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Crumb Rubber Asphalt: A Systematic Review of Performance, Durability and Sustainability

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Abstract

Crumb Rubber Asphalt (CRA) is among the most established high-value pathways for recycling end-of-life tires in transport infrastructure. However, despite decades of research and field application, the literature remains dispersed across binder modification, mixture performance, incorporation technologies, long-term durability, environmental implications and circularity. This study presents a systematic review of peer-reviewed journal articles indexed in Scopus and Web of Science (WoS) that address the use of crumb rubber in asphalt binders and mixtures. The review is structured around four interrelated questions: how incorporation route governs rubber-bitumen interaction; how crumb rubber affects rutting, fatigue, low-temperature cracking and moisture susceptibility; how aging, emissions and life-cycle impacts shape the sustainability case for CRA; and which unresolved methodological limitations still restrict broader implementation. The evidence shows that crumb rubber generally improves rutting resistance, elastic recovery, fracture tolerance, and, in several surface applications, acoustic performance. These benefits, however, are not intrinsic to rubber addition alone. They depend on a process-sensitive design window involving rubber gradation, rubber content, base-binder chemistry, digestion temperature, interaction time, blending energy, storage conditions, and the use of complementary technologies such as warm-mix additives, rejuvenators, pre-swelling treatments or hybrid modifiers. Wet-process systems remain the most mature and technically reliable route, whereas dry-process technologies offer implementation simplicity but exhibit greater variability in material response. Terminal-blend technologies improve workability and storage stability, although, in some cases, they partially reduce the elastomeric contribution associated with intact rubber particles. From a sustainability perspective, CRA clearly contributes to waste-tire valorization and may reduce life-cycle burdens when durability gains are realized and production conditions are optimized. Nevertheless, these environmental advantages are conditional rather than universal. Future research should prioritize standardized reporting, multi-scale mechanism-to-performance integration, realistic weathering and aging protocols, harmonized life-cycle assessment and credible end-of-life recycling pathways for rubberized asphalt systems.

Keywords: crumb rubber asphalt; asphalt rubber; waste tires; life-cycle assessment; circular economy

1. Introduction

The increasing generation of end-of-life tires has become a persistent environmental, regulatory and engineering challenge. At the same time, pavement systems are being required to deliver longer service life, higher functional performance and lower life-cycle impacts under increasingly demanding traffic and climate conditions. Within this context, crumb rubber asphalt (CRA) has emerged as one of the most mature and strategically relevant high-value applications of waste tire rubber in transport infrastructure. As emphasized by Lo Presti (2013), the long-standing interest in rubberized asphalt has been driven not only by the need to divert a problematic waste stream from disposal, but also by the expectation of enhancing the mechanical and functional performance of asphalt pavements. Shu and Huang (2014) similarly highlighted that waste tire rubber occupies a particularly relevant position among recycled modifiers because it addresses both infrastructure performance and solid-waste valorization.

The CRA literature has expanded substantially over the last two decades. Earlier studies focused primarily on feasibility, constructability and immediate rheological effects, whereas more recent work has broadened the scope to include mixture mechanics, fracture resistance, field durability, emissions, life-cycle performance and circularity. Bressi et al. (2019) showed that crumb-rubber pavement research has evolved into a mature and internationally distributed scientific field, while Picado-Santos et al. (2020) demonstrated that the literature now spans not only wet-process asphalt rubber, but also dry-process systems, terminal-blend binders, functional properties, energy use, emissions, life-cycle costs and circular-economy implications. Lyu et al. (2024) further confirmed that aging characterization and sustainability implications have become central themes in contemporary crumb-rubber asphalt research.

A major difficulty in interpreting this body of literature is that CRA should not be treated as a single material class. Rather, it comprises a family of process-dependent engineered systems that differ substantially in modification mechanism, production logistics and performance expression. In the wet process, crumb rubber is blended with the binder before mixture production, promoting swelling, absorption of light fractions and rheological transformation of the asphalt phase. In the dry process, rubber is introduced directly into the mixture and interacts with the asphalt system during mixing, curing and early service. Terminal-blend technologies, in turn, are designed to produce a more homogeneous and storage-stable rubberized binder under severe industrial processing conditions. As Han et al. (2016) and Picado-Santos et al. (2020) observed, these routes are not equivalent and should not be interpreted as technically interchangeable.

At the binder scale, crumb rubber modification generally increases viscosity, enhances elastic response, raises softening point, and changes the temperature susceptibility of the system. Airey et al. (2004), Peralta et al. (2012), Ibrahim et al. (2013), Tang et al. (2016) and Xu et al. (2016) all showed that these responses are strongly conditioned by rubber morphology, binder chemistry, and process severity. Terminal-blend studies by Huang et al. (2017), Li et al. (2017) and Lin et al. (2017) further revealed that the same processing conditions that improve pumpability and storage stability may also attenuate the elastomeric contribution of the rubber phase. Consequently, the role of crumb rubber is not merely additive; it is process transformative.

At the mixture scale, the most consistently reported benefit is improved resistance to permanent deformation. Chiu and Lu (2007), Kok and Çolak (2011), Moreno et al. (2013) and Fontes et al. (2010) all reported favourable rutting-related responses in rubberized mixtures. Improvements in crack-related response have also been repeatedly reported. Mamlouk and Mobasher (2004), Shirini and Imaninasab (2016), Silva et al. (2018), Rodríguez-Fernández et al. (2020) and Jin et al. (2024) observed favourable effects on fracture tolerance, fatigue-related behaviour or thermal cracking. However, these benefits remain strongly dependent on route-specific processing, curing, mixture volumetrics and compaction quality. Moisture susceptibility, in particular, remains one of the least convergent topics in the literature.

