

Review

Circular Economy for Transport Infrastructure: An Overview of the Sustainable Use of Recycled Asphalt Shingles in Asphalt Mixtures

Marco Pasetto , Safeer Haider and Emiliano Pasquini * 

Department of Civil, Environmental and Architectural Engineering, University of Padua, 35131 Padua, Italy; marco.pasetto@unipd.it (M.P.); safeer.haider@studenti.unipd.it (S.H.)

* Correspondence: emiliano.pasquini@unipd.it

Abstract: In North America and Europe, asphalt shingle waste created during the installation of roofing membranes and tear-off shingles retrieved at the end of the membrane's life cycle are two major sources of municipal solid waste. Since almost 15–35% of recycled asphalt shingles (RAS) consist of an asphalt binder, the effective recycling of RAS into asphalt mixtures could also allow a reduction in the consumption of non-renewable resources such as asphalt binders. In this context, several studies investigating the use of RAS in asphalt mixtures can be found in the literature, although they exhibit widespread and sometimes conflicting information about the investigated materials, the mix preparation and testing methodologies and the experimental findings. Given this background, this review paper aims at summarizing the existing information and research gaps, providing a synthetic and rational picture of the current literature, where similar attempts cannot be found. In particular, different research studies show that the use of RAS in asphalt mixtures is an economical as well as an eco-friendly option. RAS with up to 20% by weight of binder or 5% by weight of aggregate/mixtures (eventually in combination with 15% reclaimed asphalt pavement aggregate) were found to be relatively suitable to improve the performance properties of asphalt mixtures, both in the laboratory and in the field. Adding RAS to asphalt mixtures could enhance their stiffness, strength and rutting resistance (i.e., high-temperature properties), while negatively affecting the mixtures' fatigue and thermal cracking resistance. However, the addition of specific biomaterials (e.g., bio-binders, bio-oils) or additives to asphalt mixtures can mitigate such issues, resulting in lower brittleness and shear susceptibilities and thus improving the anti-cracking performance. On the other hand, the literature review revealed that several aspects still need to be studied in detail. As an example, RAS-modified porous asphalt mixtures (fatigue, rutting, moisture susceptibility and thermal cracking) need specific research, and there are no comprehensive research studies on the effects of the RAS mixing time, size and mixing temperature in asphalt mixtures. Moreover, the addition of waste cooking/engine oils (biomaterials) as asphalt binder rejuvenators in combination with RAS represents an attractive aspect to be studied in detail.

Keywords: recycled asphalt shingles; circular economy; smart pavements; asphalt mixtures



Citation: Pasetto, M.; Haider, S.; Pasquini, E. Circular Economy for Transport Infrastructure: An Overview of the Sustainable Use of Recycled Asphalt Shingles in Asphalt Mixtures. *Appl. Sci.* **2024**, *14*, 10145. <https://doi.org/10.3390/app142210145>

Academic Editor: Ning Li

Received: 4 October 2024

Revised: 31 October 2024

Accepted: 4 November 2024

Published: 6 November 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

It is well known that there is an urgent need to reduce the energy consumption in paving activities and utilize sustainable methods that benefit the environment, users and industry. In most cases, recycling byproduct materials saves money and reduces the need for virgin materials. However, the use of alternative materials is effective provided that the pavement's performance properties are not compromised [1–5]. Asphalt mixes cover approximately 90% of the road pavements worldwide. The long-term viability of these roadways is critical, and the recycling of materials has been proven to be a cost-effective and environmentally responsible solution. Materials such as reclaimed asphalt pavement

(RAP), recycled concrete aggregates, waste plastic, steel slag, discarded tire crumb rubber, fly and bottom ash and recycled asphalt shingles have all been used to prepare asphalt mixtures. Indeed, the utilization of waste products in the production of hot-mix asphalt (HMA) can lead to (1) a decrease in the virgin materials that are used; (2) a reduction in emissions, energy consumption and by-product materials that are disposed of in landfills; (3) a reduction in public anxiety regarding emissions; and (4) increased paving construction competitiveness [6–9].

In this regard, RAS addition to HMA is gaining increasing interest. As an example, nearly 11 million tons of asphalt shingles are produced yearly in the United States [10–12]. This recycled asphalt shingle waste is produced from two primary sources, i.e., post-consumer and post-industrial roofing membranes. Over ten million tons of recycled asphalt shingles were obtained from post-consumer shingles (tear-off scrap shingles—TOSS). The remaining 1 million tons of waste consist of shingles produced during the installation of roofing membranes, commonly known as manufactured waste scrap shingles (MWSS) [13–16]. Hence, TOSS have been mostly used to improve the performance properties of modified asphalt mixtures due to the large quantity of such scrap waste available, although MWSS-modified asphalt mixtures have also been investigated.

In this regard, this paper provides a critical overview of the existing literature to synthesize the diverse information provided in several research studies addressing different materials and methodologies.

2. Motivation and Objectives

Sustainable landfill disposal, as well as the use of non-renewable resources, is a world-wide problem. Sustainable construction involves developing roads, buildings and energy and water infrastructure with due consideration of their economic, social and environmental implications. On a broader scale (related to transport infrastructure), sustainable pavements meet basic human needs, use resources effectively and preserve/restore the surrounding ecosystems. In this regard, RAS (both MWSS produced during installation and TOSS obtained at the end of life) can be effectively recycled into asphalt mixtures, since they are mainly composed of bitumen, so that a significant reduction in the consumption of such non-renewable resources can be achieved. Given this background, this review article could help in understanding the benefits and drawbacks of using roofing shingle waste in asphalt pavements in order to effectively promote circular economy principles. In particular, this paper aims at summarizing the existing information and research gaps, providing a synthetic and rational picture of the current literature, where similar attempts cannot be found.

3. Recycled Asphalt Shingles (RAS)

3.1. Shingle Composition

There are two common sources of asphalt shingles, i.e., organic and fiberglass. Organic shingles consist of 30 to 35% asphalt binder, with mineral fibers ranging from 5 to 15%, while mineral and ceramic-coated granules vary from 30 to 50%. Fiberglass shingles contain 15–20% asphalt binder, 15% felt, 15–20% mineral filler, and 30–50% mineral granules, with a ceramic coating. Moreover, glass fiber shingles have a fiberglass-reinforced backing, while organic shingles have a cellulose-felt base derived from paper [17–20]. A schematic view of RAS is given in Figure 1.

As can be seen from Figure 1, shingles consist of organic or fiberglass fibers impregnated with an asphalt binder and surfaced with granules to avoid physical or sun damage. The back surface is coated with fine sand to avoid adhering during transport and packaging.

Asphalt shingles are mostly produced from an oxidized asphalt binder (blowing of air at 230–260 °C). During “air blowing”, the asphalt binder used to produce shingles is subjected to oxygen as part of the manufacturing process to enhance the viscosity and minimize the temperature susceptibility. As a consequence, the asphalt binder is pre-aged, and the oxidative hardening process renders it substantially stiffer. As roofing membranes

are typically exposed to the environment for at least 15 or 20 years, the effect of stiffening on post-consumer TOSS is more pronounced.

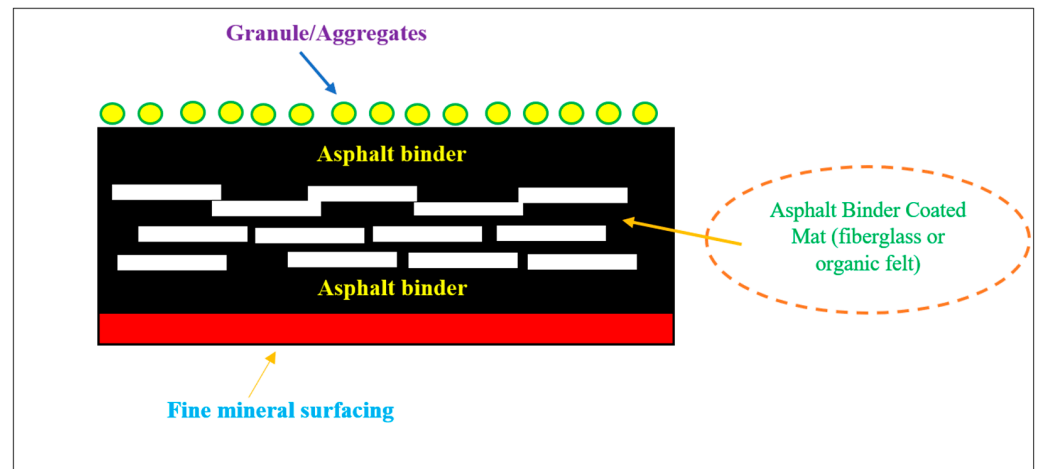


Figure 1. Schematic view of RAS composition [21].

