Heliyon 10 (2024) e27776

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

Valorization of recycled wastes in pavement preventive maintenance: A review on reclaimed asphalt pavement and recycled waste tire

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ARTICLE INFO

Keywords:
Recycled wastes
Asphalt pavement
Pavement preventive maintenance
Reclaimed asphalt pavement
Recycled waste tires

ABSTRACT

Pavement preventive maintenance (PPM) is critical to ensuring traffic efficiency, road user experience, and safety. However, it imposes significant costs in annual road infrastructure budgets because it requires high-quality and natural material resources. This study provides a systematic and comprehensive review on the use of recycled wastes as an alternative for the natural materials used in PPM mixes. Specifically, the use of recycled waste tires (RWT) and reclaimed asphalt pavement (RAP) in chip seals, microsurfacing, slurry seals, and thin asphalt overlays were discussed. The current state-of-practice in terms of material specification and mix design were comprehensively investigated for PPM mixes containing RAP (RAP-PPM) and PPM with RWT (RWT-PPM). Laboratory and field performances of waste-treated PPM mixes were elaborated and compared with conventional PPM treatments to determine the feasibility of the RAP-PPM and RWT-PPM technologies. Furthermore, current research gaps were identified, and prospects for future investigations were discussed. It is envisaged that this study can provide a sufficient theoretical basis for the widespread practical application and beneficial use of this valuable technology, towards promoting sustainability in pavement maintenance practice.

1. Introduction

The use of recycled wastes as a pavement maintenance material can help ease landfill pressures and reduce the demand of extraction/recycling. This is one way of getting the road construction industry on track towards sustainable construction practices. Current research and practice tend to concentrate more on the use of recycled waste materials in different layers of new asphalt concrete pavements. However, highway agencies around the world are dealing more with maintenance and pavement preservation works rather than on new construction of roads. In China, the Ministry of Transport estimated that as of 2021, there were 5.28 million kilometers of roadways, of which 5.25 million kilometers, representing 99.4% of the total length of the roads, required maintenance [1]. Beginning in 2030, the Federal Highway Administration (FHWA) estimates that between 65 and 83 billion USD annually, or roughly 40% of the budget for all transportation-related expenses in 2010, will be spent on repairing and maintaining highways and bridges in the United States [2]. The Canadian province of Quebec also noted the same pattern. Needless to say, road maintenance is becoming more and more crucial for the safe use of public fund, the effectiveness of transportation, the experience of road users, and

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https://doi.org/10.1016/j.heliyon.2024.e27776
Received 17 October 2023; Received in revised form 3 March 2024; Accepted 6 March 2024
Available online 11 March 2024

safety.

Pavement preventive maintenance (PPM) is an essential component of pavement maintenance programs and is aimed at addressing minor surface defects, preventing them from becoming major issues. Among the various PPM treatment types, chip seals (CS), microsurfacing (MS), slurry seals (SS), and thin hot mix asphalt overlays (THMAO) are most commonly used. Each has its benefits and limitations, and the selection of the appropriate treatment for a given pavement preservation project can depend on the pavement condition, traffic volume, and budget constraints. Primarily, the materials used in PPM mixes are natural aggregates, virgin and polymer modified asphalt binders, chemical additives, and mineral fillers, which significantly contributes to the huge funding requirements associated with pavement maintenance schemes. Therefore, researchers have been aiming to adopt the use of recycled materials in pavement maintenance programs as this can help minimize cost, reduce the use of natural resources, eliminate waste materials generated for disposal, reduce energy consumption, and reduce greenhouse gas emissions [3].

Reclaimed asphalt pavement (RAP) obtained after milling and screening of existing asphalt pavements is the most common recycled material used in road construction, especially in the lower courses (base, sub-base, etc.), as these absorb materials in larger quantities than the upper courses. In the current decade, it has been proposed to maximize the usage of RAP in the pavement surface layers by a 100% replacement of the virgin materials used [4]. However, there have been some concerns with the use of high RAP dosages in asphalt concrete pavements (ACP), including negative effects on the mechanical performance (fatigue cracking, low-temperature cracking, and moisture susceptibility) [5–12]. Consequently, RAP is commonly recommended to be used in asphalt mixtures in limited amounts of no more than 40% [13], which leaves the problem of surplus amounts still remaining in the stockpile largely unutilized. The use of RAP in PPM treatments (RAP-PPM) has attracted much attention from researchers and transportation agencies [14–19] as another way of utilizing the surplus RAP in stockpiles and landfills. Thus, a comprehensive understanding of the RAP-PPM technology is needed in order to meet the relevant criteria for mix design, mechanical and functional performance, and durability.

Another recycled material that is widely used in asphalt mixtures is recycled waste tires (RWT), with its first application dating back to the 1960s when the number of scrap tires began to increase and environmental awareness became stronger. According to Thomas et al. [20] almost one billion tires reach their end of service life every year, and over 50% of these end-of-life tires (ELTs) are discarded without any proper treatments. It is estimated that by the year 2030, the total number of ELTs will reach up to 1.2 billion. Up until recently, direct landfilling and burning of scrap tires served as the primary methods of handling them, which resulted in significant soil and air pollution. The increase in the amount of waste tires generated can be directly linked to the enormous numbers of automobiles and tires produced each year. For example, in China alone, 240 million vehicles were produced as of the end of 2018, and the rubber tire sector had produced 816 million pieces overall, with automobile tires accounting for around 648 million of those [21,22]. Based on information published by the China Industry Information Network [23], a total of 14.58 million tons of waste tires were generated in 2018, of which only 5.69 million tons were recovered for use as fuel, representing a recycling rate of less than 40%. In the United States, about 54.1% of the yearly production of waste tires in 2007 were recycled for use as fuel; this figure dropped to 43% in 2017 [24]. In Brazil, waste tires are mostly used to produce gasoline. Although the tire-derived-fuel approach is beneficial for dealing with RWTs, it emits significant amounts of harmful chemicals [25]. In addition, there is still a very limited amount of RWT usage with this method, which has led to the accumulation of waste tires in landfills. Since asphalt pavements are also constructed in large quantities each year, the development of crumb-rubber-modified asphalt binders (CRMA) is the only ideal market with a significant potential for addressing the issue of scrap tire pollution [26]. CRMA provides numerous advantages over virgin asphalt, including a road's resistance to rutting, fatigue cracking, and moisture damage [27–31], all of which are necessary to handle the challenge of growing traffic loads in various climates. Additionally, CRMA has been demonstrated in practice to be a very efficient and affordable substitute for polymer-modified asphalt (PMA). In many nations, a basic transportation network has already been built, and it has been crucial to focus on preventative maintenance of existing roads to increase their lifespan. Numerous novel methods, such as chip or slurry seal, thin hot mix overlays, and micro-surfacing, are being developed quickly to address this difficulty. The use of crumb rubber (CR) in PPM treatments can help with the disposal issue while also enhancing the qualities of the PPM mix. Currently there is on-going research on how to successfully implement the CR-PPM technology and researchers have approached this topic from different aspects including the CR-PPM mix formulation, laboratory and field performance, construction practice, environmental impacts, etc. In addition, it can be argued that the cost of transporting and processing recycled waste materials into desired properties can only be justified by using them in value added applications such as in pavement preventive maintenance (PPM) treatments.

Therefore, the objective of this study is to provide sufficient context on the existing state of knowledge on both RAP-PPM and RWT-PPM technologies in order to establish a general trend in the various research findings, identify potential challenges, and provide some perspectives for future research. Following this introduction, Section 2 presents a brief overview on pavement preventive maintenance treatments. Section 3 and Section 4 discuss the existing state of knowledge on RAP-PPM and RWT-PPM, respectively, summarizing the general trend in the research findings. Section 5 identifies research gaps for both technologies and provides some recommendations for future research. Finally, the summary and conclusions of the study are presented in Section 6.

2. Brief overview on PPM treatments

Pavement preventive maintenance treatments (PPM) are an essential part of pavement preservation programs aimed at correcting minor surface deficiencies and preventing them from becoming major problems. Before any PPM treatment is implemented, two critical factors must be considered. First, not all existing pavements are suitable for PPM treatment. For example, PPM treatments should not be performed on pavements with problems such as rutting, fatigue cracking, moderate to severe transverse cracking, and severe roughness [32]. Second, PPM treatments must be performed in a timely manner to effectively extend pavement life [33] (Fig. 1), which would depend on the condition of the pavement, pavement structure, foreseen traffic, and climate [34].

Some of the above problems can be resolved by minor resurfacing when the pavement quality has decreased by 40% and 75% of the intended service life has been reached (Fig. 1). If the pavement is in poor condition (PCI of 25–49), it can be resurfaced on a large scale, and if the PCI is between 0 and 24, indicating very poor condition, it can be reconstructed. However, the application of PPM treatment is most effective when the pavement is still structurally sound and exhibits little or no distress, often characterized with a PCI between 70 and 84, as shown in Fig. 1.

The most common PPM treatments include chip seal (CS), microsurfacing (MS), slurry seal (SS), and thin hot mix asphalt overlays (THMAO), as described below. Each method has its own scope of application, and the selection of the appropriate method for a particular pavement preservation project may depend on pavement condition, traffic volume, and budget constraints.

2.1. Chip sealing

The PPM most commonly used treatment for asphalt pavements is chip seal. This involves spraying a coating of asphalt emulsion and a layer of aggregate chips over the existing surface. Since CS is expected to last at least five years, a pavement may require three or four applications of CS to reach its intended service life. CS provides a number of benefits, including a surface wearing course, protection of the underlying pavement against water penetration, improvement or restoration of skid resistance, correction of oxidation aging, and treatment of minor surface cracks in the asphalt pavement [35]. Depending on the condition of the pavement, different types of CS, such as single CS, double CS, and racked-in CS, can be constructed, as shown in Fig. 2.

The main distinguishing features between the different types of CS shown in Fig. 2 are the construction sequence, the number of sealed layers, and the changes in aggregate NMAS [35]. The most typical type of CS is the single CS, which involves a single application of uniformly graded aggregate followed by a single application of binder (Fig. 2a). The single CS type is commonly used for normal situations where there are no unusual circumstances that require a particular type of CS. However, for heavily used pavements and conditions that require additional waterproofing or less traffic noise, the double CS type is preferable. The double CS requires two successive applications of the bituminous binder and uniformly graded aggregate, making it more robust than the single CS (Fig. 2b). In general, the NMAS of the aggregate in the second application is about half that of the first application. The racked-in CS (Fig. 2c) are special CS that temporarily protect a single-type CS from damage by using choke stones to create interlocking between the CS aggregates. The choke stones are designed to prevent the aggregates from dislodging before the binder is fully cured, and are therefore more necessary in regions where there is a lot of rotational movements [35].

Although it seems to be common practice to apply CS to pavements with structural defects, it is important to know that CS does not increase the structural capacity of the pavement. Therefore, CS sealcoating is not recommended as a PPM treatment for poorly maintained pavements with severely cracked or weathered surfaces because it is likely to be more expensive in the long run [35]. A variety of factors must be considered when designing a CS system. The best local aggregates with the most compatible binders should be selected, and climate and traffic conditions should also be considered. It should be noted that all materials must meet the project criteria described in AASHTO R102 [36]. The procedures for determining the application rates for each CS type are based on the McLeod technique and the modified Kearby approach once the binder and aggregate are selected [37,38].

