos, J., Zhang, G., Robert, D., & Giustozzi, F. (2025). Recycled used cooking oil (UCO) as a rejuvenator in high content reclaimed asphalt pavement (RAP) mixes: A life cycle assessment (LCA). *Science of the Total Environment*, *961*, Article 178376. https://doi.org/10.1016/j.scitotenv.2025.178376

Uibu, M., Kuusik, R., Andreas, L., & Kirsimäe, K. (2011). The CO_2 -binding by Ca-Mg-silicates in direct aqueous carbonation of oil shale ash and steel slag. *Energy Procedia*, *4*, 925–932. https://doi.org/10.1016/j.egypro.2011.01.138

United Nation Environment Programme. (2024). *Emissions Gap Report 2024*: *No more hot air ... Please! With a massivegap between rhetoric and reality*, *countries draft new climate commitments*. Nairobi. https://www.unep.org/emissions-gap-report-2024

United Nations Framework Convention on Climate Change. (2015). *The Paris Agreement*. *United Nations Framework Convention on Climate Change*. Phoenix Design Aid, Denmark.

Vamsikrishna, G., & Singh, D. (2023). Comparison of rutting resistance of plant produced asphalt mixes using hamburg wheel tracker and surrogate simple performance tests: IDEAL-RT and HT-IDT. *Journal of Materials in Civil Engineering*, *35*(12), Article 04023471. https://doi.org/10.1061/JMCEE7.MTENG-16205

Venudharan, V., Biligiri, K. P., Sousa, J. B., & Way, G. B. (2017). Asphalt-rubber gap-graded mixture design practices: A state-of-the-art research review and future perspective. *Road Materials and Pavement Design*, *18*(3), 730–752. https://doi.org/10.1080/14680629.2016.1182060

Vigneswaran, S., Yun, J., Jeong, K., Lee, M., & Lee, S. (2023). Effect of crumb rubber modifier particle size on storage stability of rubberized binders. *Sustainability*, *15*(18), Article 13568. https://doi.org/10.3390/su151813568

Wan, C., Zhong, M., & Yinghao, Z. (2024). A study on the three-dimensional contact quantitative analysis of coarse aggregate in steel slag asphalt mixture based on X-ray CT. *Case Studies in Construction Materials*, *21*, Article e03600. https://doi.org/10.1016/j.cscm.2024.e03600

Wang, T., Xiao, F., Amirkhanian, S., Huang, W., & Zheng, M. (2017). A review on low temperature performances of rubberized asphalt materials. *Construction and Building Materials*, *145*, 483–505. https://doi.org/10.1016/j.conbuildmat.2017.04.031

Wang, Y., Wang, X., & Zhang, L. (2021). Pavement and noise reduction performance of open-graded asphalt friction course improved by waste tire crumb rubber. *Advances in Civil Engineering*, *2021*, Article 9937293. https://doi.org/10.1155/2021/9937293

Wang, L., Yang, X., & Leonelli, C. (2022a). Analysis of optimal RAP content based on discrete element method. *Advances in Materials Science and Engineering*, *2022*, Article 2878848. https://doi.org/10.1155/2022/2878848

Wang, W., Cheng, H., Sun, L., Sun, Y., & Liu, N. (2022b). Multi-performance evaluation of recycled warm-mix asphalt mixtures with high reclaimed asphalt pavement contents. *Journal of Cleaner Production*, *377*, Article 134209. https://doi.org/10.1016/j.jclepro.2022.134209

Wang, X., Guo, G., Zou, F., Zhao, H., & Li, Y. (2022c). Enhancing self-healing properties of microcrack on aged asphalt incorporating with microcapsules encapsulating rejuvenator. *Construction and Building Materials*, *344*, Article 128123. https://doi.org/10.1016/j.conbuildmat.2022.128123

Wang, F., Xiao, Y., Cui, P., Ma, T., Liu, X., Wang, F., & Zhang, L. (2024a). Enhancement mechanism of asphalt mixture skeleton structures due to morphological characteristics of steel slag. *Construction and Building Materials*, *432*, Article 136703. https://doi.org/10.1016/j.conbuildmat.2024.136703

Wang, H., Qian, J., Zhang, H., Nan, X., Chen, G., & Li, X. (2024b). Exploring skid resistance over time: Steel slag as a pavement aggregate—comparative study and morphological analysis. *Journal of Cleaner Production*, *464*, Article 142779. https://doi.org/10.1016/j.jclepro.2024.142779

Wang, Y., Dou, G., Wang, S., & Wang, J. (2024c). The effect of refined separation on the properties of reclaimed asphalt pavement materials. *Buildings*, *14*(6), Article 1608. https://doi.org/10.3390/buildings14061608

Wen, Y., Liu, Q., Chen, L., Pei, J., Zhang, J., & Li, R. (2020). Review and comparison of methods to assess the storage stability of terminal blend rubberized asphalt binders. *Construction and Building Materials*, *258*, Article 119586. https://doi.org/10.1016/j.conbuildmat.2020.119586

Williams, B. A., Willis, J. R., & Shacat, J. (2020). *Asphalt pavement industry survey on recycled materials and warm-mix asphalt usage*: *2020*. National Asphalt Pavement Association.