3.2. RAS Processing

RAS processing consists of mainly six steps, i.e., collection, asbestos testing, sorting, grinding, screening, and storage, as shown in Figure 2.

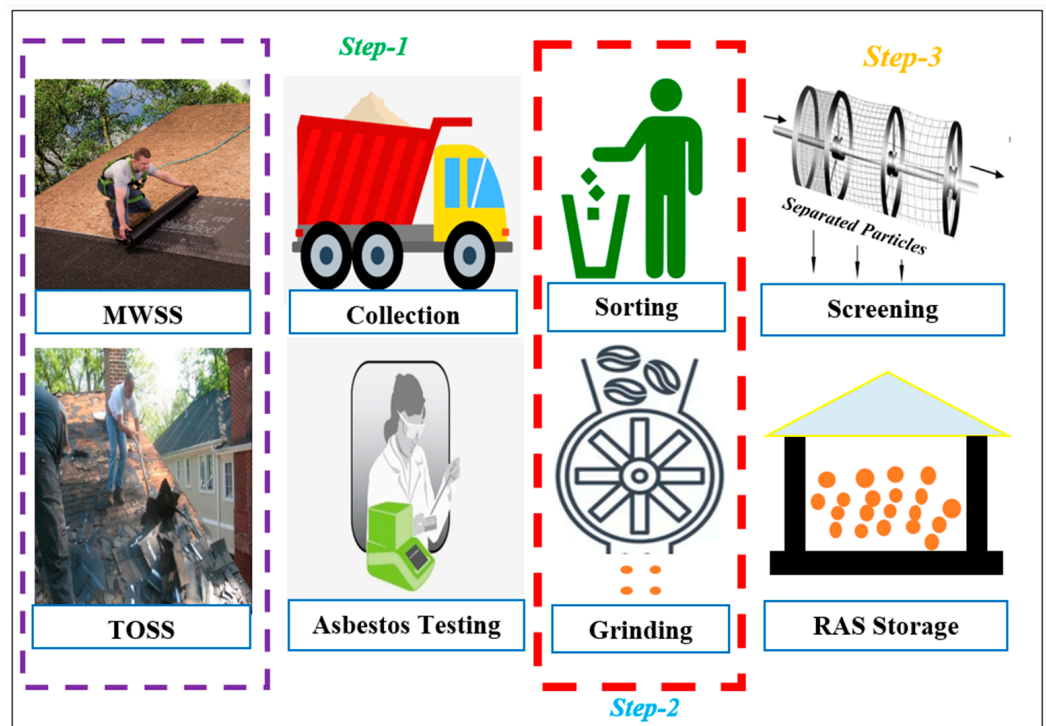


Figure 2. Processing flow chart for asphalt shingles [22].

Figure 2 highlights two key challenges associated with collecting RAS, i.e., quality (cleanliness) and long-term supply. MWSS are relatively clean and they consist of relatively less aged bitumen in comparison to the bitumen in TOSS shingles, but their availability is limited. On the other hand, TOSS contain more stiff/oxidized bitumen since they are subjected to environmental exposure during their service life. Hence, a softer virgin binder may be necessary to adjust the mix design according to the specifications [22,23]. Moreover, the TOSS's cleanliness (or contamination) is a significant issue. Asbestos exposure, for

example, can cause cancers of the larynx and ovary, lung cancer, and mesothelioma. According to recent research, asbestos exposure has also been linked to cancers of the throat, stomach, and colorectum. However, in RAS, the asbestos level of such shingles is almost less than 1%. Thus, the related health issues are generally negligible. Finally, MWSS require very minimal sorting work, while TOSS, on the other hand, need comprehensive sorting due to their higher impurity content [22].

The grinding machine converts the shingle particles into smaller pieces of less than 13 mm. All existing research studies have used RAS in asphalt mixtures with a size of less than 13 mm or as an ultra-fine powder. In the case of RAS with a size greater than 13 mm or beyond the specifications, the operators should ideally screen the processed RAS with a trommel screener to remove large pieces. Storing processed RAS in the ideal conditions is very important to avoid agglomeration. Because of the reduced size of RAS particles, a stockpile can absorb a lot of water, causing issues with HMA mixing (inadequate coating), compaction (mat softness), and performance (increased stripping potential), as well as requiring more energy for drying. Stored RAS should ideally be protected [13].

3.3. RAS Modification Mechanism

The addition of RAS generally affects the chemical properties of the asphalt binder which can be observed through Fourier transform infrared spectroscopy (FTIR) and saturate, aromatic, resin, and asphaltene (SARA) analysis. Test results show that there is a linear relationship between the carbonyl index and RAS content, whose increase gradually leads to higher asphaltene and lower maltene content [24–28]. Atomic force microscopy (AFM) can also be useful to scan the interfacial zones of recycled asphalt shingles and virgin asphalt binders. In this context, Zhao noticed both bees and humps in the AFM images of the interfacial zone, showing poor compatibility between the shingles and virgin bitumen. Zhao also used confocal laser scanning microscopy and found a relatively larger concentration of wax crystals in the shingle binder compared to virgin bitumen. However, wax crystals were not detected in shingle-modified bitumen, possibly due to the absorbance of the wax crystals by the RAS binder. Moreover, in high-pressure gel permeation chromatography, it was noticed that an increase in the RAS content in virgin bitumen led to high-molecular-weight fractions [29].

4. RAS Laboratory Mixing Methods

In essence, there are two mixing methods to add RAS to asphalt mixtures, i.e., the wet and dry mixing methods.

4.1. Wet Mixing Method

A schematic view of the wet laboratory mixing method used to add RAS to asphalt binders is given in Figure 3, where it can be seen that an RAS powder (less than 0.075 mm) or small particles are mixed with a virgin binder with the help of a standard or high-shear mixer to achieve an RAS-modified asphalt binder.

Then, such a binder is blended with aggregates to prepare RAS-modified asphalt mixtures. In this method, relatively high effort (time, temperature, shear stress, etc.) is required to achieve the homogenous mixing of the RAS powder/particles in the binder.

4.2. Dry Mixing Method

A schematic view of the dry laboratory mixing method used to add RAS to asphalt mixtures is given in Figure 4, where it can be seen that shingles are mixed directly with aggregates prior to adding the virgin binder to prepare RAS-modified asphalt mixtures.

During the preparation of asphalt mixtures, the RAS asphalt binder partially/completely mixes with the virgin asphalt binder. The degree of blendability of the RAS asphalt binder with the virgin asphalt binder depends upon different factors, like the mixing methodology, time, use of rejuvenators, types of rejuvenators, and temperature.