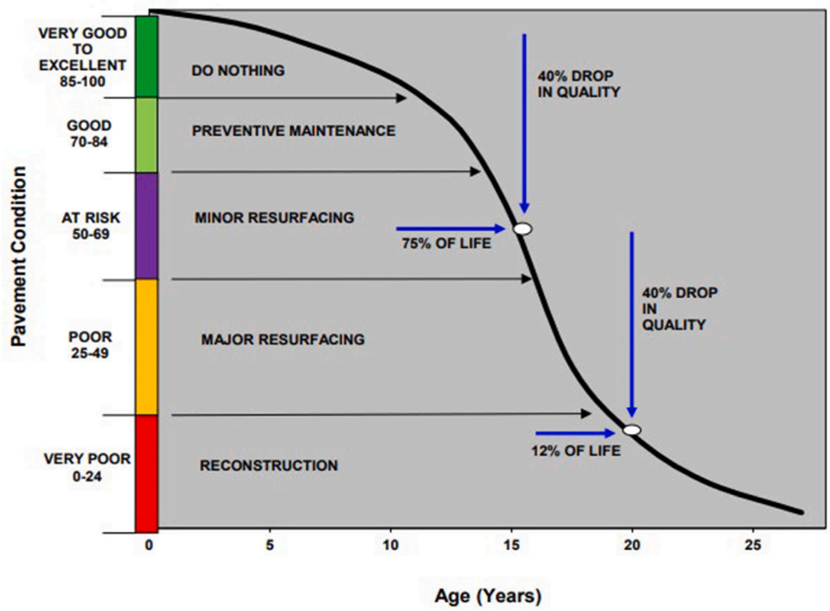


Fig. 1. Pavement deterioration curve.

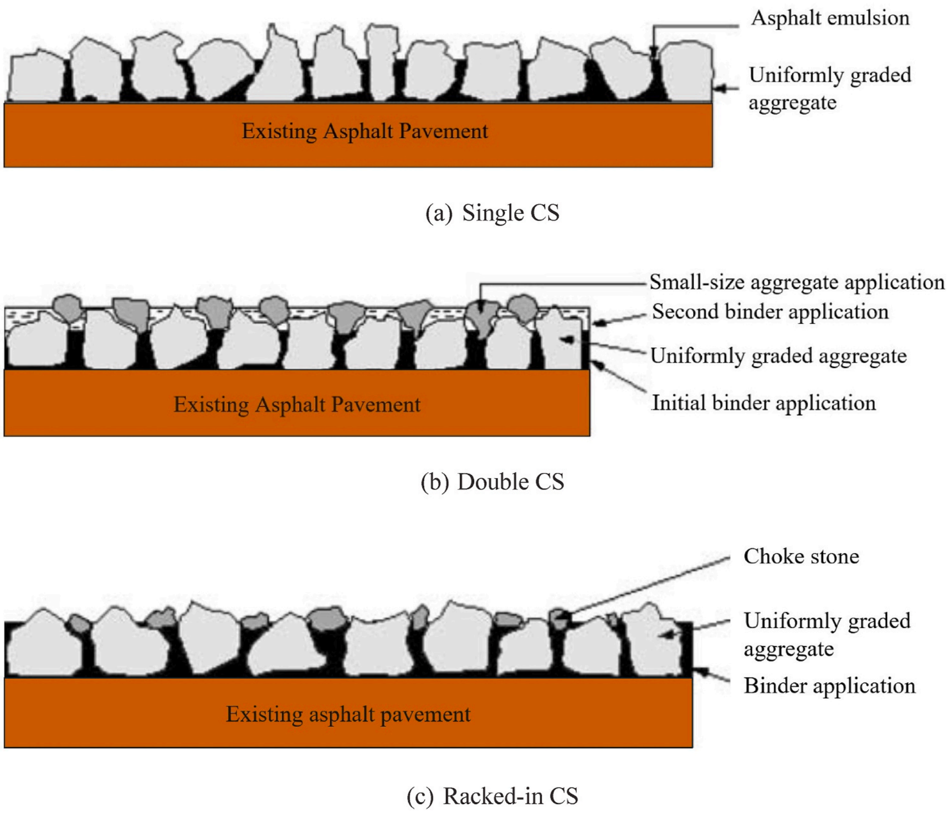


Fig. 2. Schematic structure of common CS types.

2.2. Slurry seals

A slurry seal (SS) is a PPM mixture that has a slurry state (i.e., it is free flowing, has a definite volume but not a solid form, and has a higher density and consistency than a liquid) [39]. Normally, a SS undergoes a curing phase that takes between 30 min and 12 h to reach a solid state. Because of its modified behavior, SS is different from conventional surface treatments such as spray sealers and chip sealers. The advantages of SS treatment include lower cost, environmental friendliness, faster construction time, waterproofing, and sealing of microscopic cracks and surface joints [39,40]. However, the structural integrity of an existing pavement should not be improved by using SS, nor should it be used to alter the surface profile, fill potholes, minimize cracking, or prevent rutting. If a project exhibits any of the above impairments, repairs must be made before slurry seal is applied [41]. Applying a pavement preservation treatment before the PCI of the pavement falls below 80 would be the best line of action.

To ensure that a SS project performs as intended, a mix design must be performed to determine the compatibility of aggregate, emulsified asphalt, water, mineral filler, and other additives. Mix designs should be used to determine how well the above components work together and their relationship to each other. Standard protocols for the development of SS mixes are described in ASTM D3910 [42] and ISSA A105 [43].

2.3. Microsurfacing

Microsurfacing is a bituminous slurry surfacing that can be applied in layers of varying thicknesses for rut fill and corrective overlays, as well as for surface courses that require good surface texture [40,41]. It consists of a polymer-modified emulsion binder, chemical additives and mineral fillers. Special additives are used in the always polymer-modified MS emulsion to provide a "chemical" separation that is less dependent on temperature and environmental variables. Compared to SS, micro surfacing provides a more robust surface, is longer lasting (6–8 years), can be driven on sooner after paving, and can be used in colder areas with higher humidity [40, 44]. It is important to note that microsurfacing, such as SS, should not be used to improve the structural integrity of an existing pavement, fill potholes, or increase traffic capacity [40].

The mix design for MS primarily describes how the raw materials conform to specified tolerances, the required quantities of each component, and reports compliance with the performance test criteria specified in the local specifications. Specifically, the mix parameters for MS are established for aggregate and binder properties, abrasion loss, service life or cohesion of the material, excess binder content, mix consistency, and mix performance in accordance with ISSA A143 [44] and ASTM D6372[45].

2.4. Thin hot mix asphalt overlay (THMAO)

Thin hot mix asphalt overlays (THMAO) are PPM treatments that are preferentially used to improve ride quality, reduce pavement irregularities, maintain surface geometry, reduce noise levels, save life cycle costs, and provide long service life [46,47]. The NMAS of a THMAO is less than 12.5 mm and is placed at a thickness of less than 4 cm using conventional construction techniques, as with any conventional hot mix asphalt [32,48,49]. Fig. 3 shows the three main categories of THMAO mix, including dense-graded (Fig. 3a), gap-graded (Fig. 3b), and open-graded (Fig. 3c).

The NMAS of each of the THMAO types shown in Fig. 3 (a - c) can be either 4.75 mm or 9.5 mm, according to specifications of various jurisdictions in the United States including Florida, Virginia, Georgia, Maryland, and the National Centre for Asphalt Technology (NCAT) [50]. Open-graded friction course (OGFC), stone matrix asphalt (SMA), and ultra-thin bituminous surface (UBBS), which are designed with an NMAS of 12.5 mm or more, are three special asphalt mixtures that are sometimes used as thin overlays. However, THMAO differs from these in its low NMAS. Although THMAO and conventional surface courses emphasize material quality (high quality aggregate, high performance asphalt, and less natural sand), THMAO does not provide as much structural support and should not be used to repair structural deficiencies [48]. As with any preservation strategy, THMAO should be installed before pavement deterioration reaches a critical point where more extensive rehabilitation is required. At the time of installation, it should be dry and temperate outside, with a surface temperature of at least 4.5 °C [48]. A tack coat should be applied after sweeping the surface, and the mix should be poured immediately after "breaking" the tack coat. Rolling should be done as close to the paver as possible, as compaction is critical for smoothness and performance. Depending on the mix and rolling schedule, compaction may be accomplished with fewer rollers, and thinner layers may cool faster, reducing the temperature window for compaction [48].

Table 1 provides a summary comparison of the various PPM treatments discussed in this study in terms of their application, expected pavement life extension, primary material components, and specified mix design standards and guidelines.

3. State-of-the-knowledge on RAP-PPM technology

Incorporating reclaimed asphalt pavement (RAP) into PPM mixes can help agencies prioritize and allocate resources effectively, resulting in cost savings, lower consumption of natural materials, and improved pavement performance. In the material processing phase, RAP is excavated from a stockpile, processed in a fractionation plant and uniformly graded according to the NMAS of the mix [14,52], The processed RAP is separated into two fractions: the coarse fractions, which account for about 40% of the total processed RAP, are used for CS treatment, while the medium to fine fractions, which make up for the remaining 60%, are used for SS, MS, and THMAO treatments, as shown in Fig. 4.

Although there is currently no standardized practice for the design of RAP-PPM mix, the processing of RAP materials should meet local quality requirements of conventional PPM mixes. A RAP stockpile with consistent and correct grading could be an additional aggregate source for adjusting production grading, while the use of locally acceptable ratios of recovered binder can be specified to determine acceptable RAP content. This section reviews the literature on the current state of knowledge of RAP-PPM and highlights the general trend of research findings.

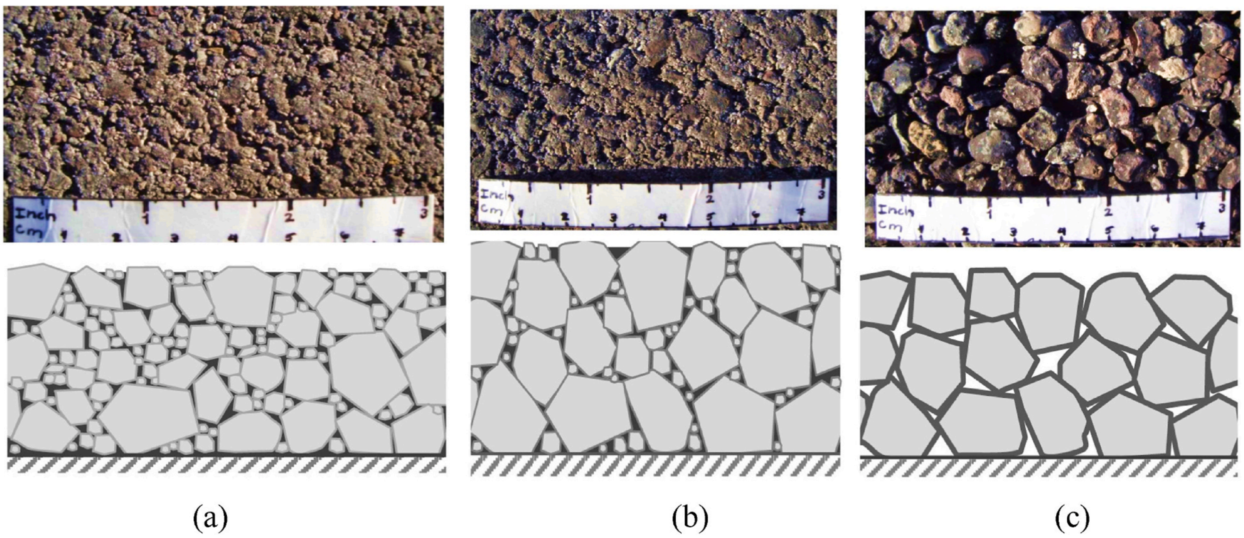


Fig. 3. Surface appearance and cross-section of THMAO: (a) Dense-graded (b) Gap-graded, (c) Open-graded.