Xiang, Y., Fan, H., & Liu, Z. (2020). Structural characteristics of silane-modified ground tyre rubber and high-temperature creep property of asphalt rubber. *Construction and Building Materials*, *236*, Article 117600. https://doi.org/10.1016/j.conbuildmat.2019.117600

Xiao, F., Yao, S., Wang, J., Wei, J., & Amirkhanian, S. (2020). Physical and chemical properties of plasma treated crumb rubbers and high temperature characteristics of their rubberised asphalt binders. *Road Materials and Pavement Design*, *21*(3), 587–606. https://doi.org/10.1080/14680629.2018.1507922

Xie, J., Zhang, Y., Yang, Y., Ma, Y., Li, J., & Huang, M. (2020). The effect of activation method of rubber on the performance of modified asphalt binder. *Materials*, *13*(17), Article 3679. https://doi.org/10.3390/ma13173679

Xin, K., Jin, D., Handler, R. M., & You, Z. (2024). Life cycle assessment of rubber modified asphalt pavement in Michigan: A case study. In G. Flintsch, E. Amarh, J. Harvey, I. Al-Qadi, H. Ozer, & D. LoPresti (Eds.), *Pavement*, *Roadway*, *and Bridge LIFE Cycle Assessment 2024*, *Isprb Lca 2024* (Vol. 51, pp. 220–233). Virginia Tech. https://doi.org/10.1007/978-3-031-61585-6_22

Xing, Y., Guo, Z., Su, W., Zhang, H., Chen, J., Tian, J., Yuan, J., & Di Wu. (2022). Vanadium-bearing steel slag catalysts for the selective catalytic reduction of NO_x by NH_3. *New Journal of Chemistry*, *46*(31), 14944–14957. https://doi.org/10.1039/D2NJ02419E

Xing, C., Li, M., Liu, L., Lu, R., Liu, N., Wu, W., & Yuan, D. (2023). A comprehensive review on the blending condition between virgin and RAP asphalt binders in hot recycled asphalt mixtures: Mechanisms, evaluation methods, and influencing factors. *Journal of Cleaner Production*, *398*, Article 136515. https://doi.org/10.1016/j.jclepro.2023.136515

Xu, P., Gao, J., Pei, J., Chen, Z., Zhang, J., & Li, R. (2021a). Research on highly dissolved rubber asphalt prepared using a composite waste engine oil addition and microwave desulfurization method. *Construction and Building Materials*, *282*, Article 122641. https://doi.org/10.1016/j.conbuildmat.2021.122641

Xu, X., Leng, Z., Lan, J., Wang, W., Yu, J., Bai, Y., Sreeram, A., & Hu, J. (2021b). Sustainable practice in pavement engineering through value-added collective recycling of waste plastic and waste tyre rubber. *Engineering*, *7*(6), 857–867. https://doi.org/10.1016/j.eng.2020.08.020

Xu, J., Fan, Z., Wang, D., Leng, Z., Lu, G., & Liu, P. (2023). Experimental characterization of the compatibility between bitumen and fillers from a perspective of bitumen components and filler characteristics. *Materials and Structures*, *56*(7), Article 116. https://doi.org/10.1617/s11527-023-02207-8

Xu, H., Chen, A., Wu, S., Li, Y., Li, J., Zhu, Y., Wu, J., Zhou, Y., & Feng, J. (2024). Mechanism of asphalt concrete reinforced with industrially recycled steel slag from the perspectives of adhesion and skeleton. *Construction and Building Materials*, *424*, Article 135899. https://doi.org/10.1016/j.conbuildmat.2024.135899

Yan, Y., Roque, R., Cocconcelli, C., Bekoe, M., & Lopp, G. (2017). Evaluation of cracking performance for polymer-modified asphalt mixtures with high RAP content. *Road Materials and Pavement Design*, *18*(sup1), 450–470. https://doi.org/10.1080/14680629.2016.1266774