CRA also occupies an increasingly important place in the sustainability debate. On the one hand, it valorizes waste tires and may reduce life-cycle burdens when durability gains are achieved. On the other hand, such benefits are not automatic. They depend on production temperature, plant emissions, local waste-management pathways, electricity mix, transport distances, service-life assumptions and end-of-life scenarios. Farina et al. (2017), Wang et al. (2018), Bueno et al. (2021), Piao et al. (2022) and Lyu et al. (2024) collectively suggest that CRA can be environmentally advantageous under favourable conditions, but the literature still lacks full methodological harmonization across life-cycle studies.

To clarify the logic of the review before the methodological details are presented, Figure 1 summarizes the overall analytical framework adopted in this manuscript.

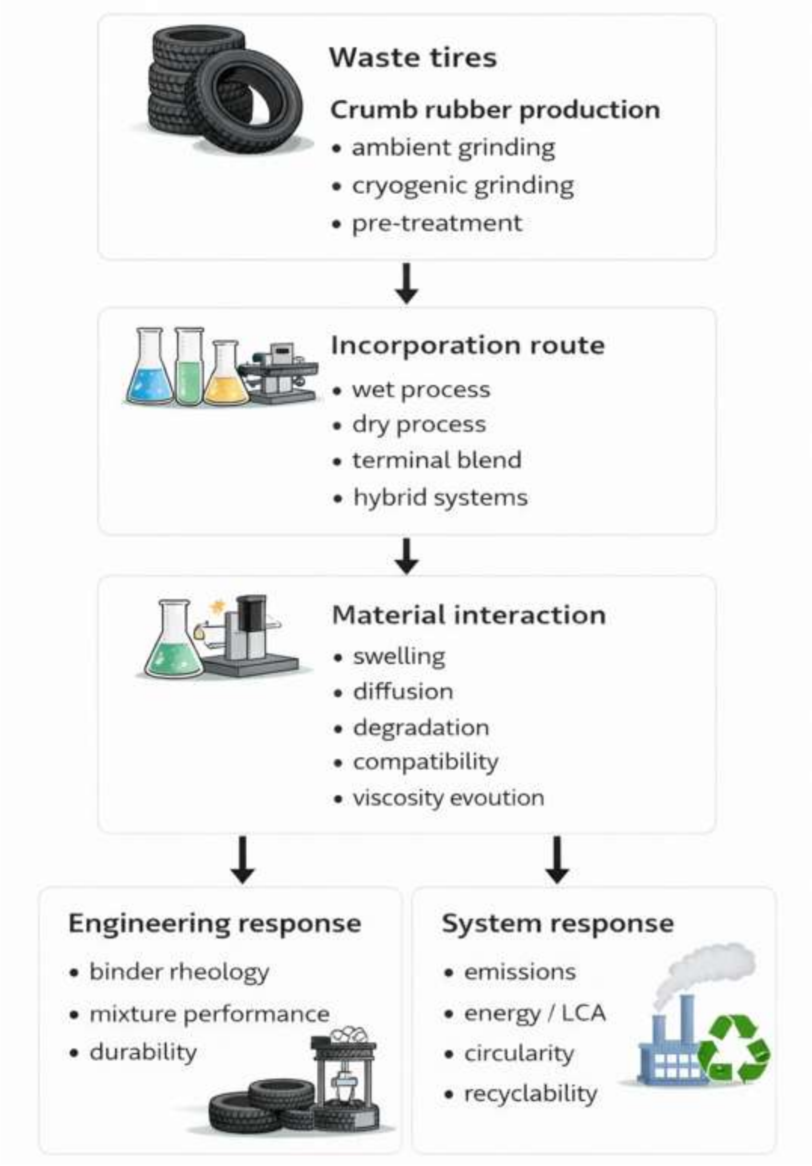

Figure 1. Conceptual framework of the review.

Existing reviews have made substantial contributions, but many remain centered on specific subdomains, such as route-specific technologies, low-temperature behaviour or binder aging. The present study therefore aims to provide an integrative systematic review of the peer-reviewed literature indexed in Scopus and Web of Science, with emphasis on incorporation technologies, binder-scale mechanisms, mixture-scale performance, aging evolution, sustainability and circularity. Rather than merely cataloguing reported advantages and drawbacks, this review seeks to explain why CRA performance varies across studies and which variables most strongly govern transferability from laboratory evidence to field-oriented pavement systems.

2. Methodology

2.1. Review Design and Reporting Framework

This study was conducted as a systematic literature review aimed at synthesizing the scientific evidence on crumb rubber asphalt (CRA), with emphasis on incorporation technologies, engineering performance, durability, emissions, life-cycle implications and circularity. The review process was structured in accordance with the PRISMA 2020 reporting framework (Page et al., 2021). The review was guided by the following research questions:

(1) how do wet-process, dry-process, terminal-blend, and emerging hybrid routes differ in terms of rubber–bitumen interaction, constructability and reproducibility?

(2) what is the available evidence on the effects of crumb rubber on binder rheology and mixture-scale performance, including rutting, fatigue, low-temperature cracking and moisture susceptibility?

(3) how do aging, emissions, life-cycle impacts, and end-of-life considerations influence the sustainability case for CRA?

(4) which methodological limitations still hinder comparability across studies and broader implementation in practice?

2.2. Research Strategy

The literature search was carried out in the Scopus and Web of Science databases because of their broad international coverage and relevance to asphalt materials, pavement engineering and sustainability research. Searches were performed on 1 March 2026, and the time window was restricted to studies published from January 2000 to December 2025. This period was selected to capture both the consolidation of conventional crumb-rubber technologies and the more recent expansion of the field toward warm-mix technologies, aging assessment, environmental emissions, life-cycle evaluation and circularity.