Table 1
Comparison of different PPM treatments.

PPM Type	Typical reasons for PPM treatment	Expected performance extension (years)	Primary material type	Mix design requirements	Ref (s)
CS	Water infiltration; low skid resistance; oxidation; ravelling; minor surface cracks	≥5	Aggregate and asphalt emulsion	AASHTO R102	[35,36,38]
SS	Flushing, polished aggregate, ravelling, oxidation and light to moderate cracking, low skid resistance,	5–7	Type I, Type II, or Type III aggregates[a]; unmodified or polymer modified asphalt emulsion, chemical additives, and mineral filler	ISSA A105/ ASTM D3910	[40–43]
MS	Flushing, polished aggregate, ravelling, oxidation and light to moderate cracking, minor ruts	6–8	Polymer-modified quick-set (QS) asphalt emulsions, Type II or Type III aggregates[a], chemical additives, and mineral filler	ISSA A143/ ASTM D6372	[44,45,51]
THMAO	Raveling, longitudinal cracking (wheel-path and non-wheel-path), transverse and fatigue cracking, rutting or shoving	7–16	≤12.5 mm NMAS aggregate; unmodified or polymer modified asphalt binder	AASHTO M323	[32,46]

[a] Aggregate types as outlined by the International Slurry Surfacing Association (ISSA).

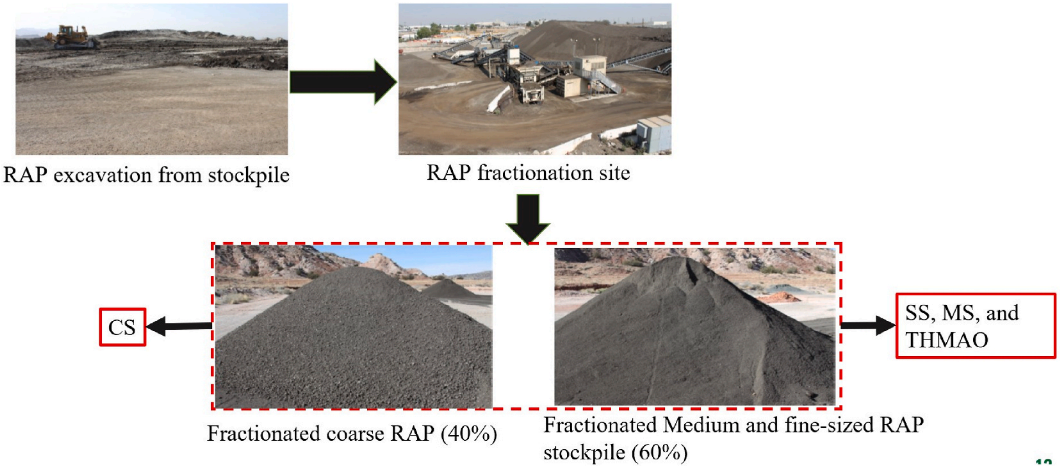


Fig. 4. RAP material processing for use in PPM treatments.

3.1. Chip seals containing RAP

RAP is a very cost-effective material for use in chip seal, although it is relatively new. Tarefder and Ahmad [53] conducted a study in New Mexico to compare the costs of using RAP and virgin aggregates in chip seals. Of the six districts studied, three used RAP-CS, including District 1, District 3, and District 6. It was found that RAP-CS pavements were 23% more economical than the conventional CS in District 1 and 37% more economical in District 6. Transportation agencies that want to take advantage of RAP by extending it to CS often test the materials and mix design against various standards that normally apply to conventional CS. Compatibility testing, particle size gradation, cleanliness and sand equivalents, requirements for the absence of hazardous materials, wear testing, techniques for calculating emulsion and aggregate application rates, and emulsion specifications and grade selection (e.g., polymer modification, tire rubber modification) are some of the tests and material properties criteria [14]. The RAP stockpile must not be contaminated with soil, metal, or fibers [54]. Also, depending on the specific PPM treatment, additional criteria must be satisfied in order for the performance of the source aggregate to match the performance of conventional PPM treatment [14].

Rahaman et al. [55] extracted RAP materials from ultra-thin bonded bituminous surface (UBBS) and evaluated their chip retention properties. Although the results were not very impressive, Rahaman et al. [55] indicated that RAP can still increase chip retention, provided the right type of aggregate and asphalt emulsion are used,. The University Research Centre (URC) in the USA, a pioneering organisation in the use of RAP-PPM, conducted routine in-service monitoring of the performance of RAP-CS and virgin CS. There was no evidence of chip loss on the RAP part, but there was on the untreated CS section. The RAP section also outperformed the virgin CS test section by an equal or greater margin when measuring surface cracking, rutting, and surface texture. However, some agencies, such as San Bernardino County (SBC) in California, and the New Mexico Department of Transportation (NMDOT), found lower pavement friction, which was attributed to either the use of low quality RAP aggregate or a higher RAP content [14]. On New Mexico Highway 124 (NM124), 100% RAP was reportedly used for the chip seal project [53]. Fig. 5 shows the surface characteristics observed at various times after construction.

After one day of construction, numerous loose pieces could be seen on the RAP-CS, as shown in Fig. 5a. After a week of construction, however, there did not appear to be many free or unbonded fragments in the RAP-CS (Fig. 5b). When this pavement was examined one year after its construction, no surface deformation could be detected except for some loose and broken aggregates (Fig. 5c). Although aggregate size and macrotexture are known to increase surface friction in CS, the aggregates can be easily polished due to their mineral composition [14]. A black appearance was also observed on the surface of RAP-CS after one year of construction (Fig. 5d), indicating negligible oxidation.

To further improve performance, several regional programs have incorporated polymer-modified rejuvenated emulsions (PMREs) into RAP-CS [15,54]. In 2013, the Lake Los Angeles region used RAP-CS containing PMRE and assessed the compatibility of RAP and natural aggregates. Despite construction difficulties such as fluctuating or high moisture content, contaminated RAP aggregate on the first day of the project, and inclement weather, the chip seal performed well [15]. Modification of emulsified asphalt (EA) using polymers or polymer excipients is an effective way to improve both the interfacial adhesion between EA and RAP aggregate and the cohesion between EA and the RAP residual aged asphalt [56]. Functional groups in the polymer material or composite chemically interact with organic functional groups on the asphalt surface to form covalent bonds and improve the coating performance of EA on RAP. Depending on the type of polymer or polymer composite used, the modification mechanism can also be a physical process. For example, in the work of Zhou et al. [56], a polymer composite of silane coupling agent (SCA) and polycarboxylate superplasticizer (PCS) was used to modify emulsified asphalt mortar (EAM), and no new functional groups were formed, indicating a physical modification process. Zhou et al. [56] found that the dispersion degree of EAM and its coating degree on RAP were effectively improved after SCA/PCS composite modification.

To sum up, RAP-CS is an environmentally-sustainable and economical PPM technology, but some adjustments to the application rates of chip seal emulsions and RAP treatments are required [14]. Although polymeric materials can be used to modify EA to improve coating performance on RAP, it is important to consider factors such as polymer type and amount and their effects on the long-term performance of RAP-CS to facilitate practical applications.

3.2. Microsurfacing treatment containing RAP

According to various researchers [16,17,54,57–59], RAP, can fully or partially replace virgin aggregates (VA) in MS treatments. The International Slurry Surfacing Association (ISSA) standard TB111 [60] is widely followed in the current practice of designing MS mixtures. As shown in Fig. 6, the lower and upper limits of the potential asphalt content (PAC1 and PAC2, respectively) are initially determined on the basis of the aggregate loss from the 1-h wet road abrasion test (WTAT) and the sand adhesion from the load wheel test (LWT) [60].

The tolerance limits shown in Fig. 6 are usually specified by the contractor, while the mean value of the tolerance range represents

(a) One day old chip seal (b) One week old chip seal (c) Some broken and loose chips are visible (d) Color of the pavement is black

Fig. 5. Surface appearance on NM124 as observed by Tarefdar and Ahmad [53].

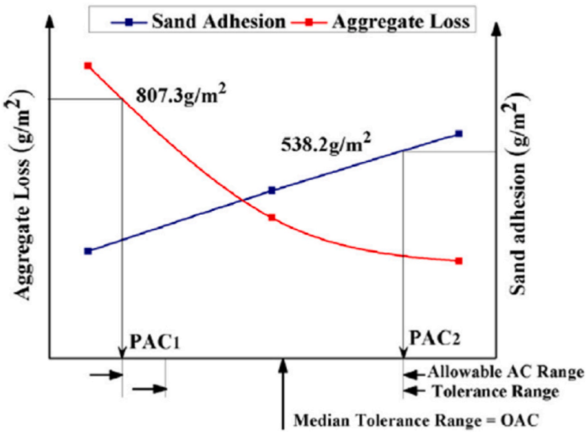


Fig. 6. Determination of OAC from ISSA guidelines(reprinted with permission from Ref. [17]).

the optimum asphalt content (OAC), which can be adjusted according to engineering judgment to accommodate the expected traffic loads [60] Therefore, an experienced engineer is required for this process [41]. According to Fig. 7, Wang et al. [17] recently proposed an amendment to the ISSA micro-surfacing mix design to allow the use of RAP.

The modified mix design was performed using four tasks, as shown in Fig. 7: Three test formulations were created: (i) a base emulsion with a Class III micro-surface and conventional asphalt content (6.0%–7.5%) was created; (ii) PAC1 and PAC2 were selected according to Fig. 6; (iii) PAC3 was determined by an LWT test at the minimum percent vertical displacement (PVD) and percent lateral displacement (PLD); and (iv) OAC was determined. To determine the three test equations, the OAC of the 0% RAP-MS should be reduced accordingly when using RAP.