Yang, X., Shen, A., Li, B., Wu, H., Lyu, Z., Wang, H., & Lyu, Z. (2020). Effect of microwave-activated crumb rubber on reaction mechanism, rheological properties, thermal stability, and released volatiles of asphalt binder. *Journal of Cleaner Production*, *248*, Article 119230. https://doi.org/10.1016/j.jclepro.2019.119230

Yang, C., Wu, S., Cui, P., Amirkhanian, S., Zhao, Z., Wang, F., Zhang, L., Wei, M., Zhou, X., & Xie, J. (2022a). Performance characterization and enhancement mechanism of recycled asphalt mixtures involving high RAP content and steel slag. *Journal of Cleaner Production*, *336*, Article 130484. https://doi.org/10.1016/j.jclepro.2022.130484

Yang, C., Wu, S., Xie, J., Amirkhanian, S., Liu, Q., Zhang, J., Xiao, Y., Zhao, Z., Xu, H., Li, N., Wang, F., & Zhang, L. (2022b). Enhanced induction heating and self-healing performance of recycled asphalt mixtures by incorporating steel slag. *Journal of Cleaner Production*, *366*, Article 132999. https://doi.org/10.1016/j.jclepro.2022.132999

Yang, M., Chang, H., Li, W., Wang, H., Lin, J., Tong, Z., & Zhang, W. (2024). High-temperature deformation and skid resistance of steel slag asphalt mixture under heavy traffic conditions. *Buildings*, *14*(12), Article 3990. https://doi.org/10.3390/buildings14123990

Ye, X., Chen, Y., Yang, H., Xiang, Y., Ye, Z., Li, W., & Hu, C. (2024). Enhancing self-healing of asphalt mixtures containing recycled concrete aggregates and reclaimed asphalt pavement using induction heating. *Construction and Building Materials*, *439*, Article 137361. https://doi.org/10.1016/j.conbuildmat.2024.137361

Yildirim, I. Z., & Prezzi, M. (2011). Chemical, mineralogical, and morphological properties of steel slag. *Advances in Civil Engineering*, *2011*, Article 463638. https://doi.org/10.1155/2011/463638

Yu, B., Lu, Q., & Xu, J. (2013). An improved pavement maintenance optimization methodology: Integrating LCA and LCCA. *Transportation Research Part A*: *Policy and Practice*, *55*, 1–11. https://doi.org/10.1016/j.tra.2013.07.004

Yu, Q., Liu, T.-J., Cai, S., Wang, F.-P., Gao, D., Wang, X.-M., Wang, Y.-T., & Zeng, Y.-N. (2021). A review on the effect from steel slag on the growth of microalgae. *Processes*, *9*(5), Article 769. https://doi.org/10.3390/pr9050769

Yu, Q., Liu, G., Shi, J., Wen, T., & Li, L. (2022). Magnetic-activated carbon composites derived from sludge and steel converter slag for wastewater treatment. *Journal of Environmental Chemical Engineering*, *10*(5), Article 108553. https://doi.org/10.1016/j.jece.2022.108553

Yu, J., Lin, Z., Zou, G., Yu, H., Leng, Z., & Zhang, Y. (2024). Long-term performance of recycled asphalt mixtures containing high RAP and RAS. *Journal of Road Engineering*, *4*(1), 36–53. https://doi.org/10.1016/j.jreng.2024.01.003

Yucel, A., Ozturk, H., & Guler, M. (2021). Influence of warm mix additive on internal structure of dry process crumb rubber modified mixtures. *Journal of Cleaner Production*, *313*, Article 127959. https://doi.org/10.1016/j.jclepro.2021.127959

Zaumanis, M., Arraigada, M., & Poulikakos, L. D. (2020). 100% recycled high-modulus asphalt concrete mixture design and validation using vehicle simulator. *Construction and Building Materials*, *260*, Article 119891. https://doi.org/10.1016/j.conbuildmat.2020.119891

Zhang, C., Tan, Y., Gao, Y., Fu, Y., Li, J., Li, S., & Zhou, X. (2022). Resilience assessment of asphalt pavement rutting under climate change. *Transportation Research Part D*: *Transport and Environment*, *109*, Article 103395. https://doi.org/10.1016/j.trd.2022.103395

Zhang, F., Wang, D., Cannone Falchetto, A., & Cao, Y. (2024a). Microwave deicing properties and carbon emissions assessment of asphalt mixtures containing steel slag towards resource conservation and waste reuse. *Science of The Total Environment*, *912*, Article 169189. https://doi.org/10.1016/j.scitotenv.2023.169189