The search strategy combined terms related to pavement application, asphalt materials, crumb rubber and performance or sustainability outcomes. The core search string used in title, abstract, and keyword fields was as follows:

(“highway” OR “road” OR “pavement” OR “flexible pavement”) AND (“asphalt” OR “asphalt mixture” OR “bituminous mixture” OR “asphalt binder” OR “bitumen”) AND (“crumb rubber” OR “tire rubber” OR “tyre rubber” OR “recycled rubber” OR “ground tire rubber” OR “rubberized asphalt”) AND (“performance” OR “rheological properties” OR “mechanical properties” OR “durability” OR “fatigue life” OR “rutting resistance” OR “aging” OR “sustainability” OR “life cycle assessment” OR “LCA” OR “environmental impact”).

2.3. Eligibility Criteria

Studies were considered eligible when they met all of the following criteria: (1) peer-reviewed journal article; (2) written in English; (3) indexed in Scopus or Web of Science; (4) directly focused on crumb rubber application in asphalt binders, asphalt mixtures, or pavement systems; and (5) reported experimental, analytical, field, environmental, or life-cycle evidence relevant to the research questions.

Studies were excluded when they: (1) addressed rubber use in materials other than asphalt pavement systems; (2) focused exclusively on non-crumb-rubber modifiers without a CRA component; (3) were conference papers, theses, editorials, notes, or patents; (4) lacked sufficient methodological information to support interpretation; or (5) were review articles. Previous reviews were consulted only to support background discussion and identify thematic evolution, but they were not treated as primary evidence in the final synthesis.

2.4. Study Selection Process

All records retrieved from the databases were exported to Mendeley version 2.143.0, and duplicates were removed before screening. The study selection process involved three sequential stages: identification, title/abstract screening and full-text eligibility assessment. A total of 3,012 records were initially identified. After duplicate removal, 2,758 unique records remained for title and abstract screening. Following this stage, 432 articles were selected for full-text assessment. Of these, 317 studies were excluded for predefined reasons and 115 studies were included in the final review.

For each included study, the following information was extracted: authorship, year, country or context, incorporation route, rubber type and gradation, rubber dosage, base-binder characteristics, processing conditions, test methods, performance outcomes, aging protocol, environmental indicators and main conclusions.

Methodological quality was appraised using a structured review form adapted to CRA studies, covering reporting completeness, material characterization, processing transparency, test reproducibility, and alignment between methods and conclusions. The purpose of this appraisal was not to exclude studies solely on quality grounds, but to support a more critical interpretation of the evidence.

The final synthesis was organized into five interconnected domains: technological pathways; binder-scale response; mixture-scale performance; aging and durability and sustainability and circularity. Figure 2 presents the PRISMA 2020 flow diagram summarizing the identification, screening, eligibility assessment and final inclusion of studies.

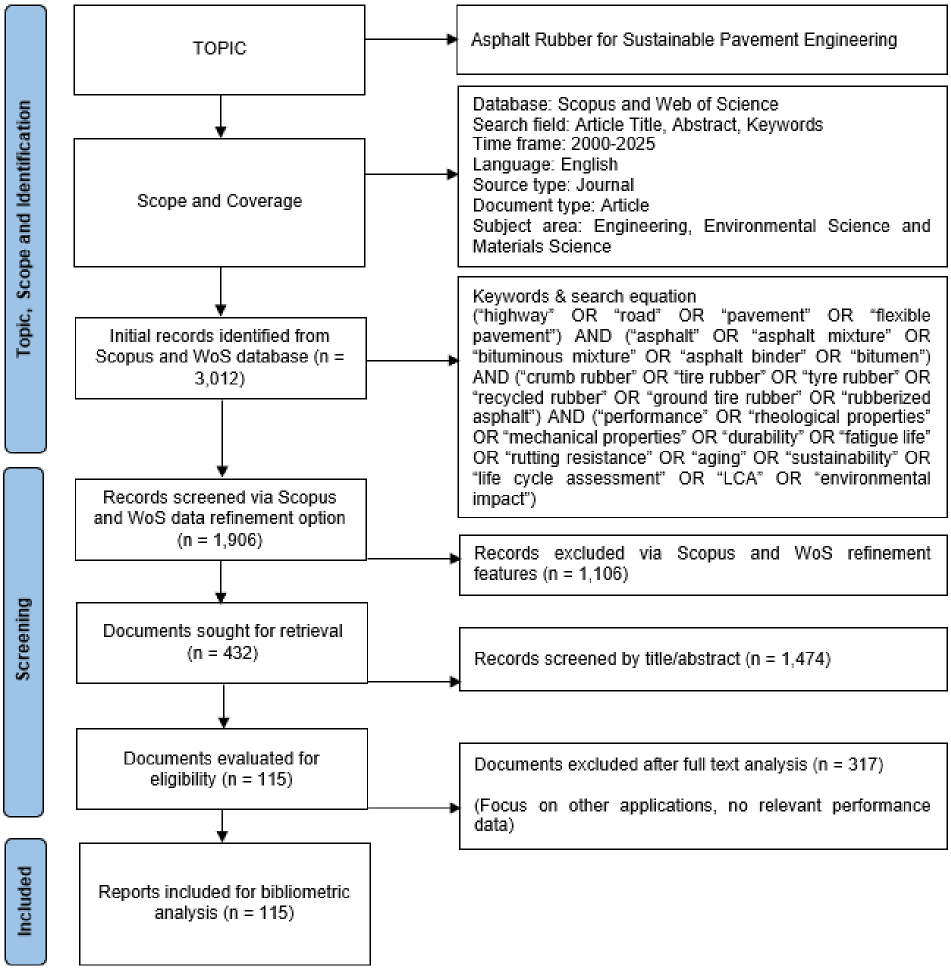

Figure 2. PRISMA 2020 flow diagram of study identification, screening, eligibility assessment and inclusion.