Improvement of mixing conditions and comprehensive performance of RAP-MS would depend on the use of appropriate content of each component in RAP-MS, including RAP, EA, and additives, as well as on the gradation of the RAP aggregate [16,17,58]. Using the mixing design proposed in Fig. 7, Wang et al. [17] found that as the RAP content increased the OAC decreased, while the mixing time and mix consistency increased. However, there seems to be an optimum RAP amount beyond which these mixing conditions will deteriorate. According to Poursoltani and Hesami [16], an increase in the RAP content above 69% will have a negative effect on the cohesion and deformation resistance of the MS mix. Robati et al. [58] also found that increasing the RAP content reduces the cohesion, deformation resistance, and performance of RAP-MS mix in a humid environment. Wang et al. [17] claimed that 40% RAP is required in MS mix to achieve optimum mixing conditions. It should be noted that there are several factors that can affect the amount of RAP required for MS application, such as the variability of RAP, the use of rejuvenating agents, RAP gradation, and compaction method [17], which explains the inconsistencies in the optimum RAP amount found in the literature. Previous efforts to further improve RAP-MS design practice have also drawn on experience from completed projects. In 2010, a RAP-MS project was completed by a Los Angeles County (LAC) contractor [15]. Although the mixing time and WTAT loss requirements were the same for RAP-MS and conventional MS, the EA content requirements were higher for RAP-MS. Poursoltani and Hesami [16] recommended that for RAP-MS with an optimum RAP content of 69%, the minimum EA content should be 1% higher than for a conventional MS mix. Due to the larger surface area of RAP aggregates compared to natural aggregates, RAP-MS mixtures require a higher percentage of asphalt emulsion, a higher required water content, and a comparatively lower additives amount [41,61]. Based on limited data from freeze-thaw cycle tests, monotonic shear loading, and the British Pendulum Test, Wang et al. [17] found that moisture resistance, shear strength, and skid resistance were improved, respectively when the cement dosage was 1% by weight of the MS mix and the aggregate gradation was equivalent to a Type III microsurfacing [60]. The aggregate gradation usually contains 0–3% of the mineral filler, which is usually cement, hydrated lime, limestone powder, or fly ash, to improve the consistency of the mix and adjust the breaking and curing properties of the mix [44]. Wang et al. [17] noted that in order to control the RAP variability during sample preparation, the RAP materials (0–9.5 mm) can be sieved into two fractions, separated by the 4.75 mm sieve and added to the MS mix. It would be interesting to investigate how different proportions of the 0–4.75 mm and 4.75–9.5 mm fractions may affect the mechanical and long-term performance of the RAP-MS mix.

Although the literature reviewed suggests that high levels of RAP can be incorporated into MS mixes with environmental and engineering benefits, critical material characteristics such as the EA amount, additives type and amount, and RAP gradation should be adequately controlled to achieve optimum performance.

3.3. Slurry seals with RAP

The practice of using RAP in slurry seals (RAP-SS) is relatively new and recent attempts have begun to develop procedures to optimize the RAP-SS mix design and investigate performance effects. One of the first issues is to establish appropriate contents of RAP, emulsified asphalt, additives, and premix water. In the work of Saghafi et al. [18], RAP-SS mix was produced by replacing 87.5% of the total aggregate in the SS mix with RAP material. It was found that the RAP-SS mix required more water and 19% less asphalt binder

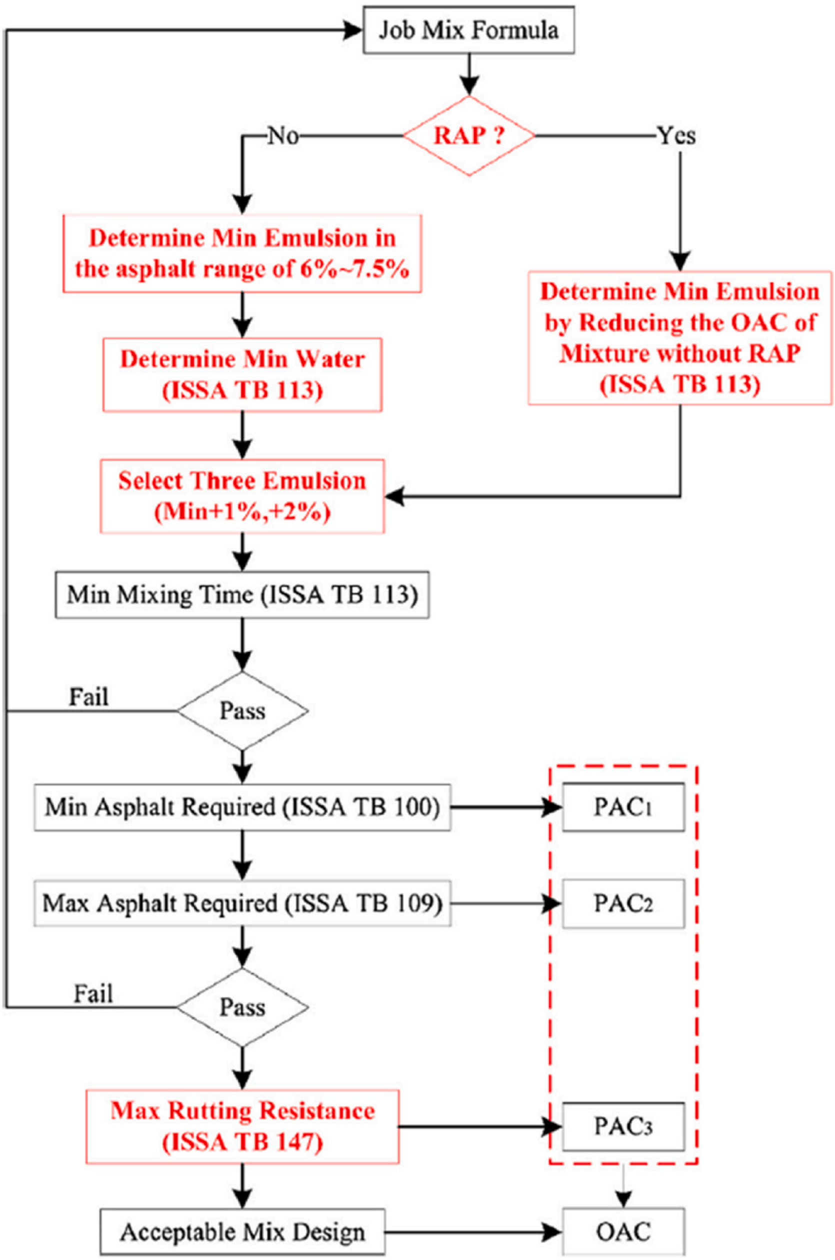


Fig. 7. Modified mix design for RAP microstructures (reprinted with permission from Ref. [17]).

than the virgin SS mix. The lower binder requirement of RAP-SS can be attributed to the contribution from the residual aged asphalt content on the surface of the RAP aggregates [15]. Due to this lower asphalt binder requirement, the total cost of RAP-SS was found to be 14% lower than conventional SS, demonstrating its economic advantage. Other critical issues in the production of RAP-SS mixtures are the compaction and curing processes. The compaction quality of slow or fast setting EA for SS should be adequately controlled, and fillers such as cement and hydrated lime (0–3% by weight of dry aggregate) are used to thicken the mix and modify the setting and curing times. Saghafi et al. [18] compared the effects of cement or hydrated lime on the setting time of conventional SS and RAP-SS. Although the additives shortened the setting time of conventional SS by about 30 min, there was no notable difference in RAP-SS. However, it should be noted that the findings of Saghafi et al. [18] are based on a laboratory study for a single type of EA (slow--setting cationic emulsion) and do not take into account the effects of RAP variability. Moreover, there is a consensus that the setting and curing conditions are closely related to the behaviour of the mixture, since the properties of the material depend on phenomena such as the cement setting reaction, the evaporation of the water, and the rejuvenation due to additives incorporated in the emulsion [62,63].

Table 2
Summary results on RAP-PPM mixture performance properties.

PPM type	RAP Amount (%)	Rejuvenator	Rutting Resistance	Low-Temperature Cracking	Fatigue Resistance	Moisture Susceptibility	Workability	Skid Resistance	Cohesion	Ref
THMAO	40	None	+			+	−			[49,75]
CS	20	None	+	O						[55]
MS	50 & 100	None	+			O			−	[58]
MS	50 & 100	None	+			+				[57]
MS	69	None	+			+			−	[16]
SS	87.5	None	+			+			−	[18]
MS	20–40	Chemical				+		+	−	[17]
THMAO	40	Biological	+	+	+					[19]

+ positive effect; − negative effect; O insignificant effects.

The prepared RAP-SS mixture is expected to have similar or better performance than the conventional SS mixture if it is to be widely used in PPM programs. Recently, Ye [64] compared the mechanical performance RAP-SS containing 100% RAP with those of conventional SS mix in terms of wear resistance, crack resistance, and rutting. Based on the results of the Hamburg Wheel Track (HWT) test, SS containing 100% RAP mostly outperforms the conventional SS mix. Other researchers [18] had shown that RAP-SS is more resistant to abrasion and deformation than conventional SS. Among the various parameters affecting the performance characteristics of RAP-SS, the internal cohesion of the EA binder and RAP's aged asphalt and the adhesion developed at the EA-RAP interface are one of the critical aspects. Wu et al. [65] investigated the molecular dynamics at the RAP-EA interface and found that the bond strength depends on the combined effect of the minerology of the RAP aggregates, curing temperature, moisture, and emulsifiers. It was found that the use of a cationic emulsified asphalt with siliceous RAP favors a stronger RAP-EA interface bond. In principle, cationic emulsifiers are preferred for acidic aggregates and anionic emulsifiers for basic aggregates [63]. The problem of adhesion between binder and aggregate becomes more serious when considering that the presence of moisture can accelerate both adhesive and cohesive failures by reducing the compatibility between EA and RAP or causing emulsification of the bituminous phase [66,67]. In practice, moisture penetrates into the asphalt mixture, especially into the interface between asphalt and aggregate, which leads to a reduction in the asphalt-aggregate bond strength and the occurrence of distresses such as asphalt film stripping [68]. To reduce the effects of moisture damage and improve the early bond strength, cement is usually added to the EA binder as a a filler [69–71]. Lyu et al. [69] observed from microscopic images that cement can consume the water from the emulsified asphalt and accelerate the demulsification process, thereby increasing the interfacial strength of EA-RAP and improving the moisture resistance. Appropriate cement content (1–3%) could effectively stimulate the process of cement hydration and the demulsification process, and appropriately promote the formation of denser spatial network structure of cement-emulsified asphalt binder to achieve the function of bonding with RAP and pore filling [70]. Increasing other hydration characteristics of cement, including the number of nucleation sites, calcium-to-silicon ratio (Ca/Si), degree of hydration, and types of hydration products, also improves the adhesion and water resistance of the RAP-EA interface [71,72]. However, this depends on the interfacial water content, as too high water content can reduce the RAP-EA interfacial adhesion and make the influence of cement hydration products negligible [71]. In general, a proper understanding of the molecular-level interaction between EA and RAP can provide insight into the mechanism of strength enhancement of RAP-SS and ultimately help determine the best modification strategies [73].

The limited literature currently available seems to indicate the feasibility of using RAP in SS mixes, exhibits improved mechanical performance and cost efficiency. On the other hand, RAP-SS is a technique that conserves natural materials as it minimizes the use of natural aggregates and hydrocarbon binders of petroleum origin and prevents the generation of waste and the occupation of landfills. However, it is important to emphasize that more detailed studies are needed on various aspects such as durability and the effects of material variability, and that the experience gained from completed projects must be used to refine the requirements for RAP-SS and advance its application.