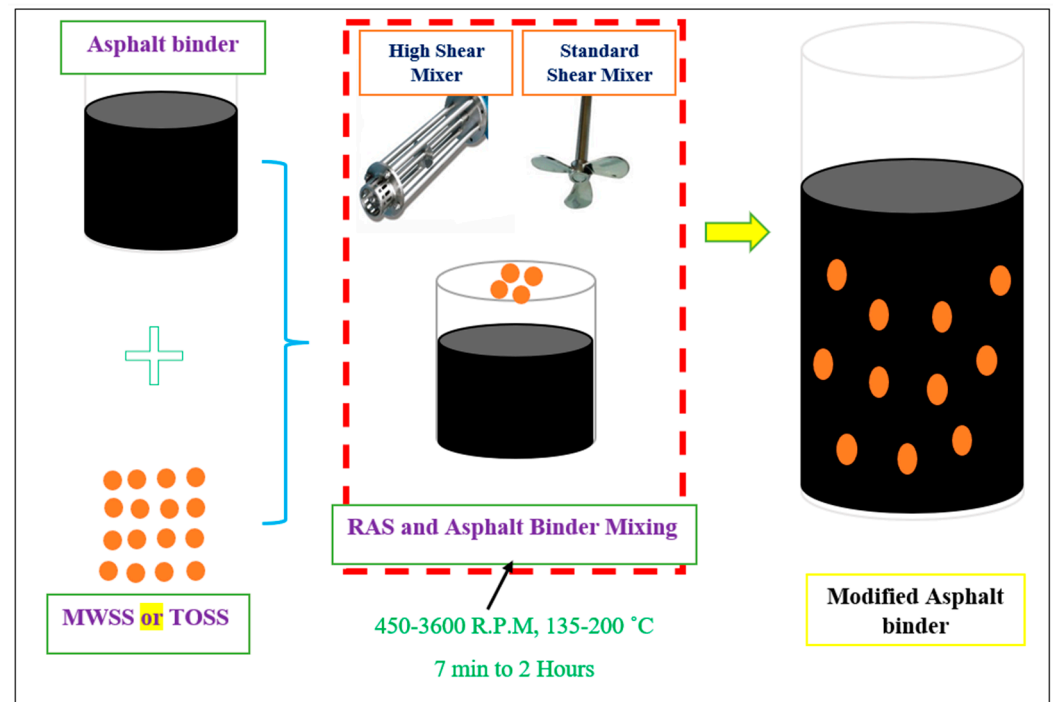


Figure 3. RAS wet mixing method in laboratory [8,18,24,30,31].

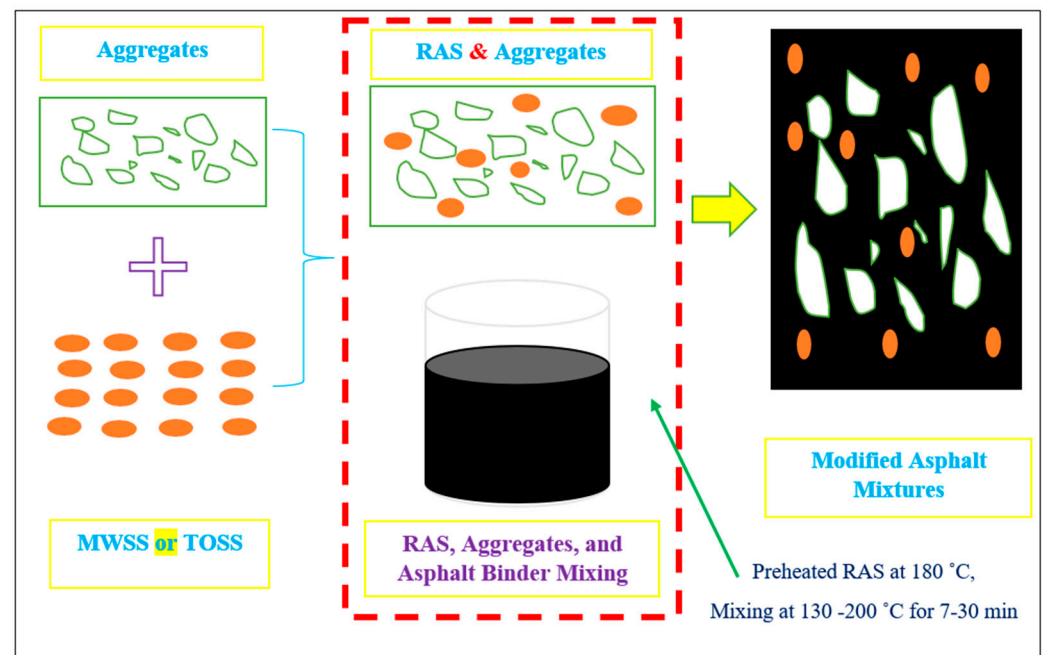


Figure 4. RAS dry mixing in laboratory [18,32].

The dry mixing method is relatively easier and more convenient, especially for real-scale production at the plant, with respect to the wet mixing method, which requires greater effort to prepare homogeneous blends of recycled asphalt shingle-modified bitumen at a large scale. However, in the dry mixing method, there only the partial modification/interaction between the shingles and virgin bitumen is possible, while a stable and homogeneous RAS-modified binder is generally achieved thanks to wet modification (either involving an extracted RAS binder or fine RAS particle addition).

5. Effect of RAS on Performance Properties of Asphalt Binders and Mixtures

Overall, RAS addition to asphalt binders or asphalt mixtures generally increases the stiffness and strength of bituminous materials. As a result, RAS-modified flexible pavements perform relatively better in warmer regions. However, RAS-modified mixtures can be characterized by relatively low fatigue and thermal cracking resistance due to reduced ductility. In this regard, the addition of some recycling agents or specific additives can improve the cracking resistance [24,33,34]. In this section, the effects of RAS (either on asphalt binders or asphalt mixtures) on high-/low-temperature resistance, fatigue, and moisture susceptibility are summarized from existing research studies. The main findings related to RAS-modified asphalt blends are summarized in Tables 1 and 2.

Table 1. Previous research studies on RAS-modified asphalt materials: summary of methods and experimental conditions.

Reference Study	RAS Type and Particle Size	RAS Mixing Details in Asphalt Binder	RAS Dosage (% by Binder/Mix Weight)	Mixing Method Used Dry/Wet	Asphalt Mixture Type
[1]	TOSS ≤ 12.5 mm	N/G	5, 6% by aggregate	N/G	HMA
[8]	TOSS extracted binder	Mixing at 3600 rpm for 30 min	5% by binder	Wet	Binder only
[11]	TOSS < 12.5 mm	N/G	4% only by aggregate (aggregate replacement)	Dry	WMA, HMA
[12]	TOSS binder	N/G	N/G	Wet	Binder only
[13]	TOSS < 9.5 mm	N/G	2.5, 5, 7.5, 10, 12.5% by mixture	Dry	HMA WMA
[14]	TOSS < 13 mm	N/G	1, 2, 3, 4, 5, 6% by aggregate weight	Dry	HMA
[15]	TOSS < 12.5 mm	N/G	N/G	N/G	HMA
[16]	MWSS, TOSS binder	N/G	15, 30, 100% by binder	Wet	Binder only
[17]	TOSS 70% < 1 mm	Mixing at 750 rpm, 30 min, 135 °C to obtain BMAS	5, 15, 30, 40% by binder	Wet	Binder only
[18]	TOSS < 0.075 mm	Mixing 30 min at 180–200 °C	N/G	Both	HMA
[19]	TOSS binder	N/G	5% by binder	Wet	Binder only
[20]	TOSS binder	N/G	20% by binder	Wet	HMA, WMA
[30]	TOSS < 9.5 mm	Mixing at 180 °C, 1 h, 450 rpm	5, 15, 30, and 40% by binder	Wet	Binder only
[31]	MWSS, TOSS < 9 mm	Mixed with binder (1.5–2 h)	0.6–1.5% by mix	Wet	HMA
[24]	MWSS and TOSS extracted binder	Virgin and extracted binder blended for 7 min	5, 10, 15, 30, 45, 60, 80, 100% by binder	Wet	Binder only
[32]	TOSS ≤ 2.36 mm	5 min mixing with aggregate before adding binder	5% by mix	Dry	WMA
[34]	MWSS and TOSS extracted binder	N/G	5, 10, 15, 20% by binder	Wet	Binder only
[35]	MWSS < 12.5 mm	N/G	3, 5, 7, 10% of total mix	Dry	HMA
[36]	RAS < 12.5 mm	N/G	3, 5% by aggregate	Dry	HMA
[37]	MWSS and TOSS Both (19 mm)	N/G	3, 5% by binder	Dry	HMA

Table 1. Cont.