The main reasons for exclusion at the full-text stage included lack of direct focus on crumb rubber asphalt systems, insufficient methodological transparency, and absence of performance, environmental or durability outcomes relevant to the review questions.

3. Results and Discussion

3.1. Publication Landscape and Technological Pathways

The contemporary CRA literature reflects a mature but still rapidly evolving research field. Earlier studies were predominantly concerned with the feasibility of incorporating tire rubber into asphalt and with the immediate rheological consequences of modification. Over time, the literature shifted toward a more diversified agenda, including mixture mechanics, cracking resistance, field durability, warm-mix technologies, aging, emissions and life-cycle sustainability.

This thematic broadening is consistent with the evolution observed in recent review papers. Picado-Santos et al. (2020) showed that the literature increasingly distinguishes among wet process, dry process, and terminal-blend technologies while simultaneously integrating performance and sustainability dimensions. Lyu et al. (2024), in turn, demonstrated that aging, rheological characterization and environmental assessment have become central themes in the most recent decade.

A first-order distinction in the literature concerns the route through which crumb rubber is introduced into the asphalt system. The three main technological families are wet process, dry process, and terminal blend, with more recent studies also exploring semi-wet, pre-swelled, hybrid and pelletized solutions. In the wet process, crumb rubber is blended with the asphalt binder before mixture production. This route is the most intensively investigated and generally the most effective in generating a measurable rheological transformation. In the dry process, crumb rubber is added directly into the mixture, usually through the aggregate stream or during mixing. This route is attractive from the standpoint of plant implementation because it can simplify logistics and reduce dependence on specialized binder handling. In the terminal-blend route, crumb rubber is exposed to more severe blending conditions, usually at terminal or refinery scale, producing a more homogeneous and pumpable binder.

Before discussing performance outcomes, Table 1 compares the principal characteristics of the dominant crumb-rubber incorporation technologies.

Table 1. Comparative characteristics of major crumb-rubber asphalt technologies.

Technology	Process description	Main advantages	Main limitations	Representative references
Wet process	Crumb rubber is blended with hot bitumen before mixture production	Strong binder modification; improved rutting and cracking resistance; mature engineering base	High viscosity; temperature sensitivity; storage and handling demands	Lo Presti (2013); Airey et al. (2004); Peralta et al. (2012); Neto et al. (2011); Venudharan and Biligiri (2017); Picado-Santos et al. (2020)
Dry process	Crumb rubber is added directly into the mixture, usually through heated aggregates	Simpler plant implementation; lower logistics complexity; attractive for direct field use	Higher variability; curing sensitivity; inconsistent moisture and fatigue results in some studies	Hernández-Olivares et al. (2009); López-Moro et al. (2013); Feiteira et al. (2014); Farouk et al. (2017); Silva et al. (2018); Rodríguez-Fernández et al. (2020)

Terminal blend	Rubber is intensively processed at terminal or refinery scale to obtain a homogeneous binder	Better pumpability and storage stability; easier transportation and plant handling	Possible attenuation of elastomeric contribution through severe degradation of rubber particles	Han et al. (2016); Huang et al. (2017); Li et al. (2017); Lin et al. (2017); Tang et al. (2019)
Hybrid / pre-swelled / pelletized systems	Rubber is pre-treated or incorporated through combined strategies	Potential balance between workability and performance; promising industrial scalability	Still less standardized; limited long-term field evidence	Gandhi et al. (2014); Oliveira et al. (2013); Wang et al. (2018); Jin et al. (2024)

The literature does not support the assumption that these technologies are functionally equivalent. On the contrary, route-specific processing determines the balance among swelling, diffusion, viscosity increase, storage stability and degradation of the rubber phase. This is one of the main reasons why apparently contradictory performance findings coexist in the literature.

To synthesize this route-dependent logic, Figure 3 presents the causal chain linking processing route to pavement-level and system-level outcomes.

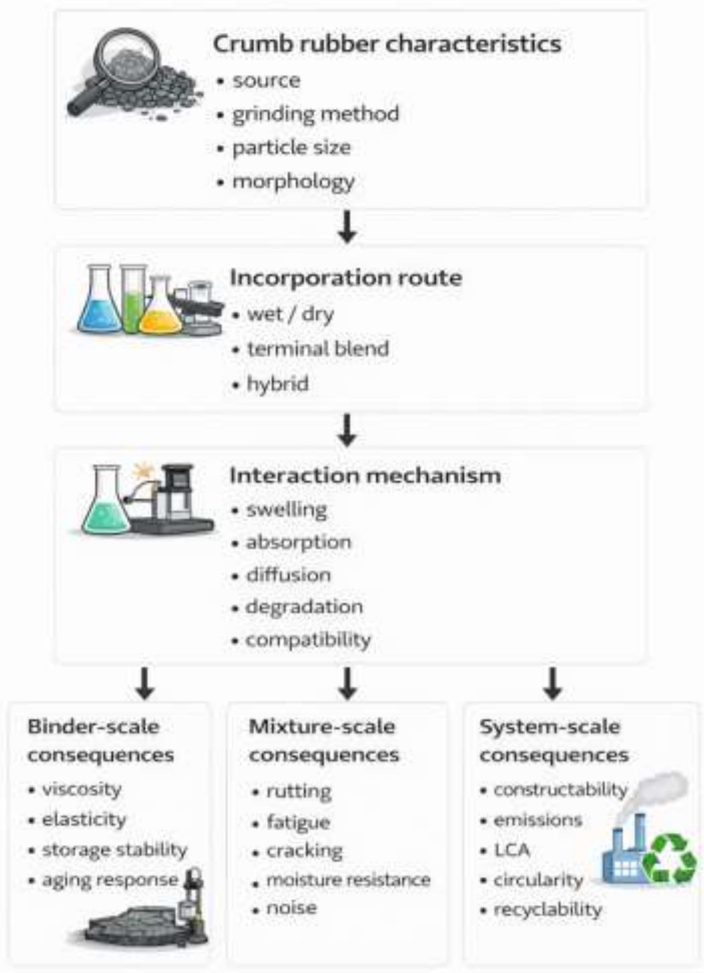

Figure 3. Route-dependent evolution of crumb-rubber asphalt behavior.