3.4. Thin hot mix asphalt overlays containing RAP

Due to the great benefits of THMAO in restoring surface quality and functional performance, it is currently considered as a primary PPM technology in pavement maintenance programs [32,46,74]. It has been recommended to use large amounts of RAP in THMAO mixtures to offset the cost of natural materials and the use of polymers in asphalt binders [32,49]. RAP should be processed for size and consistency if it is to be added to the THMAO mix [46]. The RAP should be crushed and screened to ensure that the NMAS of the mixture is not exceeded by the maximum RAP size. It is important to measure and verify the RAP gradation and asphalt composition to ensure consistency. The amount of RAP that can be used in the mixture depends on how variable the RAP material is for these measurements. According to Brown and Heitzman [49], high contents of RAP in THMAO mixtures can be very useful because they contain a considerable amount of material that passes through the No. 200 sieve (0.75 mm). Since 4.75 mm NMAS requires a higher proportion of fine particles than coarse aggregate [49], it is advantageous for the mix design of THMAO with 4.75 mm NMAS to use only a small proportion of coarse aggregate. Therefore, it is recommended for THMAO-RAP to consist mainly of 4.75-mm NMAS and smaller particles [46]. In general, the use of fine-grained mixtures can improve THMAO in many ways, e.g. by making it extremely dense and impermeable, while being very flexible and crack resistant [49]. However, the polishing resistance of the RAP aggregates is not decisive, as the coarse aggregates in the combination control friction to a greater extent [46]. A high proportion of fine-grained RAP (40 percent) and rejuvenating agent (>8 percent dosage, depending on the type of rejuvenator) can increase the resistance of THMAO mixes to low-temperature fracture, fatigue cracking, and rutting damage, as shown in a recent laboratory study by Podolsky et al. [19]. It has also been observed that the incorporation of RAP in significant amounts can improve the stiffness and resistance to reflective cracking of THMAO mixtures [74]. Although the increase in THMAO stiffness had a positive effect on moisture and rutting resistance, the workability of the mix was negatively affected. To address the associated workability concerns, it is recommended to add WMA additives instead of reducing the significant amount of RAP in the THMAO mix [49,75].

The above literature has demonstrated the feasibility of using RAP in PPM treatments by slightly adjusting the appropriate mixture designs. In addition, most of the studies compared the performance of the prepared RAP-PPM mixture to that of conventional PPM, and Table 2 gives a summary of some of the main findings.

4. Use of recycled waste tires in PPM treatments

As the amount of scrap tires produced continues to exceed the amount returned to the construction cycle, finding alternative uses for them in pavement maintenance offers tangible environmental and economic benefits. Moreover, the use of RWTs in this way is very important to keep the road construction industry as globally sustainable as possible. Some recent studies [76–79] have addressed the feasibility of using RWT in PPM mixtures, especially as rubberized chip seals, crumb rubber microsurfacing, and crumb rubber slurry seal treatments. This topic is of crucial importance for the current and future development of pavement preventive maintenance.

4.1. Rubberized chip seal technology

In recent years, the newly introduced rubberized chip seal has attracted great interest from researchers due to its environmental friendliness and cost-effectiveness [80,81]. There are two ways to incorporate CR into CS treatments: either by a wet process, in which the base asphalt or emulsified binder is modified with CR to produce asphalt rubber chip seals (ARCS), or by a dry process, in which part of the mineral aggregate is replaced with CR to produce rubber aggregate chip seal (RACS). This section discusses the available literature on both processes.

4.1.1. Asphalt rubber chip seal (ARCS)

The use of asphalt rubber (AR) as a binder in chip seals is considered a suitable approach to address common CS problems, including bleeding in the wheel paths, raveling in non-wheel path areas, and low skid resistance, especially in areas with high temperatures and high traffic volumes. ARCS technology is not new in many countries such as the United States [82,83], South Africa [84–86], Australia [87], and China [88–90]. A comparison of the different countries' experiences with ARCS is summarized below.

(1) South Africa

South Africa has more than 30 years of experience with ARCS technology and has used it in the form of single CS, double CS, and stress-absorbing membrane interlayers (SAMI), which typically consist of a single CS with 13.2 mm or 9.5 mm NMAS aggregate covered by an asphalt layer to form a bituminous composite system [85,86,91,92]. The AR binder (also referred to as bitumen rubber) materials for CS are the same as for asphalt mixtures and primarily include about 78% base asphalt of penetration grade 80/10, 20% crumb rubber, and 2% extender oil [84,85,91]. Case studies of ARCS projects on heavily deteriorated road sections in South Africa showed that the double CS of 19 mm and 9.5 mm (19/9.5) bitumen rubber (BR) was more effective than the single BRCS in terms of life cycle costs and service life extension [85,86]. Adjustment made in the CS design guide [93] recommend a higher binder application rate (approximately 5 l/m^2) for ARCS and was used in the case study projects. Although the binder application rate was high in these projects, the texture depth met the local minimum requirements and the thick binder films provided a waterproof pavement. A major challenge with higher binder application rates is the increased risk of bleeding. Researchers [85,86] claimed that for the 19/9.5 mm double seals, the shape of the aggregate, the relative size difference between the two sizes, and the spread of the larger aggregate were mainly responsible for the better performance of ARCS in terms of aggregate loss or bleeding. This superior performance of ARCS has also been attributed to the natural rubber incorporated into the bitumen, as well as the antioxidants (carbon black, etc.) derived from the tires [84]. Typical crumb rubber contains about 40% carbon black, a natural antioxidant that has been shown to prevent ageing of the BR binder on the road [91]. According to Hoffman and Potgieter [84], the digestion of rubber in bitumen significantly improves several properties, including extension of the temperature range, longer service life, better adhesion, lower temperature sensitivity, stress-absorbing properties, lower embedment, lower absorption, and better elasticity and fatigue cracking resistance.

(2) United States of America

ARCS has been used for more than 40 years by various state agencies in the United States (US), including California [82], Texas [94,95], Arizona [96], Oregon [97], Kansas [98], Nevada, and others, because ARCS has the advantage of being resistant to reflective cracking compared to conventional CS. However, there have been some issues with the use of ARCS in extreme weather conditions and high traffic volumes, as it has been shown to cause problems such as bleeding, flushing, and rutting [82,95,99]. For example, in 2003, within six months of construction of an ARCS warranty project on State Route 86 in Imperial County, California, flushing, bleeding, and rutting occurred in the truck lane [99]. Field and laboratory investigations conducted on this project in 2005 could not clearly identify the causes of ARCS failure [99]. In order to better specify the application of ARCS to improve performance under extreme conditions, Caltrans built a total of twelve CS test road sections in two phases. The first phase was conducted in 2005 and included six ARCS sections with different asphalt types, aggregates, and application rates, while the second phase was conducted in 2007 and included six conventional CS sections with different PMB types. Rizzutto et al. [100] summarized the results of this project and reported that after three to five years, the six ARCS test sections performed better than the Phase II test sections in terms of aggregate retention, flushing, crack reduction, and aesthetics. It was recommended that instead of the typical uniform binder application rate, a variable application rate be specified for ARCS that should include a low binder application rate in the wheel track and a high binder application rate in the non-wheel track to reduce the problems of flushing/bleeding and aggregate loss, respectively [101]. In addition, a coarser, single-sized aggregate chips (12.5 mm) and a stiffer asphalt binder were recommended to achieve the best ARCS performance in hot climates and heavy traffic.

Since 1995, many other ARCS projects have also been undertaken in California using varying amounts of rubber binder (10–20%), with performance generally rated as good after more than 10 years of construction [98]. In Kansas, Nevada, and Oregon, the many ARCS projects were also found to perform well for the most part, although there were some problems, such as aggregate loss, flying chips, and varying degrees of bleeding [98].

(3) Australia

In Australia, ARCS technology is primarily used in the form of strain-absorbing membranes (SAM) and stress-absorbing membrane interlayers (SAMI) on cracked/stressed pavements to alleviate stresses in the pavement and reduce the potential for reflective cracking in the surface. A SAM is subjected to general traffic loading, whereas a SAMI is installed as an intermediate layer between an asphalt layer and the underlying layer, where traffic is generally limited or temporary. Detailed local guidelines for the use of ARCS have been in place since the 1990s [102] and are generally contained in the polymer modified binder (PMB) specifications of the state road authorities in Australia (Austroads [103], TMR, RMS, DPTI, and VicRoads [104]). In comparison, VicRoads and DPTI are probably the two Australian jurisdictions that mostly use ARCS in their PPM treatment programs. The VicRoads standards document " Section 408 Sparyed bituminous surfacings" [104] is performance-based and requires that certain performance characteristics (e.g. depth of surface texture) be maintained during the defect liability period. It contains guidelines for the selection of binders that provide equivalent performance. The VicRoads document provides a list of binder types that are acceptable for the treatment specified by the authority. This differs slightly from Austroads guidelines [103], which suggest binder types based on operating conditions (e.g. site severity and traffic loading). The contractor usually has the option of choosing an AR binder produced on-site, an AR binder from the terminal or a non-AR PMB. In addition, on VicRoads projects, all waterproofing measures are usually planned by the contractor. This differs from TMR practice, where the contractor often designs the waterproofing measures. VicRoads also tend to have longer defect liability periods, so the contractor takes more responsibility for the waterproofing measures.

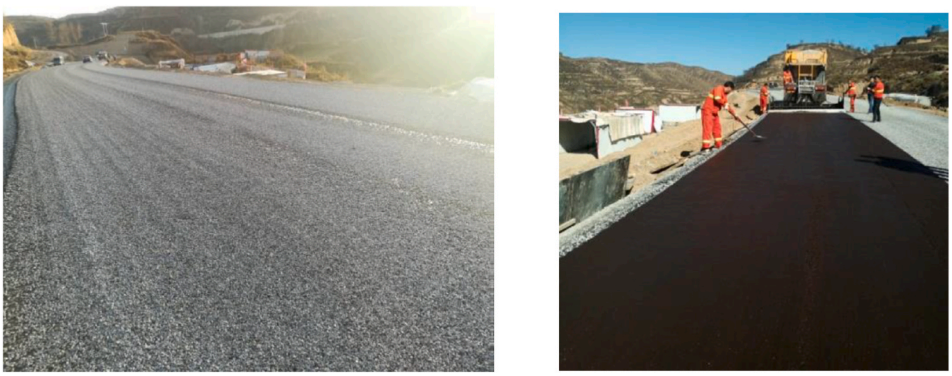
Research and field assessments are currently been undertaken to refine the design, construction, and performance monitoring procedures for ARCS in the Australian context. These efforts are aimed at optimizing the use of this technology and ensuring its successful implementation on different road networks.

(4) China

For more than a decade, China has been increasingly using RWT in chip seals to address the recurring problems of pavement maintenance, especially in parts of the country where the climate is extremely cold in winter and very hot in summer. In 2011, a cape seal with a combination of ARCS and microsurfacing was built on a city street in Xi'an, China. A test section was also built in East Gansu with a three-layer surface course consisting of two underlying ARCS layers and an overlying micro surfacing layer to meet the high traffic demands [90]. Fig. 8 shows the construction of the multi-layer cape-seal. During the spraying of the asphalt rubber, the temperature was strictly controlled to 190 °C–200 °C. The application rate of the asphalt rubber was 1.5–1.6 kg/m2, and the driving speed of the asphalt spreader was controlled at 5–10 km/h to ensure uniform spraying. After spraying the asphalt, the chippings were spread (Fig. 8a), the ARCS layer compacted, and the microsurfacing mix laid. As a rule, the microsurfacing layer must be laid at least 2 days after completion of the lower chippings seal for cape sealings to ensure that most of the chippings are firmly bonded to the asphalt rubber membrane, as shown in Fig. 8b.