Reference Study	RAS Type and Particle Size	RAS Mixing Details in Asphalt Binder	RAS Dosage (% by Binder/Mix Weight)	Mixing Method Used Dry/Wet	Asphalt Mixture Type
[38]	TOSS and RAP extracted binder	N/G	5% by aggregate	Dry	HMA
[39]	MWSS and TOSS ultrafine powder	Shingle mixing 180 °C, 30 min, 1500 rpm	10, 20, 40% by binder	Wet	Binder only
[40]	TOSS < 12.5 mm	N/G	3% by binder	Dry (plant mix) Wet (lab tests)	HMA
[41]	TOSS < 12.5 mm	N/G	3, 5% by mixture	N/G	HMA
[42]	MWSS < 12.5 mm	N/G	0–10% by mixture	Dry	HMA
[43]	TOSS < 12.5 mm	N/G	5% by mixture	Dry	HMA
[44]	TOSS < 9 mm	N/G	5% RAS	N/G	HMA
[45]	TOSS < 12.5 mm	N/G	2.5, 5, 7.5% RAS by mix	Dry	HMA
[46]	TOSS ≤ 3 mm	N/G	2.5, 7% RAS by mix	Both	HMA
[47]	TOSS < 12.5 mm	N/G	10, 15, 17, 30, 34% by mix	N/G	HMA
[48]	TOSS binder	N/G	5–10% by binder	Wet	WMA
[49]	MWSS, TOSS < 12.5 mm	N/G	5% by mix	N/G	HMA
[50]	MWSS < 1 mm	N/G	5, 10% by aggregate	N/G	HMA
[51]	TOSS < 12.5 mm	N/G	5% by mix	Both	HMA
[52]	MWSS < 12.5 mm	N/G	3, 5% by aggregate	Dry	HMA, WMA
[53]	TOSS < 12.5 mm	N/G	5% by mix	Dry	HMA
[54]	MWSS, TOSS binder	Shingle mixing 180 °C, 30 min, 1500 rpm	2.5, 5, 10% by binder	Wet	Binder only
[55]	TOSS < 12.5 mm	N/G	5% by mix	N/G	HMA
[56]	TOSS ≤ 4.75 mm	Shingle mixing 150 °C, 1500 rpm	2.5, 5% by mix	Wet	HMA
[57]	MWSS, TOSS < 9.5 mm	N/G	4.5 and 6% by mix	Both	HMA
[58]	TOSS < 9.5 mm	N/G	3.5 and 7% by mix	Dry	WMA, HMA
[59]	TOSS < 12.5 mm	N/G	5% by mix	Dry	HMA
[60]	TOSS < 12.5 mm	N/G	N/G	Dry	HMA

BMAS: Bio-modified asphalt shingles, HMA: hot-mix asphalt, N/G: not given, RAP: recycled asphalt pavement aggregate, UV: ultraviolet, WMA: warm-mix asphalt, WEO: waste engine oils.

Table 2. Performance properties of RAS-modified asphalt materials (schematic key findings).

Reference Study	Binder	Mix	Test Methods Used
High-Temperature Performance			
[1,15,31,40,43–45,47,51,52,58] [31,40,42,53,57,59] [14,50] [32] [42] [60]	---		HWTT (AASHTO T-324) Dynamic Modulus (AASHTO T-342) APA (AASHTO TP-63) Dynamic Modulus (AASHTO T-342) French Wheel Track Test (EN 12697-22) Flow Number Test (AASHTO TP 79-13)
[8,12,16–20,24,34,39,40,46,51,54,57]		---	DSR (ASTM D7175-08)
[11,18,55] [41]	---		HWTT (AASHTO T-324) APA (AASHTO TP 63-09), Dynamic Modulus (AASHTO T-342), Resilient Modulus Test (ASTM D 7369-09)

Table 2. Cont.

Reference Study	Binder	Mix	Test Methods Used
Low-Temperature Performance			
[36] [48]	---	↑	TSRST (AASHTO TP10-93) ABCD (AASHTO M-320)
[17]	↑	---	Three-Point Bending Beam Test (CEN/TS 15936)
[50,51] [1] [13] [38] [57]	---	↓	IDT Test (ASTM D 4123) Creep Compliance Test (AASHTO T-322) Acoustic Emission Test SCB (ASTM D-8044) FPBBT (AASHTO T321)
[16,19,20,51,54]	↓	---	BBR (AASHTO M-320)
[18,45] [35,42,55] [31,41,58] [32] [44] [11] [37] [40]	---	↔	SCB (ASTM D-8044) TSRST (AASHTO TP10-93) FPBBT (ASTM D7460-08) ACCD IDT Test (AASHTO T322-07) DC (T) (ASTM D7313) BBR (AASHTO M-320) Creep Compliance Test (AASHTO T-322)
[8,39]	↔	---	BBR (AASHTO M-320)
Fatigue Resistance			
[1] [31] [42] [45] [46] [58]	---	↑	Creep Compliance Test (AASHTO T-322) Direct Tension Cyclic Fatigue Test (AASHTO TP 107-14) TCFT (EN 12697-26) Push Pull Fatigue Test (AASHTO T-400) Shear strength test SCB (ASTM D-8044)
[18,20,57] [40] [41]	---	↔	SCB (ASTM D-8044) IDT Test (ASTM D 4123) FPBBT (AASHTO T321)
[15,43,44,49,55,59,60] [50,51] [32] [46] [47] [56]	---	↓	SCB (ASTM D-8044) IDT Test (ASTM D 4123) Texas Overlay Test Shear Strength Test DC (T) (ASTM D7313) FPBBT (AASHTO T321)
[51]	↓	---	DSR (ASTM D7175-08)
Moisture Resistance			
[32,44,52] [14,42]	---	↑	HWTT (AASHTO T-324) TSR (AASHTO T-283)
[58]	---	↓	TSR (AASHTO T-283)
[11,40,43,47]	---	↔	HWTT (AASHTO T-324)

Performance increases ↑, neither increases nor decreases ↔, performance decreases ↓, empty box ---,
 ACCD (asphalt concrete cracking device test), APA (asphalt pavement analyzer), BBR (bending beam rheometer),
 DC (T) (disk-shaped compact tension test), DSR (dynamic shear rheometer), FPBBT (four-point bending beam
 test), HWTT (Hamburg wheel track test), IDT (indirect tensile test), SCB (semicircular bend test), TCFT (tension
 compression fatigue test), TSRST (thermal stress restrained specimen test), TSR (tensile strength ratio).

In Table 1, the RAS type, particle size, mixing details, RAS dosage, and other additives eventually used in combination with RAS are summarized for each research study analyzed. Meanwhile, in Table 2, conclusions regarding the key findings, as well as the test methods used to assess the performance properties of the RAS-modified asphalt materials in each research article, are presented.

In Table 1, it can be seen that most researchers used tear-off scrap shingles (in large quantities, obtained from construction and demolition waste or at the end of membrane life) with a particle size smaller than 12.5 mm. Some researchers used extracted RAS (either MWSS or TOSS) binders and some used RAS particles of less than 12.5 mm. Both the dry and wet mixing methods were used to add RAS in asphalt blends. In the dry method, up to 12.5% RAS by mix weight was added in different research studies. Meanwhile, in the wet mixing method, up to 80% RAS by binder weight (which approximately corresponds to 4% by mix weight) was added. Reclaimed asphalt pavement and rejuvenators in combination with RAS were also used in some research to study the performance properties of modified asphalt materials. In all research studies, RAS were added in hot-mix asphalt, except for six articles, in which RAS-modified warm-mix asphalts were studied.

As reported in Table 2, to assess the high-temperature performance of RAS-modified asphalt mixtures, the DSR test, Marshall stability test, Hamburg wheel track test, flow number test, dynamic modulus test, resilient modulus test, French wheel track test, and asphalt pavement analysis have been performed. On the other hand, the low-temperature performance is determined with the TSRST, ABCD, acoustic emission test, and BBR, while the fatigue performance is assessed using the push–pull fatigue test, shear strength test, fatigue crack test, overlay test, and DSR. Moreover, the semicircular bend test, four-point bending beam test, disk-shaped compact tension test, tension compression test, creep compliance test, and indirect tensile test are common tests used to evaluate both the fatigue and low-temperature performance of RAS-modified asphalt materials. The tensile strength ratio and HWTT are used to determine the moisture susceptibility of mixtures.