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3.2. Binder-Scale Response

At the binder scale, the literature is relatively convergent. Crumb rubber generally increases viscosity, enhances elastic recovery, and modifies the viscoelastic spectrum of the binder. Airey et al. (2004) showed that crumb-rubber interaction depends strongly on crude source and base-binder viscosity. Peralta et al. (2012) demonstrated that mutual changes occur in both the rubber and the asphalt phase during binder production. Ibrahim et al. (2013) synthesized much of this early rheological literature and confirmed that rubber addition commonly produces more viscous and more elastic binders. Tang et al. (2016), Xu et al. (2016), and Chen et al. (2019) further showed that process severity, activation strategy and complementary modifiers strongly affect rheological response.

From an engineering perspective, these rheological changes are generally beneficial at high temperatures because they increase resistance to permanent deformation. However, they also create one of the main barriers to practical implementation: high viscosity. Excessive viscosity can complicate pumping, coating, compaction, and storage. This explains the growing literature on warm-mix additives, waxes, chemical activation and optimized blending conditions intended to reduce processing temperatures without eliminating the beneficial role of rubber.

Conventional wet-process binders often require agitation and controlled residence time to avoid separation, whereas terminal-blend technologies are specifically designed to improve stability during transport and storage. Yet, as Han et al. (2016), Huang et al. (2017), Li et al. (2017) and Lin et al. (2017) made clear, improved stability may come at the cost of more severe rubber degradation. Therefore, the engineering challenge is not simply to stabilize the modified binder, but to do so without erasing the viscoelastic functionality that motivated rubber modification.

Wang et al. (2017) concluded that crumb rubber often improves low-temperature performance and crack-related resistance, although the magnitude of the effect depends on route, formulation, and test method. Chang et al. (2020), Wang et al. (2012) and Lyu et al. (2024) similarly indicated that low-temperature response depends on the balance between retained rubber elasticity and aging-induced stiffening.

Table 2 condenses the main binder-scale findings reported in the literature.

Table 2. Binder-scale effects of crumb rubber modification.

Property / phenomenon	Typical trend	Main controlling variables	Representative references
Viscosity	Usually increases substantially	Rubber content, particle size, temperature, digestion time, base-binder chemistry	Airey et al. (2004); Peralta et al. (2012); Ibrahim et al. (2013); Tang et al. (2016); Xu et al. (2016)
Elastic recovery	Usually increases	Rubber morphology, interaction time, degree of swelling	Lo Presti (2013); Peralta et al. (2012); Chen et al. (2019)
Storage stability	Often problematic in conventional wet process; improved in terminal blend	Process severity, agitation, degradation level, compatibilizers	Han et al. (2016); Huang et al. (2017); Li et al. (2017); Lin et al. (2017); Tang et al. (2019)
High-temperature performance	Generally improved	Rubber dosage, activation, blending severity	Kok and Çolak (2011); Xu et al. (2016); Chen et al. (2019); Wang et al. (2020)

Low-temperature performance	Often favorable, but not universally	Retained elasticity, aging severity, evaluation metric	Wang et al. (2012); Wang et al. (2017); Chang et al. (2020); Lyu et al. (2024)
Aging response	Often improved for crack-related behavior, but route- and metric-dependent	Thermal aging, UV exposure, degradation of rubber phase	Xiao et al. (2009a); Wang et al. (2016); Qian et al. (2020); Lyu et al. (2024)

3.3. Mixture-Scale Performance

At the mixture scale, the strongest and most consistent body of evidence concerns rutting resistance. Numerous studies report that rubberized asphalt mixtures, especially those produced using wet-process binders, outperform conventional asphalt mixtures in wheel tracking and permanent deformation resistance. Chiu and Lu (2007), Kok and Çolak (2011), Moreno et al. (2013), Chávez et al. (2019) and Yazdipanah et al. (2021) all found improvements in rutting-related indicators, although the magnitude of the effect varied according to rubber content, aggregate gradation, effective binder content, curing and complementary modifiers.

Evidence regarding fatigue and fracture performance is also broadly favourable, although more heterogeneous than rutting evidence. Crack resistance tends to improve when the mixture design allows the rubberized binder to function effectively within the aggregate skeleton, particularly in gap-graded or open-graded systems where higher effective binder contents can be accommodated. Picado-Santos et al. (2020) identified fatigue and crack-related improvement as one of the most recurrent benefits of asphalt rubber mixtures, while Jin et al. (2024) and Silva et al. (2018) provided more recent evidence supporting improved crack tolerance in well-designed rubberized systems.

Low-temperature cracking follows a similar pattern. CRA mixtures often show better resistance to thermal cracking than conventional mixtures, especially when the binder retains sufficient elasticity and when the mixture is not excessively stiffened by aging or poor volumetric control. However, as with binder-scale evidence, the beneficial response is strongly dependent on process route and thermal history.

The most controversial topic remains moisture susceptibility. The literature presents contradictory results: some studies report improved or equivalent tensile strength ratio and moisture resistance, while others observe deterioration. This inconsistency is especially apparent in dry-process systems and in warm-rubber combinations. The most plausible interpretation is that moisture susceptibility is not an intrinsic weakness of crumb-rubber asphalt; rather, it is a process- and design-dependent response governed by aggregate mineralogy, coating quality, air-void structure, viscosity, curing and compaction.