After completion of the ARCS and microsurfacing, the various layers were inspected for appearance, quality, surface smoothness, etc. The inspection revealed that the test track was generally well constructed. However, due to the relatively cold climate at the time of construction of the test track and other factors, such as lack of machinery, technical personnel, etc., major problems were encountered in the application of ARCS, such as uneven distribution of aggregate chips, especially in horizontally curved sections.

In subsequent years, other large-scale applications of ARCS technology have been carried out in different parts of the country, including Sichuan Province in 2012, Highway 308 in Gansu Province in 2013, and the national and provincial highway maintenance project in Yingshan, Hubei in 2014 [105]. In most of these projects, ARCS was used as SAMI, with strict requirements on material quality and construction quality control. In general, rubberized asphalt with 30 or 40 mesh CR at a dosage of 18%–20% is considered acceptable for ARCS mixes in China [105–107]. Mineral aggregate with single particle size (9.5–13.2 mm or 4.75–9.5 mm) is specified



(a) ARCS layer (b) Microsurfacing layer

Fig. 8. Construction of cape seal test section in East Gansu, China [90].

for single CS applications [105,107]. In the ARCS production stage, the temperature is usually controlled in the range of 180^{O}C–190^{O}C to allow for the swelling and reaction phases to be completed [105–108]. The swelling phase takes about 25–30 min and requires temperature control between 180 °C and 185 °C, while a temperature of 185 °C–190 °C is prescribed for the reaction phase, which also takes another 25–30 min [105,106]. During construction, the uniformly graded aggregate chips are first applied at a spread rate of 10.0–12 kg/m^2 [107], followed by a uniform spreading of the AR binder at a controlled rate of 1.0–2.0 kg/m^2 [109]. After synchronous distribution of the binder and the aggregate chips, rolling is carried out immediately at a rolling speed of between 5 km/h and 8 km/h [105]. Zhang et al. [110] found that the friction coefficient in the early stage of rolling is mainly determined by the structural depth of the ARCS layer and the angularity of the crushed stone, while the structural depth is mainly affected by the particle size of crushed stone and the thickness of the AR binder layer. Wei [105] recommended that the AR binder should rise to a height of about 60%–70% of the total structural depth (H) to ensure that the single-sized aggregate chips are firmly embedded in the asphalt, as shown in Fig. 9.

Quality control of the rolling operation is of crucial importance as it prevents the structure from having an asphalt film that is too thick, which can lead to oil spillage, or an asphalt film that is too thin, which can affect the durability and performance of the ARCS structural layer.

Table 3 provides a summary comparison of ARCS specifications based on experience in different countries.

As can be seen from Table 3, the ARCS requirements of the different countries differ in terms of the type of base asphalt binder, the CR content, the application rate of the ARCS binder, the aggregate particle sizes, and the additives used. Current practice in the different countries is that ARCS technology is applied by hot paving, where the ARCS material is applied at elevated temperatures (usually between 160 and 220^{O}C). Although this approach has been very successful in improving the performance of chip seals, occupational health and safety concerns are a major setback to its widespread use. In 2015, a PPM treatment trial was conducted in Australia, monitoring and comparing the air quality emissions of ARCS and conventional PMB chip seals. It was found that ARCS had higher levels of suspended particulate matter and volatile organic compounds (VOCs) in the first 3 h after construction than the PMB chip seals [87]. The higher emission levels of ARCS are mainly due to the higher processing temperatures resulting from the higher viscosity of the AR binder. In this decade, many researchers have proposed an appropriate technical measure to mitigate these problems, which includes the use of emulsified CRMA binder (E-CRMA). Two main methods are generally used for the preparation of E-CRMA binders. The first technique involves forming emulsions with CR degradation products that are "incorporated" into hot asphalt to produce "liquefied" rubber-modified asphalt binders with a very low solids content (down to 2% or less). This approach can allow up to 25% CR or more in the CRMA binders, but requires the use of sophisticated and expensive equipment, as the interaction between asphalt and CR particles must take place under special circumstances at very high temperatures of up to 260 °C [113]. In the second method, some additives are added during the CR/asphalt mixing process. These additives include dodecylbenzene, p-toluene sulfonic acids, hydrocarbon oil, and polyphosphoric acids. It is known that both the chemical degradation of the rubber into the asphalt and the incorporation of aromatic components into the CR polymer chains are accelerated by hydrocarbon oil [114,115]. The interaction between the devulcanized CR and the double bonds of the asphalt is accelerated by dodecyl-benzene sulfonic acid (DDBSA) [116], while polyphosphoric acid can be used to react with a variety of functional groups in the asphalt and dissolve agglomerates of the asphaltene [117,118]. In some patents, CRMA is treated with DDBSA to reduce its viscosity [119,120], while other researchers have used slurry oil from the fluidized catalytic cracking process in petroleum refineries and obtained promising results [113]. In these patents, CR is often used at a dosage of 5–10% in the CRMA binder, which has been shown to meet the requirements for various types of asphalt pavements and crack fillers in slurry or chip seal construction. The benefits of each of the above techniques include a reduction in CRMA viscosity during the emulsification process, allowing ARCS to be placed at the same temperature as a standard emulsion (typically between 60^{O}C and 71^{O}C) [121]. Although studies have shown that hot-applied ARCS has relatively better performance and adhesion strength [77], cold application of ARCS remains a promising alternative that has shown better or comparable performance to conventional emulsion (CRS -2) and polymer-modified emulsion (CRS–2P) sealers in terms of aggregate loss, binder adhesion, rutting resistance, and short-term aging in the laboratory [81,121–123]. In addition, the cold ARCS was found to have a longer service life, better performance over a 12-month period after construction, higher short-term aging resistance, and is more cost-effective than CRS–2P and CRS -2 chip seals [124–126]. The combination of ARCS with warm-mix asphalt (WMA) technology is also a measure to reduce the higher emission levels [127], as studies have shown that WMA can effectively reduce the viscosity of CRMA and enable production at lower temperatures [128].

In some jurisdictions, extender oils and blending agents are added to the ARCS binder in varying amounts depending on the source of the asphalt binder, the topographic area, and the time of year, as shown in Table 3. The highly aromatic extender oil with a high flash point dissolves the fine rubber particles and causes a strong swelling of the coarse rubber crumb, which increases the viscosity of the

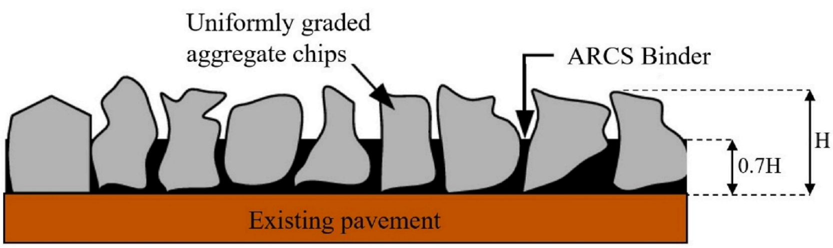


Fig. 9. Schematic diagram of synchronized ARCS application and stone embedment depth.

Table 3
Comparison of different countries ARCS specification.

Jurisdiction		Typical base asphalt binder type	Predominant aggregate chips size (mm)	CR content (% w/w)	Additional component	Typical binder application rate (l/m^2)	Ref (s)
South Africa		Pen. grade 80/100	13.2 for single CS and 19/9.5 for double CS	18–24	Extender oil (0–4%)	4.7–5.3	[93]
USA	Arizona	PG 64–16, PG 58–22, PG 52-28	12.5 or 9.5	20 +-3	N/A[a]	1.8–2.7	[96]
	Texas	AC-10					[95]
	California	PG 76–22; PG 70–22; PG 68-			Extender oil (2–6%)	2.2–2.7	[88,100,111];
China		#70 or #90 Paving grade asphalt	9.5–13.2	18–20	N/A[a]	1.0–2.0 kg/m2	[90,105,106,108,109]
Australia	Victoria	Class 170 bitumen (C170)	7, 10, or 14 for single CS and 10/5, 10/7, 14/7, or 20/7 for double CS	15–18	Extender oil (4 parts max. by volume)	≥1.8	[104]
	Queensland				Varies depending on pavement temperature		[112]

[a] Not available.

substance, as stated in the study by Potgieter and Van Zyl [6]. The result is a product with lower temperature susceptibility and increased flexibility, elasticity and adhesion. Extender oil is added to the AR mixture in such a small quantity that it has little or no effect on the chemical composition of the asphalt binder and does not affect the stability and durability of the chemical components of the asphalt.

The binder application rate is important to achieve good results over an entire pavement surface with a similar degree of loading. An excess of binder in the wheel tracks will cause flushing and a lack of binder in the non-wheel tracks will result in aggregate raveling. Therefore, calibration and verification of application rates are critical to achieving a high-quality chip seal. In the various countries listed in Table 3; the binder is usually applied evenly with a spreader vehicle that sprays the ARCS binder. However, researchers have recommended that for ARCS, the application rate of the binder should not be applied evenly, but varied between the wheel track and non-wheel track to reduce flushing/bleeding and aggregate loss on the two sections, respectively. This can be achieved by using a variable rate spreader. The use of a variable-rate spreader to place the binder has been shown to be effective when placing ARCS under the same climatic conditions and higher truck loads [82,100].

Overall, the literature suggests that ARCS is an effective and sustainable solution for pavement maintenance work. With continued research and innovation, the use of ARCS can be further optimized and expanded to meet the growing demand for durable and cost-effective PPM treatments around the world.

4.1.2. Rubber aggregate chip seal

When CR is used to modify an asphalt binder, only small quantities of scrap tires are consumed in the environment. According to Gheni et al. [129], asphalt binder modification with 15% CR can consume about 0.45 lb./yd^2 (0.17 kg/m^2) of CR, which is equivalent to 317 tires per mile (about 198 tires per km) for a two-lane road. However, if CR is used as a complete replacement for mineral aggregate in chip seal, about 5.75 lb./yd^2 (2.18 kg/m^2) of CR is consumed, which equates to 4000 tires per mile (about 2486 tires per km) for a two-lane road. In view of this, several attempts have been made to replace some or all of the aggregates in conventional CS with CR to produce rubber aggregate chip seal (RACS). Rahman et al. [121] investigated the aggregate loss of RACS produced with a 90–10 aggregate blend (90% light aggregates and 10% CR). Based on the results of the sweep test and the Pennsylvania test, the rubber aggregate increased the aggregate loss in the RACS samples. Similar results were also obtained in another study [123], in which granite and rubber aggregates were combined in a ratio of 90:10 and 80:20. Poor adhesion between the emulsion and the rubber aggregate was presumed to be the cause for the increased aggregate loss in the RACS samples. In other studies, researchers [129–132] claimed that it is possible to partially or completely replace the mineral aggregates in chip seals with CR without adversely affecting the raveling performance. However, certain adaptations are required, such as extending the curing time for RACS [130], using a steel roller compactor instead of a rubber tire compactor [131], using a CR processed at room-temperature [129], and using higher binder application rates [76,81]. However, it should be noted that a higher binder application rate is associated with an increased risk of bleeding and potential skid resistance problems due to a higher aggregate embedment depth [81].