5.1. High-Temperature Performance of RAS-Modified Asphalt Binders and Mixtures

Several researchers have found that RAS-modified asphalt mixtures have relatively higher stiffness, Marshall stability, and high-temperature performance, mainly due to the stiff aged bitumen coming from RAS [24]. Moreover, they require smaller quantities of virgin asphalt binders than conventional asphalt mixtures, making them eco-friendlier and relatively more economical [50].

In asphalt binders, RAS can be added as a fine RAS powder or extracted RAS binder. Elseifi et al. determined that the addition of an RAS fine powder to an asphalt binder increased its stiffness, viscosity, and high-temperature performance. In their study, the upper limit of the performance grade (PG) of the virgin asphalt binder increased from 52 °C to 58 °C due to RAS addition [39]. Zhou et al. studied an extracted RAS binder from both MWSS and TOSS shingles. The addition of the RAS binder increased the complex shear modulus (DSR test results), asphaltene (SARA analysis) content, and carbonyl index (FTIR); the result was a stiffer and less temperature-susceptible modified binder [25]. MWSS-extracted RAS binders have an average high PG of 131 °C, while TOSS-extracted binders have an average high PG of 178 °C. The high PG of extracted RAS binders causes blendability issues, so a maximum of 30% in total of the virgin asphalt binder has generally been recommended [34].

5.2. Low-Temperature Performance of RAS-Modified Asphalt Binders and Mixtures

Elseifi et al. evaluated the low-temperature performance of an RAS fine powder-modified asphalt binder and concluded that the elongation at failure at low temperatures of the modified binder was reduced, i.e., the ductility of the binder decreased [39]. Hassan et al. concluded that 10% RAS addition in asphalt binders could not fulfil the Superpave low-temperature criteria [54]. However, the addition of some rejuvenators/recycling agents and bio-binders can improve the low-temperature performance. Oldham et al. evaluated the

low-temperature performance of an RAS-modified asphalt binder in combination with a bio-binder and concluded that the bio-binder's addition in an RAS-modified binder improved the fracture energy at low temperatures with respect to the virgin asphalt binder [17].

Maher et al. concluded that RAS-modified asphalt mixtures without the incorporation of RAP performed relatively well in low-temperature regions. At 3% RAS addition, the failure temperature (using TSRST) of the mixture was approximately -35°C . Overall, the addition of 5% RAS and 15% RAP with some appropriate recycling agents led to similar mixture performance to virgin asphalt mixtures [41]. Arnold et al. used the acoustic emission technique to evaluate the low-temperature performance of RAS-modified asphalt mixtures. It was concluded that increasing the RAS content decreased the embrittlement temperature (i.e., decreased the low temperature performance). Meanwhile, increasing the mixing temperature of the specimens increased the embrittlement temperature (improving the low-temperature performance) [13]. However, a bio-binder improved the thermal cracking resistance of RAP/RAS-modified asphalt mixtures [14].

5.3. Fatigue Performance of RAS-Modified Asphalt Binders and Mixtures

Fatigue failure is one of the main issues in flexible pavements due to the cumulative damage induced by traffic load repetitions. Wu et al. found that RAS-modified mixtures had almost the same fatigue resistance as neat mixtures. Moreover, in a statistical analysis, it was noticed that an RAS-modified binder had relatively higher failure stress and lower failure strain [40]. Maher et al. concluded that 3% RAS-modified asphalt mixtures had almost better fatigue resistance than a control mix [41]. Baaj et al. used both RAP and an asphalt shingle modifier in asphalt mixtures and noticed a significant improvement in the fatigue resistance of the modified mixtures [42]. Aguirre et al. used the strain energy values (J_c) to assess the fatigue performance and found that the J_c values for the control mixes were larger than those for the RAS-modified mixtures. Moreover, rejuvenated mixtures had lower (J_c) values than RAS-modified mixtures [43]. Ghabchi et al. found that the addition of 5% RAS and 5% RAP in PG 64-22 was the optimum value to increase the fatigue resistance of the modified mixtures [1].

Ozer et al. determined that a 2.5% RAS-modified PG 46-34 binder had relatively better fracture energy and fatigue resistance than the PG 58-28 one [45]. Kanaan et al. used both stress and strain control modes to assess the fatigue resistance of RAS-modified mixtures. The results showed that an increase in RAS content decreased the fatigue resistance in strain control mode and improved the fatigue resistance in stress control mode [46]. Aguirre et al. performed semicircular bending tests and found that rejuvenator addition in RAS-modified mixtures decreased the strain energy even below the minimum threshold value (0.5 kJ/m^2), i.e., modified mixtures had less intermediate temperature crack resistance [43]. Haddadi et al. used RAS/RAP mixtures and found that an increase in the asphalt binder content above the optimized value could increase the fatigue crack resistance of the modified mixtures [60]. Tapsoba et al. suggested the addition of 40% RAP and up to 5% shingles in order to improve the fatigue resistance of conventional asphalt mixtures [36].

5.4. Moisture Damage Resistance of RAS-Modified Asphalt Mixtures

The tensile strength ratio (TSR) is the most common parameter used to evaluate the moisture susceptibility of asphalt mixtures. Nam et al. used 4.77% optimum virgin asphalt binder and noted a 54% TSR value for virgin asphalt mixtures without shingles. The addition of 3% and 6% RAS led to 81 and 87% TSR values, respectively [14]. Wu et al. concluded that the addition of RAS had no effect on the moisture susceptibility of asphalt mixtures [40]. Baaj et al. suggested that the addition of 5% RAS and 15% RAP slightly affected the moisture resistance of modified mixtures, while 10% RAS and 25% RAP gave TSR values lower than the acceptance limit (80%) [42]. Aguirre et al. used the Hamburg wheel track test to evaluate the rut depth as well as moisture damage resistance. They concluded that there was no stripping inflection point in both virgin and RAS-modified

asphalt mixtures. Thus, RAS addition does not increase the moisture susceptibility of asphalt mixtures [43].

Tran et al. discovered that 25% RAP and 5% RAS did not affect the moisture damage resistance of modified asphalt mixtures [44]. Mogawer et al. found that RAS/RAP-modified mixes had relatively higher moisture damage resistance. Moreover, WMA provided similar or better moisture damage resistance [32]. Shivaprasad et al. used two different aggregate sources, but mostly RAS-modified test specimens had more than 80% TSR values, which is a common acceptance criterion [52]. Buss et al. found that there was an inverse relationship between the RAS quantity and moisture damage resistance. However, in the Hamburg wheel track test, there was an improvement in the stripping inflection point and rutting depth with an increase in the RAS quantity. The increase or decrease in RAS mixtures' moisture damage resistance is strictly related to the specifications [58].

6. Field Performance of RAS-Modified Asphalt Mixtures

In 1993, RAS-modified dense-grade asphalt and stone mastic asphalt (SMA) mixtures were prepared using two pen-grade bitumens (85/110, 120/150) and three different RAS types (i.e., end-life roofing membrane shingles, felt-backed MWSS, and fiberglass MWSS). In the laboratory, specimens were prepared for dense-grade as well as stone mastic asphalt [33]. Then, some field experiments were performed to obtain the actual performance of the modified mixtures. According to the volumetric analysis and binder extraction, RAS decreased the quantity of the virgin binder required for the conventional mixtures. Moreover, 5% RAS did not affect the thermal cracking and moisture susceptibility of the corresponding virgin binder reference mixtures. However, the permanent deformation performance of the mixes improved [33].

In 1998, a field study related to the use of RAS in asphalt mixtures was documented by the Georgia Department of Transportation. In 1994 and 1995, Watson performed tests on two sections of flexible pavement built with 5% RAS. Visual inspection showed that the RAS-modified flexible pavements performed relatively better than conventional asphalt mixtures. It was also concluded that adding RAS to an asphalt mixture renders it stiffer in comparison with traditional asphalt mixtures, improving the high-temperature performance while compromising the low-temperature performance of asphalt mixtures. Their study recommends the addition of 5% RAS in order to improve the high-temperature performance in Georgia's warm climates [61].