Another dimension that deserves greater visibility is functional performance. Surface layers produced with asphalt rubber have often been associated with improved acoustic behaviour. Field studies on rubberized surfaces indicate that CRA can reduce tire-pavement noise, particularly when mixture macrotexture and interconnected void structure are favourably configured.

Table 3 summarizes the dominant mixture-scale findings.

Table 3. Mixture-scale performance of crumb-rubber asphalt.

Performance domain	Predominant finding	Main sources of variability	Representative references
Rutting resistance	Generally improved	Route, rubber content, effective binder, compaction, aggregate gradation	Chiu and Lu (2007); Kok and Çolak (2011); Moreno et al. (2013); Fontes et al. (2010);

			Chávez et al. (2019); Yazdipanah et al. (2021)
Fatigue resistance	Frequently improved	Test mode, strain level, aging, route, mixture structure	Mamlouk and Mobasher (2004); Xiao et al. (2009b); Picado-Santos et al. (2020); Jin et al. (2024)
Low-temperature cracking	Often improved	Retained elasticity, mixture stiffness, thermal conditioning	Wang et al. (2017); Shirini and Imaninasab (2016); Puga and Williams (2016); Jin et al. (2024)
Moisture susceptibility	Contradictory	Aggregate type, viscosity, coating quality, air voids, curing	Chávez et al. (2019); Farouk et al. (2017); Nguyen and Tran (2018); Picado-Santos et al. (2020)
Reflection cracking	Often favorable	Interlayer design, route, field conditions	Chen et al. (2013); Silva et al. (2018)
Dynamic modulus / stiffness	Variable but often favorable at high temperature	Aging, temperature, route, activation level	Feiteira et al. (2014); Rodríguez-Fernández et al. (2020); Jin et al. (2022)
Acoustic performance	Often improved in surface layers	Surface texture, void structure, mixture type	Paje et al. (2010); Paje et al. (2013); Licitra et al. (2015); Jin et al. (2024)

3.4. Aging and Durability

Aging is one of the most strategically important themes in the modern CRA literature because it connects initial laboratory performance to long-term field behaviour. Lyu et al. (2024) showed that recent studies on crumb-rubber asphalt aging are concentrated around four main domains: aging methods, chemical and microstructural characterization, rheological-mechanical evolution and environmental implications. Their synthesis also showed that most studies still focus on thermal aging, whereas ultraviolet aging and realistic weathering scenarios remain comparatively underexplored.

Thermal aging has received the greatest attention. Xiao et al. (2009a), Lee et al. (2008), Lee et al. (2011), Li et al. (2021), Li et al. (2022a) and Tang et al. (2019) all examined the effect of laboratory aging on rubberized binders and/or mixtures. A recurring conclusion is that crumb-rubber systems often retain favourable crack-related behaviour after aging, particularly at low temperatures. However, the field does not support a simplistic claim that crumb-rubber asphalt is always more aging-resistant. The actual response depends on route, process severity, aging protocol and the evaluation indicator selected.

UV and weathering studies are growing but remain less abundant than thermal-aging studies. Qian et al. (2020), Wu (2017), Wang et al. (2021), Zadshir et al. (2020), Zhang et al. (2020), Zhou et al. (2020) and Lyu et al. (2021) showed that UV exposure and combined environmental factors can significantly alter interfacial behaviour, rheological properties, and cracking resistance. The literature therefore suggests that single-factor thermal aging is insufficient to represent the complex service environment of asphalt pavements.

Another critical issue is the scale gap between binder aging and pavement aging. Many studies characterize aged binders in detail, but fewer translate those changes into mixture-level or field-level consequences. Yet pavement performance depends on how physicochemical changes in the binder modify damage accumulation within the entire mixture structure. This is why route-specific and multi-scale evaluation is essential.

To synthesize the durability logic before the sustainability section, Figure 4 presents the multi-factor aging framework emerging from the literature.