Other factors that may affect the flow properties of RACS include the type of aggregate, CR content, and laboratory testing equipment. Recently, Pourhassan et al. [76] conducted a study to investigate the influence of these factors using laboratory and field data. In contrast to the conventional sweep test, Vialit test, and Pennsylvania test methods, which do not simulate the actual traffic conditions on the chip seal and sometimes lead to inconsistent results [130,133], Pourhassan et al. [76] used a small-wheel traffic simulator (SWTS) to apply loads similar to rolling vehicle tires, and investigated the raveling resistance of the RACS specimens. In comparison, the RACS samples containing a mixture of mineral aggregate (with lower flocculation index and higher water absorption) and rubber aggregate with a content of 50% or less exhibited better raveling performance. The flakiness index, defined as the percentage by weight of the aggregate used whose smallest dimension is less than three-fifths of its average dimension, is a key factor in the design of chip seals, and aggregates with a lower flakiness index are recommended for CS [129,134].

The water absorption of the aggregate is another important design parameter, as it supports the demulsification process of the emulsified asphalt. When the emulsion is mixed with aggregate, it demulsifies, causing the asphalt droplets to coalesce and squeeze out the water between them to form a continuous asphalt film. Once this film is formed, the aggregates absorb most of the water from the emulsion, while the remaining portion evaporates. As CR lacks water absorption capacity, it is useful to mix it partially with a mineral aggregate with higher water absorption capacity. This can help to accelerate the flocculation and curing of the binder and reduce the formation of water bubbles, which is the main reason for weaker bond between aggregate and emulsion. Fig. 10 (a – c) is a simplified schematic representation of the decomposition of the emulsion in RACS.

As already mentioned, one of the objectives of CS treatment is to improve surface friction and restore skid resistance, which largely depends on the proportion of aggregates in the CS mix. Therefore, the effect of rubber aggregate on the friction and skid resistance properties of CS needs to be well understood to promote RACS practice. Gheni et al. [129] investigated the surface texture and skid resistance of RACS and found that the mean texture depth (MTD) increased with increasing CR content, regardless of the mineral aggregate or emulsion type used. A similar trend was also observed by Pourhassan et al. [76]. Microtexture measurements showed a rougher surface of the CR particles than that of the mineral aggregates, especially for the CR processed at room temperature, which was explained as the main reason for the higher MTD results. However, the skid resistance test results using the British Pendulum Tester (BPT) did not correlate well with surface texture measurements, which Gheni et al. [129] attributed to the shortcomings of the BPT instrument on coarse textured surfaces such as chip seals. In a later study, Pourhassan et al. [134] replaced the solid rubber pad in the BPT device with a rubber brush and obtained results with the modified BPT that were in good agreement with the surface texture results from the sand spot test and 3D scanning.

In general, the research and application of RACS is still in its infancy, although the results seem to indicate good feasibility. While the studies have shown how various parameters such as aggregate properties, CR type and amount, emulsion type and application rate, etc., affect RACS performance, it would be interesting to identify the most influential factor, as this could help to efficiently control the RACS design process for an appropriate loading and environmental condition.

4.2. Use of crumb rubber in microsurfacing and slurry seals

Crumb rubber microsurfacing (CRMS) treatment is a relatively new area of research and few literature reports are available. However, if properly applied, it could possibly reduce the cost of MS mixes (since it reduces the dependence on natural materials) and minimize the amount of scrap tires disposed into the environment. The ISSA A143 requirement is commonly used to design and evaluate the performance of MS mixtures, and studies have shown that the addition of CR powder to MS treatments can significantly alter the properties and performance of the blend, even when only small amounts are added [135]. Conventional mix design parameters of MS mix include mixing time, wet abrasion loss, wet cohesion, lateral and vertical displacements, and excess asphalt [44]. As researchers [136,137] have noted, CRMS requires a certain amount of emulsified asphalt (EA) to achieve adequate performance characteristics. Sangiorgi et al. [137] designed CRMS mixes using basalt and porphyritic aggregates with 0% and 1.5% CR by mix weight. For the 1.5% CRMS mix, an optimum EA content of 14% (1% more than for the control mix) was considered suitable to achieve

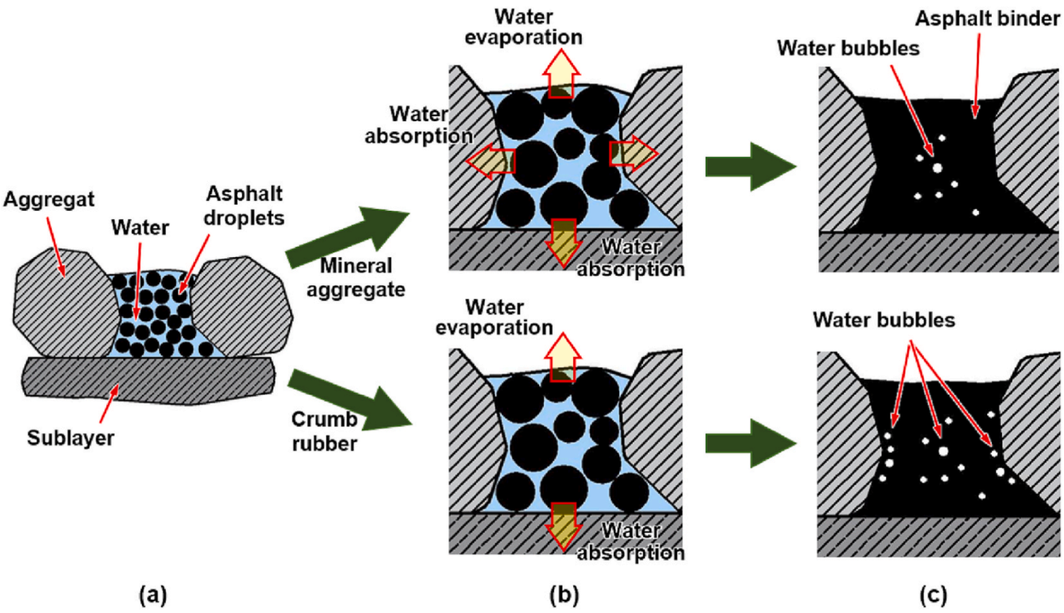


Fig. 10. Schematic representation of emulsion breakup in RACS: (a) the initial stage, (b) water starts to break out and the droplets coalesce (c) binder is fully demulsified, and some water is trapped leading to voids (reprinted with permission from Ref. [76]).

the same initial setting and curing time as the control mix. Other researchers also determined an optimum EA content of 14% for CRMS [136]. CR has a lower affinity for emulsion than conventional mineral aggregates used in MS. Therefore, an additional EA content is required for CRMS mixtures to meet the preliminary ISSA requirements [44]. The properties of CR, including rubber content, rubber particle size and gradation, must also be specified in the CRMS mix design. Researchers [78,136,138] pointed out that CR with a finer particle size gradation is advantageous in terms of mix time and load-carrying capacity. In terms of rubber powder content and rubber particle size, it is generally recommended not to exceed 3% and 0.4 mm (40-mesh), respectively [78,136,138]. Fig. 11 (a – c) shows the effect of CR dosage on the mix design parameters of CRMS with finer rubber particles passing through the No. 100 sieve (0.15 mm) [136]. Effects on mix time and cohesion (Fig. 11a), percentage material addition (Fig. 11b), and aggregate loss and deformation behaviour (Fig. 11c) are specifically shown.

As can be seen in Fig. 11b, an increase in the rubber powder content leads to an increase in the amount of water required, while the dosage of additives remains unchanged. The mix time of the CRMS samples is above the ISSA minimum requirement of at least 120 s, and the CRMS samples tend to show better cohesion results than the control MS mix (Fig. 11a). This indicates that the use of fine-grained rubber in MS treatments favours the initial cohesion of the material and the time of traffic reopening. In terms of wet abrasion and average vertical and lateral deformation resistance, the 0.5% CR achieved the best performance (Fig. 11c). As only a small proportion of the fine aggregate is replaced by rubber powder, the proportion of coarse aggregate, which is mainly responsible for the bearing capacity of the mixture, remains unchanged. However, it should be noted that the results in Fig. 11 (a – c) are only based on preliminary laboratory tests and do not fully take into account the stress state of the pavement structure. Ye et al. [139] investigated the abrasion and rutting resistance of CRMS under repeated vehicle loading at high temperatures using an Asphalt Pavement Analyzer (APA) test system. It was found that the addition of CR improved the abrasion resistance and anti-rutting performance of MS, which illustrates the results from the initial laboratory study by Hesami et al. [136] in Fig. 11.

In addition to filling minor ruts and improving abrasion resistance, MS treatment is also used to improve the surface texture and functional performance of the pavement. The mix design and aggregate type play an important role in pavement texture, which in turn affects skid resistance, surface roughness, and tire-pavement noise. Recently, several studies have been conducted in this direction [78,79,137,140–142]. Bueno et al. [79] found that when rubber powder was added to the MS mixture in the dry process, the noise generated was directly proportional to the rough texture structure. Wang et al. [142] claimed that CR can reduce the tire vibration of MS surfaces by increasing the damping. Zhuang et al. [78] related the surface texture and noise behavior of CRMS to its microstructure, which is highly influenced by the sizes and content of CR particles. According to Zhuang et al. [78], the space structure can be efficiently filled with a 2% dosage of 40-mesh rubber powder, which increases the pavement surface texture and noise reduction by making the space structure denser and more complete. Callai et al. [141] tested and compared the surface texture of different MS mixes: one with asphalt emulsion, 60% crumb rubber, and 40% natural aggregate, and two mixtures with artificial geopolymer aggregates of different granulometry curves. It was found that the use of crumb rubber as aggregate, even at a smaller nominal size,

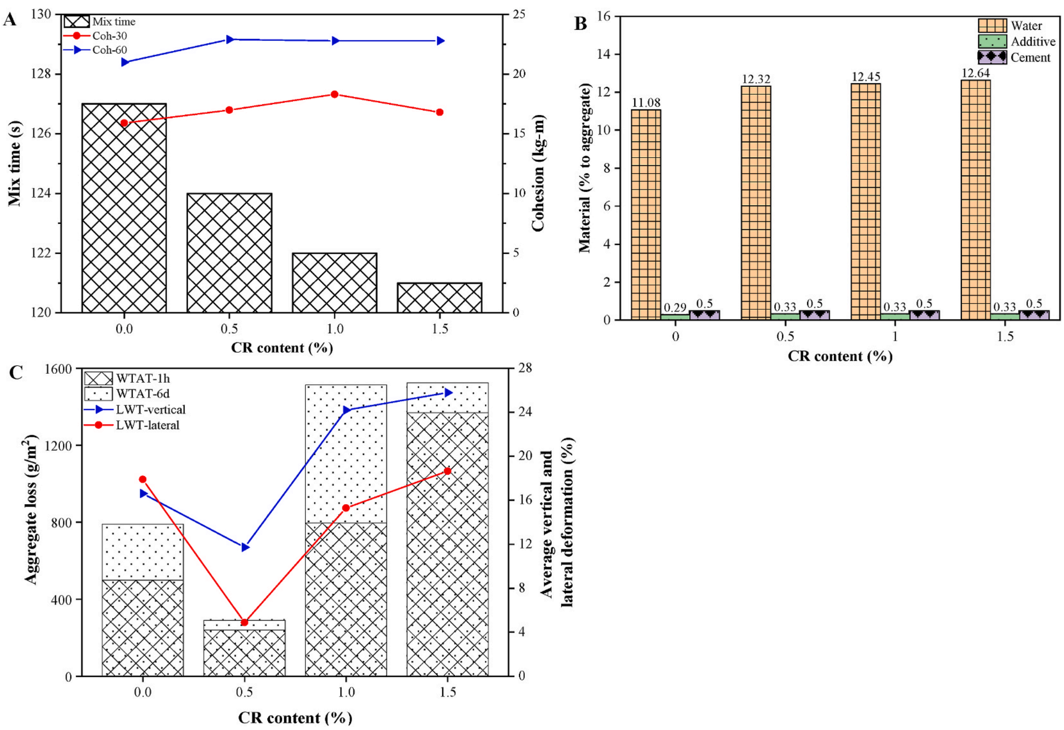


Fig. 11. Effect of CR dosage on the mix design parameters of MS: (a) Effect on mix time and cohesion; (b) Effect on material addition; (c) Effect on aggregate loss and deformation behavior (data based on [136]).

showed no relevant differences in terms of texture indicator compared to the other mixtures with the same granulometry distribution. Meiling and Zhijie [140] and Sangiorgi et al. [137] used small amounts of CR of 0–5% and 1.5%, respectively, in the CRMS design and obtained significant improvements in friction and noise reduction compared to the control mix.