McGraw performed tests on RAS- and RAP-modified asphalt mixtures. In the RAS, both end-life tear-off scrap shingles (TOSS) and manufactured waste scrap shingles (MWSS) were used. All results were derived from field test sections in Minnesota (data collection started in 2008). Three test pavement sections were continuously monitored; they were modified with 5% MWSS + 15% RAP, 5% TOSS + 15% RAP, and 20% RAP, respectively. PG58-28 as a virgin binder was used in all three mixes. Rutting was not a significant problem, while transverse cracking occurred in all sections, most of which occurred along curbs, gutters, and utilities (manholes, sewers, etc.). Because of this, it was impossible to attribute the damage to the presence of recycled materials only. After the first winter in service, the RAS pavement developed many reflective cracks and was relatively more brittle. The RAS pavement also had more transverse cracking than the control section, although no significant rutting was noticed in any of the pavement sections studied. According to the authors, other factors, such as "long haul times and late-season paving", could have contributed to the poor performance, emphasizing the necessity of maintaining the optimal compaction temperature [62].

Yang et al. conducted a research study on recycled asphalt shingles in Ontario using hot-mix asphalt and concluded that 3% recycled asphalt shingles or a smaller percentage in combination with RAP could meet the design specifications. They also performed a friction test in the field (using the British Pendulum) in the wheel paths of shingle-modified trial-laid mixes and noticed an average British Pendulum number greater than 45 with only a 2.1% standard deviation, indicating very close values to the individual values [63].

Maupin performed a comparative study of RAP-modified bituminous mixtures and shingle-modified bituminous mixtures and found similar behavior in both mixes during placement as well as compaction. In terms of rutting, RAP mixes had borderline results, while shingle-modified mixes had satisfactory results. Moreover, bitumen extracted from both types of mixes (RAP as well as shingle-modified bituminous mixture) taken from an asphalt plant showed an increase in their performance grade from PG 64-22 to PG 70-22. An economic analysis of 5% asphalt shingle-modified bituminous mixtures in reference to neat bituminous mixtures was also performed in the cited study. The researchers concluded that, in 2008, the use of an asphalt overlay of 50,000 tons of bituminous mixture with 5% recycled asphalt shingles could save up to USD 134,500 [64].

7. Overview and Prospective Developments

It is possible to conclude that tear-off scrap shingles (TOSS) are generally added to asphalt mixtures using the dry mixing method (relatively more convenient and economical), even if the wet mixing method, i.e., bitumen modification with RAS (either involving an extracted RAS binder or fine RAS particle addition), is used to determine the suitable blending and rheological properties of the modified binder. Based on a number of literature studies, RAS at up to 5% by weight of aggregate/asphalt mixtures were found to be relatively suitable to improve the performance properties of asphalt mixtures, both in laboratory studies and field applications. When properly dosed and combined with specific additives, RAS could increase the stiffness, stability, and high-temperature performance properties of asphalt mixtures without compromising the fatigue and thermal crack resistance.

On the other hand, there are still many aspects that need further research, such as (i) the influence of the mixing time, mixing temperature, and RAS type and size on the final mix properties; (ii) the possible inclusion of RAS in porous asphalts, warm-mix asphalts, and other “special mixtures”; and (iii) the use of innovative rejuvenators (e.g., bio-additives) to enhance the ductility of RAS-modified asphalts.

In particular, the following conclusions are drawn.

- Comprehensive research studies have not been performed on the RAS mixing time, RAS size (either particles < 12.5 mm or ultrafine powder of RAS), and mixing temperature (HMA, WMA, CMA) to obtain a relatively optimized modified mixture in terms of performance properties.
- Methodologies (such as the use of specific additives) able to optimize the fatigue and thermal crack resistance without compromising the high-temperature performance require detailed study.
- Due to the small number of conflicting experimental findings, there is a need to investigate the RAS-modified asphalt mixtures’ moisture susceptibility, as well as the resistance against freeze–thaw cycles of RAS-modified bituminous mixtures.
- The addition of RAS into porous asphalt mixtures has not been studied yet.
- Very few studies exist about the combination of RAS and warm-mix technologies; thus, RAS-modified WMA requires extensive investigation, taking into account the different available warm technologies.
- There is the need to deeply investigate the rheological and chemophysical properties of RAS-modified asphalt mastics.
- There is still a lack of plant-scale validation of RAS-modified bituminous mixtures to develop policies at a national level towards the use of RAS in sustainable asphalt pavements.
- There is a need to prepare a clear road map (either for the wet or dry mixing method) related to the addition of RAS in asphalt mixtures during real plant production.

Author Contributions: Conceptualization, S.H. and M.P.; methodology, S.H. and E.P.; validation, E.P. and M.P.; investigation, S.H. and E.P.; data curation, S.H. and M.P.; writing—original draft preparation, S.H.; writing—review and editing, E.P. and M.P.; visualization, S.H.; supervision, E.P. and M.P.; project administration, M.P. and E.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used in this manuscript were taken from the cited literature.

Conflicts of Interest: The authors declare no conflicts of interest.