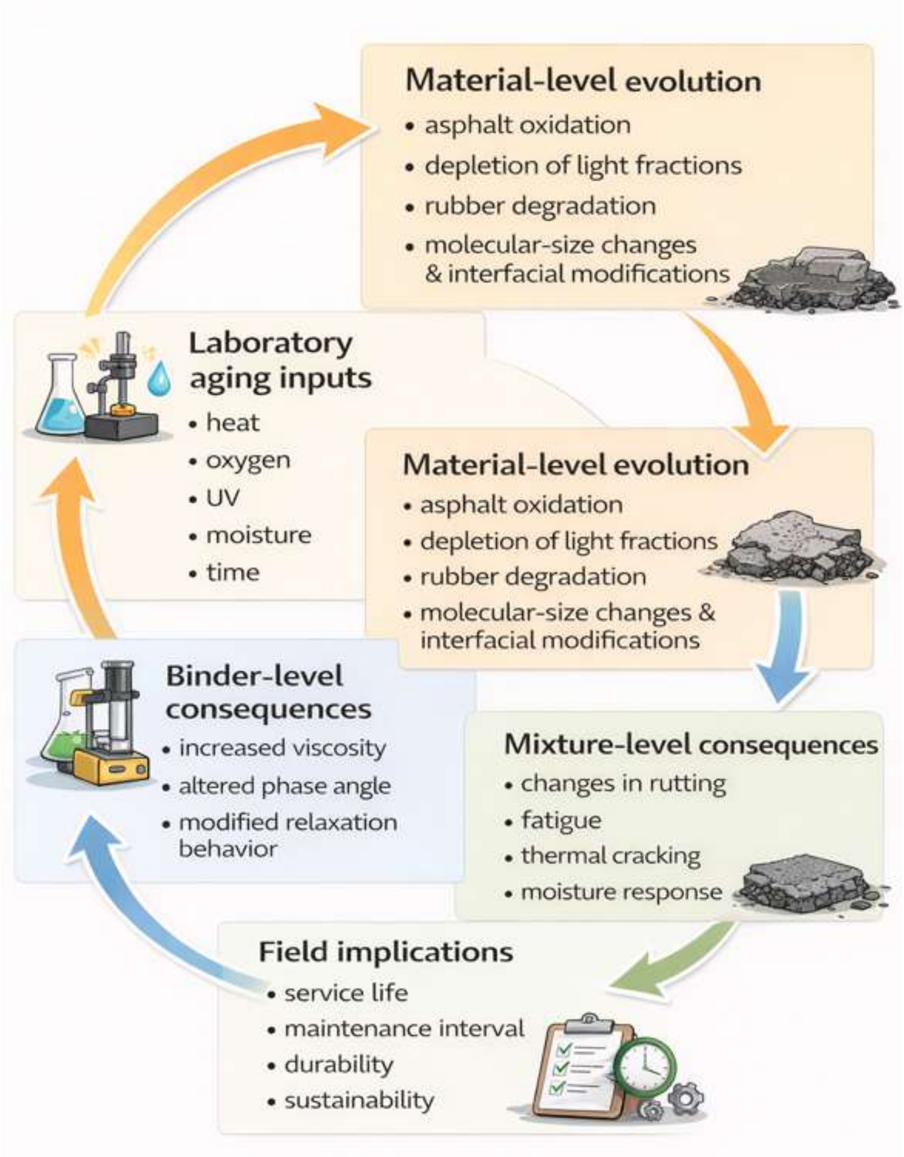

Figure 4. Multi-factor aging framework for crumb-rubber asphalt.

Table 4 condenses the main aging and durability trends reported in the literature.

Table 4. Aging, durability and environmental response of crumb-rubber asphalt.

Domain	General evidence	Main limitation	Representative references
Thermal aging	Most studied and reasonably well understood	Protocols do not fully capture field weathering	Xiao et al. (2009a); Lee et al. (2011); Tang et al. (2019); Li et al. (2021); Lyu et al. (2024)

UV aging	Increasingly studied but still limited	Lack of harmonized protocols and long-term field validation	Wu (2017); Qian et al. (2020); Wang et al. (2021); Zadshir et al. (2020)
Weathering realism	Still underdeveloped	Few studies integrate heat, UV, moisture, and traffic effects	Zhang et al. (2020); Zhou et al. (2020); Lyu et al. (2024)
Fatigue after aging	Often favorable but indicator-dependent	Contradictory findings across test metrics	Xiao et al. (2009b); Li et al. (2022a); Lyu et al. (2024)
Low-temperature cracking after aging	Frequently better than base binder systems	Depends on retained rubber elasticity and degree of degradation	Wang et al. (2017); Li et al. (2021); Lyu et al. (2024)
Plant emissions	Important sustainability concern	Need better field-linked and occupational-health protocols	Zanetti et al. (2014); Yang et al. (2019); Tang et al. (2022); Li et al. (2023)
Leaching / ecotoxicity	Generally manageable in compacted systems, but data remain limited	Strong dependence on protocol and exposure scenario	Bueno et al. (2021); Jin et al. (2024)

3.5. Sustainability, Emissions and Circularity

The sustainability rationale for CRA begins with waste-tire valorization. End-of-life tires are difficult to landfill, non-biodegradable and environmentally problematic when stockpiled. Using crumb rubber in asphalt therefore offers a clear circular-economy benefit by converting a problematic waste stream into a functional infrastructure material. Lo Presti (2013), Bressi et al. (2019), Shu and Huang (2014) and Mohajerani et al. (2020) all support this general interpretation.

However, the environmental case for CRA depends on system boundaries rather than on waste valorization alone. Farina et al. (2017), Wang et al. (2018), Bueno et al. (2021), and Piao et al. (2022) indicate that meaningful environmental gains are possible when service-life benefits are realized and production conditions are optimized. Yet such gains are highly sensitive to transport distances, allocation rules for waste tires, energy mix, process temperature, maintenance assumptions and end-of-life scenarios. Lyu et al. (2024) similarly concluded that depending on local waste-management policy, significant reductions in energy use and global warming potential are possible.

Plant emissions and occupational exposure have become major concerns in the recent literature. Zanetti et al. (2014) measured gaseous emissions from crumb-rubber mixtures during production. Yang et al. (2019) showed that emission behaviour differs between hot and warm-mix conditions. Tang et al. (2022) and Li et al. (2023) further confirmed that fume generation is a critical part of the sustainability debate. These studies collectively indicate that the environmental case for CRA must include production-stage emissions and worker exposure, rather than relying exclusively on life-cycle greenhouse-gas indicators.

True circularity also requires attention to end-of-life management. Although CRA is routinely presented as a circular solution because it incorporates waste tires, circularity should ultimately mean that rubberized asphalt itself can be recovered and re-integrated at the end of its service life. Evidence in this area is still emerging. Shen et al. (2006), Li et al. (2022b) and Li et al. (2023) suggest that reclaimed asphalt containing rubber can be reused under appropriate conditions, but the field still lacks broad, field-calibrated evidence for closed-loop recyclability.

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Table 5 summarizes the principal sustainability implications and unresolved issues.

Table 5. Sustainability and circularity implications of crumb-rubber asphalt.