Zhang, J., Chen, M., Leng, B., Wu, S., Chen, D., & Zhao, Z. (2024b). Investigation on storage stability, H2S emission and rheological properties of modified asphalt with different pretreated waste rubber powder. *Journal of Cleaner Production*, *456*, Article 142469. https://doi.org/10.1016/j.jclepro.2024.142469

Zhang, W., Xiao, C., Hong, Q., Liu, J., Yu, B., Li, Q., & Li, Z. (2024c). Testing and evaluation for skid resistance of steel slag asphalt wearing course based on surface texture characteristics. *Construction and Building Materials*, *411*, Article 134597. https://doi.org/10.1016/j.conbuildmat.2023.134597

Zhang, X., Qiu, Y., Gao, Y., Zhao, X., Li, F., Huo, J., & Zhang, Z. (2024d). Low-temperature performance of acrylonitrile-butadiene-styrene and crumb rubber compound-modified asphalt activated by waste cooking oil surface treatment. *Journal of Materials in Civil Engineering*, *36*(9), Article 4024276. https://doi.org/10.1061/JMCEE7.MTENG-18000

Zhang, Z., Sun, J., Huang, W., Zhang, X., Lu, G., Luo, S., & Wang, Y. (2025a). A dual-driven fusion model of evaluating the performance and carbon emissions for recycled waste pavement. *Resources*, *Conservation and Recycling*, *212*, Article 107895. https://doi.org/10.1016/j.resconrec.2024.107895

Zhang, Y., Li, J., Ma, T., Liu, H., Chen, C., & Hao, J. (2025b). Cold recycled mixtures prepared with finely separated RAP aggregates and modified emulsified asphalt: Adhesive performance and interface fusion characteristics. *Construction and Building Materials*, *493*, Article 143122. https://doi.org/10.1016/j.conbuildmat.2025.143122

Zhao, S., Huang, B., Shu, X., Moore, J., & Bowers, B. (2016). Effects of WMA technologies on asphalt binder blending. *Journal of*

Materials in Civil Engineering, *28*(2), Article 04015106. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001381

Zheng, X., Easa, S. M., Yang, Z., Ji, T., & Jiang, Z. (2019). Life-cycle sustainability assessment of pavement maintenance alternatives: Methodology and case study. *Journal of Cleaner Production*, *213*, 659–672. https://doi.org/10.1016/j.jclepro.2018.12.227

Zhong, T., Zheng, Y., Chen, Z., Yao, L., Zhang, W., Zhu, Y., & Fu, L. (2024). Utilization of steel slag as coarse aggregate and filler in stone mastic asphalt (SMA) mixture: Engineering performance, environmental impact and economic benefits analysis. *Journal of Cleaner Production*, *450*, Article 141891. https://doi.org/10.1016/j.jclepro.2024.141891

Zhou, T., Kabir, S. F., Cao, L., Luan, H., Dong, Z., & Fini, E. H. (2020). Comparing effects of physisorption and chemisorption of bio-oil onto rubber particles in asphalt. *Journal of Cleaner Production*, *273*, Article 123112. https://doi.org/10.1016/j.jclepro.2020.123112

Zhou, T., Li, L., Liu, R., Yu, F., & Dong, Z. (2024). Thermal effects on rheological characteristics and its evolution mechanism of bio-modified rubberized asphalt for sustainable road system: A focus on rubber particle size. *Journal of Cleaner Production*, *452*, Article 142168. https://doi.org/10.1016/j.jclepro.2024.142168

Zhu, J., Ma, T., Fan, J., Fang, Z., Chen, T., & Zhou, Y. (2020). Experimental study of high modulus asphalt mixture containing reclaimed asphalt pavement. *Journal of Cleaner Production*, *263*, Article 121447. https://doi.org/10.1016/j.jclepro.2020.121447

Zhu, C., Li, D., Zhang, H., Guo, X., Xu, F., Xiao, F., Amirkhanian, S., & Zhang, D. (2024). Effect of microwave and deodorant treatments on long-term aging characteristics of crumb rubber modified asphalt. *Case Studies in Construction Materials*, *21*, Article e03620. https://doi.org/10.1016/j.cscm.2024.e03620

Ziaee, S. A., & Behnia, K. (2020). Evaluating the effect of electric arc furnace steel slag on dynamic and static mechanical behavior of warm mix asphalt mixtures. *Journal of Cleaner Production*, *274*, Article 123092. https://doi.org/10.1016/j.jclepro.2020.123092

Ziari, H., & Abdipour, S. V. (2024). Coupled effects of crumb rubber and zeolite on the performance of dense-graded asphalt mixture: A study using a balanced mix design approach. *International Journal of Pavement Engineering*, *25*(1), Article 2308179. https://doi.org/10.1080/10298436.2024.2308179