References

- Ghabchi, R.; Barman, M.; Singh, D.; Zaman, M.; Mubarak, M.A. Comparison of laboratory performance of asphalt mixes containing different proportions of RAS and RAP. *Constr. Build. Mater.* **2016**, *124*, 343–351. [\[CrossRef\]](#)
- Pasetto, M.; Baliello, A.; Giacomello, G.; Pasquini, E. Rheological characterization of warm-modified asphalt mastics containing electric arc furnace steel slags. *Adv. Mater. Sci. Eng.* **2016**, *2016*, 9535940. [\[CrossRef\]](#)
- Pasetto, M.; Baliello, A.; Giacomello, G.; Pasquini, E. Sustainable solutions for road pavements: A multi-scale characterization of warm mix asphalts containing steel slags. *J. Clean. Prod.* **2017**, *166*, 835–843. [\[CrossRef\]](#)
- Pasetto, M.; Baliello, A.; Pasquini, E.; Poulikakos, L. Dry Addition of Recycled Waste Polyethylene in Asphalt Mixtures: A Laboratory Study. *Materials* **2022**, *15*, 4739. [\[CrossRef\]](#)
- Zieliński, P. Testing of asphalt mixtures containing an addition of reclaimed asphalt shingles. *Roads Bridges-Drog. I Mosty* **2022**, *21*, 277–292. [\[CrossRef\]](#)
- Putman, B.J.; Amirkhanian, S.N. Utilization of waste fibers in stone matrix asphalt mixtures. *Resour. Conserv. Recycl.* **2004**, *42*, 265–274. [\[CrossRef\]](#)
- Skaf, M.; Pasquini, E.; Revilla-Cuesta, V.; Ortega-López, V. Performance and durability of porous asphalt mixtures manufactured exclusively with electric steel slags. *Materials* **2019**, *12*, 3306. [\[CrossRef\]](#)
- Shirzad, S.; Hassan, M.M.; Aguirre, M.A.; Cooper, S.; Negulescu, I.I. Effects of light-activated self-healing polymers on the rheological behaviors of asphalt binder containing recycled asphalt shingles. *Transp. Res. Rec. J. Transp. Res. Board* **2018**, *2672*, 301–310. [\[CrossRef\]](#)
- Tušar, M.; Kakar, M.R.; Poulikakos, L.D.; Pasquini, E.; Baliello, A.; Pasetto, M.; Porot, L.; Wang, D.; Falchetto, A.C.; Dalmazzo, D.; et al. RILEM TC 279 WMR round robin study on waste polyethylene modified bituminous binders: Advantages and challenges. *Road Mater. Pavement Des.* **2022**, *24*, 311–339. [\[CrossRef\]](#)
- Paulsen, G.R.E.G.; Stroup-Gardiner, M.; Epps, J. Recycling Waste Roofing Material in Asphalt Paving Mixtures. *Transp. Res. Rec.* **1987**, *1115*, 171–182.
- Mokhtari, A.; Bozorgzad, A.; Hasa, E.; Lee, H.; Guymon, C.A. Field implementation of WMA mixtures containing recycled asphalt shingles (RAS). *Constr. Build. Mater.* **2020**, *250*, 118836. [\[CrossRef\]](#)
- Ding, Y.; Huang, B.; Hu, W.; Tang, B.; Yu, M.; Ding, Y.; Huang, B.; Hu, W.; Tang, B.; Yu, M. Utilizing recycled asphalt shingle into pavement by extraction method. *J. Clean. Prod.* **2019**, *236*, 117656. [\[CrossRef\]](#)
- Arnold, J.W.; Behnia, B.; McGovern, M.E.; Hill, B.; Buttlar, W.G.; Reis, H. Quantitative evaluation of low-temperature performance of sustainable asphalt pavements containing recycled asphalt shingles (RAS). *Constr. Build. Mater.* **2014**, *58*, 1–8. [\[CrossRef\]](#)
- Nam, B.; Maherinia, H.; Behzadan, A.H. Mechanical characterization of asphalt tear-off roofing shingles in Hot Mix Asphalt. *Constr. Build. Mater.* **2014**, *50*, 308–316. [\[CrossRef\]](#)
- Mivehchi, M.; Wen, H.; Wen, Y.; Wang, L. Study of Measures to Design Asphalt Mixes Including High Percentages of Recycled Asphalt Pavement and Recycled Asphalt Shingles. *Transp. Res. Rec. J. Transp. Res. Board* **2022**, *2677*, 869–879. [\[CrossRef\]](#)
- Yan, Y.; Hernando, D.; Roque, R. A solvent free method to characterize the effect of recycled asphalt shingles on virgin asphalt binder. *J. Clean. Prod.* **2018**, *208*, 795–805. [\[CrossRef\]](#)
- Oldham, D.J.; Fini, E.H.; Chailleux, E. Application of a bio-binder as a rejuvenator for wet processed asphalt shingles in pavement construction. *Constr. Build. Mater.* **2015**, *86*, 75–84. [\[CrossRef\]](#)
- Alvergue, A.; Elseifi, M.; Mohammad, L.N.; Cooper, S. Laboratory evaluation of asphalt mixtures with reclaimed asphalt shingle prepared using the wet process. *Road Mater. Pavement Des.* **2014**, *15*, 62–77. [\[CrossRef\]](#)
- Arámbula-Mercado, E.; Kaseer, F.; Martin, A.E.; Yin, F.; Cucalon, L.G. Evaluation of recycling agent dosage selection and incorporation methods for asphalt mixtures with high RAP and RAS contents. *Constr. Build. Mater.* **2018**, *158*, 432–442. [\[CrossRef\]](#)
- Cao, W.; Barghabany, P.; Mohammad, L.; Cooper, S.B.; Balamurugan, S. Chemical and rheological evaluation of asphalts incorporating RAP/RAS binders and warm-mix technologies in relation to crack resistance. *Constr. Build. Mater.* **2018**, *198*, 256–268. [\[CrossRef\]](#)
- Sengoz, B.; Topal, A. Use of asphalt roofing shingle waste in HMA. *Constr. Build. Mater.* **2005**, *19*, 337–346. [\[CrossRef\]](#)
- Best Practices for the Use of RA S in HMA: Workshop Student Handbook Product 5-6614-01-P2. 2019. Available online: <https://rosap.nrl.bts.gov/view/dot/44340> (accessed on 5 June 2024).
- John, D. Using Recycled Asphalt Shingles in Asphalt Pavements. Asphalt Magazine. 16 March 2011. Available online: <https://www.asphaltmagazine.com/using-recycled-asphalt-shingles-in-asphalt-pavements/> (accessed on 1 July 2024).
- Zhou, F.; Chen, P.; Huang, S.-C. Characteristics of Virgin and Recycled Asphalt Shingle Binder Blends. *Transp. Res. Rec. J. Transp. Res. Board* **2014**, *2444*, 78–87. [\[CrossRef\]](#)

25. Abbas, A.R.; Mannan, U.A.; Dessouky, S. Effect of recycled asphalt shingles on physical and chemical properties of virgin asphalt binders. *Constr. Build. Mater.* **2013**, *45*, 162–172. [CrossRef]
26. Pipintakos, G.; Sreeram, A.; Mirwald, J.; Bhasin, A. Engineering bitumen for future asphalt pavements: A review of chemistry, structure and rheology. *Mater. Des.* **2024**, *244*, 113157. [CrossRef]
27. Aaron, C. “Pros and Cons of Polymer Modified Shingles: Indy Roof.” Indy Roof & Restoration. 12 September 2022. Available online: <https://indyroofandrestoration.com/polymer-modified-shingles/> (accessed on 20 June 2024).
28. Yang, Q.; Lin, J.; Wang, X.; Wang, D.; Xie, N.; Shi, X. A review of polymer-modified asphalt binder: Modification mechanisms and mechanical properties. *Clean. Mater.* **2024**, *12*, 100255. [CrossRef]
29. Zhao, S. Blending Issues of Hot and Warm Mix Asphalt Containing Recycled Asphalt Pavement and Recycled Asphalt Shingle. Ph.D. Thesis, University of Tennessee, Knoxville, TN, USA, 2014. Available online: https://trace.tennessee.edu/utk_graddiss/3209 (accessed on 15 July 2024).
30. Oldham, D.J.; Rajib, A.I.; Onochie, A.; Fini, E.H. Durability of bio-modified recycled asphalt shingles exposed to oxidation aging and extended sub-zero conditioning. *Constr. Build. Mater.* **2019**, *208*, 543–553. [CrossRef]
31. Barry, K.; Daniel, J.S.; Foxlow, J.; Gray, K. An evaluation of reclaimed asphalt shingles in hot mix asphalt by varying sources and quantity of reclaimed asphalt shingles. *Road Mater. Pavement Des.* **2013**, *15*, 259–271. [CrossRef]
32. Mogawer, W.S.; Austerman, A.J.; Bonaquist, R.; Roussel, M. Performance characteristics of thin-lift overlay mixtures: High reclaimed asphalt pavement content, recycled asphalt shingles, and warm-mix asphalt technology. *Transp. Res. Rec.* **2011**, *2208*, 17–25. [CrossRef]
33. Newcomb, D.; Stroup-Gardiner, M.; Weikle, B.; Drescher, A. *Influence of Roofing Shingles on Asphalt Concrete Mixture Properties*; MN/RC-93/09; Minnesota Department of Transportation: Saint Paul, MN, USA, 1993; pp. 3–9. Available online: <https://conservancy.umn.edu/server/api/core/bitstreams/8d6cf52b-8bcb-4efb-b27f-7f74fabcf0f3/content> (accessed on 10 June 2024).
34. Zhou, F.; Li, H.; Lee, R.; Scullion, T.; Claros, G. Recycled Asphalt shingle binder characterization and blending with Virgin Binders. *Transp. Res. Rec. J. Transp. Res. Board* **2013**, *2370*, 33–43. [CrossRef]
35. Tapsoba, N.; Baaj, H.; Sauzéat, C.; Di Benedetto, H.; Ech, M. 3D Analysis and Modelling of Thermal Stress Restrained Specimen Test (TSRST) on Asphalt Mixes with RAP and Roofing Shingles. *Constr. Build. Mater.* **2016**, *120*, 393–402. [CrossRef]
36. Tapsoba, N.; Sauzéat, C.; Di Benedetto, H.; Baaj, H.; Ech, M. Behaviour of asphalt mixtures containing reclaimed asphalt pavement and asphalt shingle. *Road Mater. Pavement Des.* **2014**, *15*, 330–347. [CrossRef]
37. Moon, K.H.; Falchetto, A.C.; Marasteanu, M.; Tuross, M. Using recycled asphalt materials as an alternative material source in asphalt pavements. *KSCE J. Civ. Eng.* **2013**, *18*, 149–159. [CrossRef]
38. Cooper, S.B.; Negulescu, I.; Balamurugan, S.S.; Mohammad, L.; Daly, W.H. Binder composition and intermediate temperature cracking performance of asphalt mixtures containing RAS. *Road Mater. Pavement Des.* **2015**, *16*, 275–295. [CrossRef]
39. Elseifi, M.A.; Salari, S.; Mohammad, L.N.; Hassan, M.; Daly, W.H.; Dessouky, S. New Approach to Recycling Asphalt Shingles in Hot-Mix Asphalt. *J. Mater. Civ. Eng.* **2012**, *24*, 1403–1411. [CrossRef]
40. Wu, S.; Zhang, K.; Wen, H.; DeVol, J.; Kelsey, K. Performance Evaluation of Hot Mix Asphalt Containing Recycled Asphalt Shingles in Washington State. *J. Mater. Civ. Eng.* **2016**, *28*, 04015088. [CrossRef]
41. Maher, M.L.J.; Uzarowski, L.; Prilesky, H.; Berube, E. Laboratory Evaluation of Performance of Hot Mix Asphalt Mixes Containing Reclaimed Asphalt Roofing Shingles. In Proceedings of the 5th International Conference, Bituminous mixtures and pavements, Thessaloniki, Greece, 1–3 June 2011.
42. Baaj, H.; Ech, M.; Tapsoba, N.; Sauzeat, C.; Di Benedetto, H. Thermomechanical characterization of asphalt mixtures modified with high contents of asphalt shingle modifier (ASM[®]) and reclaimed asphalt pavement (RAP). *Mater. Struct.* **2013**, *46*, 1747–1763. [CrossRef]
43. Aguirre, M.A.; Hassan, M.M.; Shirzad, S.; Mohammad, L.N.; Cooper, S.B. Performance of asphalt rejuvenators in hot-mix asphalt containing recycled asphalt shingles. *Transp. Res. Rec. J. Transp. Res. Board* **2017**, *2633*, 108–116. [CrossRef]
44. Tran, N.; Xie, Z.; Julian, G.; Taylor, A.; Willis, R.; Robbins, M.; Buchanan, S. Effect of a recycling agent on the performance of high-RAP and high-RAS mixtures: Field and Lab Experiments. *J. Mater. Civ. Eng.* **2017**, *29*, 04016178. [CrossRef]
45. Ozer, H.; Al-Qadi, I.L.; Kanaan, A.I.; Lippert, D.L. Performance characterization of asphalt mixtures at high Asphalt Binder replacement with recycled Asphalt Shingles. *Transp. Res. Rec. J. Transp. Res. Board* **2013**, *2371*, 105–112. [CrossRef]
46. Kanaan, A.I.; Ozer, H.; Al-Qadi, I.L. Testing of fine asphalt mixtures to quantify effectiveness of asphalt binder replacement using recycled shingles. *Transp. Res. Rec. J. Transp. Res. Board* **2014**, *2445*, 103–112. [CrossRef]
47. Jahangiri, B.; Majidifard, H.; Meister, J.; Buttlar, W.G. Performance Evaluation of Asphalt Mixtures with Reclaimed Asphalt Pavement and Recycled Asphalt Shingles in Missouri. *Transp. Res. Rec. J. Transp. Res. Board* **2019**, *2673*, 392–403. [CrossRef]
48. You, Z.; Mills-Beale, J.; Fini, E.; Goh, S.W.; Colbert, B. Evaluation of Low-Temperature Binder Properties of Warm-Mix Asphalt, Extracted and Recovered RAP and RAS, and Bioasphalt. *J. Mater. Civ. Eng.* **2011**, *23*, 1569–1574. [CrossRef]
49. Cooper, S.B., Jr.; Negulescu, I.; Balamurugan, S.S.; Mohammad, L.; Daly, W.H.; Baumgardner, G.L. Asphalt mixtures containing RAS and/or RAP: Relationships amongst binder composition analysis and mixture intermediate temperature cracking performance. *Road Mater. Pavement Des.* **2016**, *18*, 209–234. [CrossRef]
50. Foo, K.Y.; Hanson, D.I.; Lynn, T.A. Evaluation of Roofing Shingles in Hot Mix Asphalt. *J. Mater. Civ. Eng.* **1999**, *11*, 15–20. [CrossRef]