Sustainability dimension	Overall interpretation	Key uncertainty	Representative references
Tire valorization	Strongly positive	Depends on local alternatives for waste-tire management	Lo Presti (2013); Shu and Huang (2014); Mohajerani et al. (2020)
Life-cycle energy and GHG	Often favorable	Sensitive to service-life extension, temperature, transport, and allocation assumptions	Farina et al. (2017); Piao et al. (2022); Lyu et al. (2024)
Warm-mix synergy	Promising route to reduce environmental burdens	Must preserve mechanical performance and aging resistance	Oliveira et al. (2013); Wang et al. (2018); Yang et al. (2017); Wen et al. (2018)
Plant emissions	Relevant concern	Need better harmonized protocols and mitigation strategies	Zanetti et al. (2014); Yang et al. (2019); Tang et al. (2022); Li et al. (2023)
Acoustic benefit	Valuable functional gain	Depends on surface design and acoustic durability	Paje et al. (2010); Paje et al. (2013); Licitra et al. (2015); Vázquez and Paje (2016)
End-of-life recyclability	Promising but underdeveloped	Lack of large-scale and long-term validation	Shen et al. (2006); Li et al. (2022b); Li et al. (2023)

3.6. Critical Gaps and Future Research Agenda

The review exposes five critical limitations that continue to hinder both scientific comparability and the effective translation of knowledge into practice. A primary issue lies in the insufficient standardization of material reporting, as many studies omit essential information on rubber origin, grinding method, particle morphology, particle-size distribution, and blending history. This lack of transparency severely compromises the interpretation of results and contributes to apparent inconsistencies across the literature.

Equally limiting is the persistent disconnect between mechanistic understanding and performance evaluation. In several cases, chemical and rheological analyses are presented without meaningful linkage to mixture behaviour or field performance, while other studies report mechanical responses without adequately characterizing the underlying rubber-binder interaction mechanisms.

Another fundamental constraint is the limited realism of current aging protocols. Research remains heavily centered on thermal aging, with comparatively little attention given to multi-factor weathering processes or long-term field validation, both of which are essential to accurately represent in-service conditions.

From an environmental perspective, the absence of harmonized sustainability assessment frameworks further restricts progress. Existing studies adopt highly variable functional units, system boundaries, inventory assumptions, and approaches to service life and end-of-life scenarios, ultimately preventing robust comparisons and reliable conclusions.

Most critically, the field has yet to fully address end-of-life circularity. While the incorporation of tire rubber into asphalt has been convincingly demonstrated, there is still a lack of clear strategies and validated pathways for the recovery and revalorization of rubberized asphalt after its service life, representing a major gap in closing the material loop.

Taken together, these gaps indicate that the CRA field is no longer limited by lack of technical promise. It is now limited primarily by lack of harmonization, insufficient field-calibrated validation, and incomplete circular design logic. These research priorities are synthesized in Figure 5.

Figure 5. Priority research agenda for next-generation crumb-rubber asphalt systems.

4. Conclusion

This systematic review demonstrates that crumb rubber asphalt has evolved from a waste-management alternative into a technically credible and strategically relevant pavement technology. The literature consistently shows that crumb rubber can enhance high-temperature performance, improve elastic response, increase resistance to permanent deformation, and, under appropriate design conditions, provide superior fracture tolerance and acoustic benefits.

At the same time, the review makes clear that CRA should not be interpreted as a single material category. Wet-process binders, dry-process mixtures, terminal-blend systems, and newer hybrid technologies are materially distinct and should not be compared as if they were functionally equivalent. Much of the disagreement reported in the literature reflects differences in rubber gradation, rubber dosage, interaction time, digestion temperature, blending energy, base-binder chemistry, curing conditions and compaction quality. In other words, crumb-rubber performance is strongly process-dependent.

From a mechanistic standpoint, the most reliable findings concern the ability of crumb rubber to modify binder rheology through swelling, absorption of lighter fractions and development of a more elastic viscoelastic structure. These effects are generally beneficial for rutting resistance and crack mitigation, but they also increase viscosity and may complicate plant production, storage, coating and compaction. Consequently, the key engineering challenge is not simply to add rubber to asphalt, but to control the interaction pathway so that performance gains are achieved without unacceptable penalties in constructability or emissions.

At mixture scale, rutting resistance is the most consistently improved performance domain. Fatigue and low-temperature cracking also tend to improve, particularly in well-designed wet-process or crack-tolerant systems, although these responses are more sensitive to test protocol, aging history and mixture volumetrics. Moisture susceptibility remains one of the least convergent topics in the field and should be interpreted primarily as a mixture-design and construction-quality issue rather than as an intrinsic weakness of crumb-rubber modification.

Aging and durability emerge as decisive themes for the next generation of research. The current body of evidence suggests that rubberized systems can retain favourable crack-related response after aging, especially at low temperature, but this benefit is conditional and may be offset by degradation of the rubber phase under severe or prolonged exposure. The field has advanced substantially in thermo-oxidative aging, yet combined weathering scenarios involving ultraviolet radiation, moisture, temperature cycling and traffic-induced damage are still insufficiently represented.

From a sustainability perspective, CRA presents a compelling but conditional environmental case. The valorization of end-of-life tires is an unquestionable advantage, and several life-cycle studies indicate that meaningful reductions in environmental burdens are possible. However, such benefits depend on production temperature, local waste-management policy, transport distances, electricity mix, allocation assumptions, maintenance frequency, and service-life extension. Emissions during production and the long-term environmental behaviour of rubberized pavements remain areas requiring greater methodological harmonization and field validation.

A further strategic issue concerns end-of-life circularity. The literature has convincingly established that waste tire rubber can be incorporated into asphalt. It has not yet established with the same degree of certainty how rubberized asphalt itself should be recovered, reprocessed, and reintegrated into future pavement cycles. This gap is particularly important for high-impact research agendas centered on circular infrastructure.

Overall, the evidence supports a balanced conclusion: crumb-rubber asphalt is neither a universally superior solution nor a marginal niche technology. It is a mature but highly process-sensitive material system whose value depends on engineering control, contextual suitability and life-cycle interpretation. The most promising direction for future work is the integration of multi-scale materials characterization, mechanistic performance evaluation, realistic aging protocols, emissions mitigation and end-of-life recyclability into a unified design logic for next-generation rubberized pavements.

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