51. Zhang, Y.; Swiertz, D.; Bahia, H.U. Use of blended binder tests to estimate performance of mixtures with high reclaimed asphalt pavement/recycled asphalt shingles content. *Transp. Res. Rec. J. Transp. Res. Board* **2021**, 2675, 281–293. [[CrossRef](#)]
52. Shivaprasad, P.V.; Xiao, F.; Amirkhanian, S.N. Performance of warm-mix asphalt mixtures containing recycled coal ash and roofing shingles with moist aggregates for low-volume roads. *Transp. Res. Rec. J. Transp. Res. Board* **2011**, 2205, 48–57. [[CrossRef](#)]
53. Tavassoti-Kheiry, P.; Solaimanian, M.; Qiu, T. Characterization of High RAP/RAS Asphalt Mixtures Using Resonant Column Tests. *J. Mater. Civ. Eng.* **2016**, 28, 04016143. [[CrossRef](#)]
54. Hassan, M.M.; Lodge, A.; Mohammad, L.N.; King, W.B., Jr. Variability and Characteristics of Recycled Asphalt Shingles Sampled from Different Sources. *J. Mater. Civ. Eng.* **2014**, 26, 748–754. [[CrossRef](#)]
55. Cooper, S.B.; Mohammad, L.N.; Elseifi, M.A. Laboratory Performance of Asphalt Mixtures Containing Recycled Asphalt Shingles and Re-Refined Engine Oil Bottoms. *J. Mater. Civ. Eng.* **2017**, 29, 04017106. [[CrossRef](#)]
56. Sharifi, N.P.; McKay, Z.; Blankenship, P.; Mahboub, K.C.; Anderson, R.M. Assessing Binder Blending Level in Asphalt Mixtures Containing Recycled Asphalt Shingles. *J. Mater. Civ. Eng.* **2019**, 31, 04019144. [[CrossRef](#)]
57. Cascione, A.A.; Williams, R.C.; Yu, J. Performance testing of asphalt pavements with recycled asphalt shingles from multiple field trials. *Constr. Build. Mater.* **2015**, 101, 628–642. [[CrossRef](#)]
58. Buss, A.; Cascione, A.; Williams, R.C. Evaluation of warm mix asphalt containing recycled asphalt shingles. *Constr. Build. Mater.* **2014**, 61, 1–9. [[CrossRef](#)]
59. Shirzad, S.; Aguirre, M.A.; Bonilla, L.; Elseifi, M.A.; Cooper, S.; Mohammad, L.N. Mechanistic-empirical pavement performance of asphalt mixtures with recycled asphalt shingles. *Constr. Build. Mater.* **2018**, 160, 687–697. [[CrossRef](#)]
60. Haddadi, S.S.; Coleri, E.; Sreedhar, S. Strategies to improve performance of reclaimed asphalt pavement-recycled asphalt shingle mixtures. *Int. J. Pavement Eng.* **2019**, 22, 201–212. [[CrossRef](#)]
61. Watson, D.E.; Johnson, A.; Sharma, H.R. Georgia's Experience with Recycled Roofing Shingles in Asphaltic Concrete. *Transp. Res. Rec. J. Transp. Res. Board* **1998**, 1638, 129–133. [[CrossRef](#)]
62. McGraw, J. Incorporation of Recycled Asphalt Shingles in Hot-Mixed Asphalt Pavement Mixtures. 2010. Available online: https://mdl.mndot.gov/_flysystem/fedora/2023-01/201008.pdf (accessed on 5 July 2024).
63. Yang, J.; Ddamba, S.; Ul-Islam, R.; Safiuddin, M.; Tighe, S.L. Investigation on use of recycled asphalt shingles in Ontario hot mix asphalt: A Canadian case study. *Can. J. Civ. Eng.* **2014**, 41, 136–143. [[CrossRef](#)]
64. Maupin, G.W. "Use of Manufactured Waste Shingles in a Hot-Mix Asphalt Field Project" Virginia Transportation Research Council (VTRC); Virginia Department of Transportation. 2008. Available online: <https://rosap.nrl.bts.gov/view/dot/19980> (accessed on 20 July 2024).

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.