Some studies have also evaluated the decision to use RWT in SS treatments as a sustainable method to reduce noise impacts in light of the positive results of the CRMS treatments. The measurements and comparisons of the acoustic properties of CRSS and conventional SS treatment by Bueno et al. [79] showed that the CRSS pavement generated less local traffic noise at 80 km/h. However, after one year, noise levels increased for both CRSS and regular SS, although the difference in their ability to reduce noise remained unchanged. According to Bueno et al. [79], this is related to an increase in surface stiffness due to early aging. The fact that there is not enough evidence to support this claim shows how consequential it is to investigate how well CRSS surfacing holds up over time. Furthermore, the CRSS mix design used by Bueno et al. [79] was based on only one CR size and content (7% w/w). In order to improve the acoustic performance of CRSS, new experimental designs with varying size and content of crumb rubber, and bituminous emulsions are needed.

5. General discussion and perspectives for future research

5.1. CR-PPM technology

The use of RWT in PPM mixes has several potential benefits, including improved functional performance of the pavement, longer service life, and environmental sustainability. It can also be used as an alternative to the natural materials used for microsurfacing, slurry seals, and chip seals which are more expensive and energy intensive. However, to fully exploit these benefits, further research is needed in several key areas, which are discussed in this response:

5.1.1. Compatibility and storage stability considerations

The successful incorporation of CR into a PPM mix depends to a greater extent on the degree of compatibility of the constituents (crumb rubber, asphalt emulsion, and mineral aggregate), as poor compatibility can lead to phase separation problems during storage and transportation and consequently poor mix performance. As studies have shown, the two factors that contribute significantly to the storage stability of CRMA binders are sedimentation and swelling of the dispersed undissolved crumb rubber [143,144]. These factors are in turn influenced by the properties of the CR particles (size, shape, content, type), the type and content of the asphalt emulsion, and the mixing conditions. Therefore, there is a need for research focusing on the interactions and compatibility between different crumb rubber sources and asphalt emulsions with different aggregates in order to optimize the mix design of CR-PPM mixtures and improve overall performance.

5.1.2. Microstructure and chemical characterization

Future research should also emphasize the importance of characterizing the microstructure of the CR-PPM mix and the chemical changes that occur in the E-CRMA binder due to aging. This characterization, when correlated with laboratory and field data, is essential for a comprehensive understanding of the factors that influence the mix properties of the CR-PPM treatments, such as the properties of the CR particles, asphalt emulsion, and additives. Common microstructural characterization techniques such as atomic force microscopy (AFM) can be used to identify topographic features and linear viscoelastic properties (e.g., stiffness and adhesion) on the CR-PPM surfaces. In addition, AFM can be used to observe and analyze the "bee structure" on the bitumen surface, providing valuable insight into the influence of factors such as chemical composition, intermolecular interactions, colloidal interactions, and binder viscosity, while phase images can provide clues to the mechanical properties of the surface features [145].

In terms of chemical characterization, a common test method, Fourier transform infrared spectroscopy (FTIR), is able to detect the chemical components of the E-CRMA binder. In particular, FTIR can be used to detect changes in the C=O and S=O groups, which are used to quantify aging [146]. Characterization of the microstructure and chemical changes in the E-CRMA binder would provide useful information for understanding the macroscopic properties and overall performance of the corresponding CR-PPM blend.

5.1.3. Functional performance of CR-PPM surfaces

Road surface texture is responsible for controlling various functional performance indicators such as noise, friction, and surface smoothness. It is well known that texture parameters, whether traditional or statistical, depend on the type or size of aggregate and the type or proportion of binder used. PPM treatments are generally used to restore the texture of the pavement and extend the life of the surface. From an acoustic perspective, there is some evidence that the addition of RWT to PPM mixtures significantly reduces noise emissions. Some researchers argued that the higher elasticity of the rubber powder affects the damping of the pavement and lowers the noise level [140], while others hypothesized that the noise reduction is due to changes in the surface stiffness of PPM and the generation of a rougher macrotexture after the addition of CR [79,137]. Similarly, it is believed that the surface friction of various PPM surfaces improves by the addition of CR to the PPM mixture. Nevertheless, it seems important to point out that the different measurements in the available literature were performed under controlled operating parameters (CR size and content, type and amount of asphalt emulsion, aggregate type, and temperature). Therefore, further experimental designs are still required to fully investigate the effects of RWT on the texture and functional performance of PPM mixtures. It is important to vary the size and content of the crumb rubber, asphalt emulsions, and aggregates to find the optimal combination that would improve the functional performance properties of the mix. Once the feasibility of the new PPM mix with crumb rubber is proven, long-term studies are also required to investigate the durability and stability of the mix under different traffic and environmental conditions.

5.2. RAP-PPM technology

The incorporation of RAP into PPM mixes is a relatively new development that has not been widely researched. Since only a few studies have been conducted so far, the biggest problem seems to be to produce a RAP-PPM mix that is workable and has good cohesion.

The insufficient bonding between the materials of RAP and the new components in the manufacture of RAP-PPM is evidenced by the low cohesion results frequently observed in research. Both the adhesion properties and workability of the RAP-PPM mix can be influenced by a number of variables, including the properties of the RAP (aggregate size, quantity, origin), the additives used, and the type and quantity of asphalt emulsion. For example, if more RAP is used in PPM, more water and fewer additives are required, which delays the setting time of the mix and leads to adhesion problems [16]. However, reducing the RAP content does not always solve this problem. Standardized performance-based criteria should be used to establish the volumetric requirements for any proposed RAP-PPM mix design, and the RAP material must be handled immediately after a mix design is established in order to reduce variability and minimize the influence of factors such as bonding and workability. It is usually preferred to use high percentage of RAP fines in PPM treatments, but this would require more asphalt emulsion to cover all the dispersed particles due to the higher surface area of fines. The surface texture and angularity of the RAP aggregate can also affect the amount of asphalt emulsion required, as a rougher surface texture and higher angularity require a higher emulsion content. Since the RAP aggregates are covered with a thin film of aged asphalt, the interfacial EA-RAP adhesion would be closely related to the interaction between the asphalt emulsion and the aged asphalt [147]. The presence of the aged binder could also influence the mechanism of emulsion breakage differently than the effects of the properties of the uncoated mineral aggregate (mineralogy and surface characteristics) [63]. Asphalt emulsion tends to agglomerate and adhere poorly to RAP with aged residual asphalt [56,65], which in turn may affect the performance and durability of the RAP-PPM mix. Surface treatment of RAP asphalt with chemicals such as hydrated lime, silane coupling agent (SCA), polycarboxylate superplasticizer (PCS), and their combinations have been shown to be effective in enhancing the interfacial adhesion properties of asphalt emulsion and RAP for targeted application in base layers of asphalt pavements using the cold-in place recycling (CIR) technique [56]. It would be beneficial to investigate how similar chemicals can be used in the RAP-PPM context. Additionally, RAP-PPM technology would benefit from both a better understanding of the interaction mechanism between asphalt emulsion and aged RAP asphalt and from a more direct quantitative measurement of interface bond strength.

Another gap in the literature is the lack of data on the long-term performance of RAP-PPM treatments. The useful life of a conventional PPM surface is approximately 7–10 years. Future studies should investigate whether this service life can be achieved or exceeded by the incorporation of RAP. The effectiveness of RAP-PPM in different climatic zones also needs to be verified. Documenting the durability of trial mixtures and finished projects will help improve the specification and mix design of a proposed PPM treatment for successful incorporation of RAP.

6. Conclusions

The need to move towards more environmentally friendly and cost-effective pavement maintenance practices has led researchers and pavement engineers to incorporate recycled wastes into PPM treatments. It is important that a comprehensive and wide-scoped assessment of the feasibility of such solutions be undertaken to provide valuable information to decision makers. With this in mind, this study provides a systematic review of the state-of-practice in the use of two types of recycled wastes (RWT and RAP) in PPM blends. General trends in the research results were summarized and the main challenges in the implementation of these technologies were highlighted. In addition, future research needs were identified. Based on this study, the following conclusions are drawn:

(1) The use of RAP in PPM blends is an innovative way to further reduce the amount of excess material remaining in stockpiles. The medium- and fine-grained fractions of the processed RAP are suitable for use in MS, SS and THMAO blends, while the coarse-grained fractions can be used in CS. With appropriate adjustments to existing mix designs of PPM treatments, the literature indicates the possibility of using up to 100% RAP in PPM. Compared to conventional PPM surfaces, the RAP-PPM surface was reported to have equivalent or better mechanical and functional performance.

(2) Bonding and workability are the main challenges affecting the widespread use of RAP-PPM technology. To address these issues, it is necessary to understand how various factors, including RAP properties (grade, quantity, source), additives, emulsion type and amount, affect bonding and workability. By identifying the most influential factors, the mix design can be easily adjusted to control the relevant parameters.

(3) The use of RWT in chip seals, whether by ARCS or RACS, is suitable for high traffic volume and high temperature roads to reduce bleeding in wheel paths and raveling in non-wheel paths, improve surface friction, and restore skid resistance. In general, the ARCS technology can be implemented by either hot or cold application. Although hot application is currently the common practice in many countries, the newly introduced emulsified ARCS is considered a promising alternative as it has a similar low paving temperature as standard emulsion.

(4) A drawback to the current implementation of ARCS technology is that the ARCS binder is sprayed onto the pavement with a uniform binder application rate, which does not take into account the different stress levels along the wheel-path and non-wheel paths. With ARCS, it seems more practical to vary the binder application rate over the entire pavement to reduce flushing and bleeding in the wheel path and raveling in the non-wheel path sections.

(5) In the MS and SS treatments, CR powder with a particle size $\leq$0.4 mm added in small amounts ($\leq$3%) can have a significant impact on mix design parameters, including mix time, wet abrasion loss, wet cohesion, lateral and vertical displacements, and

excess asphalt. Determining the optimum content of CR and asphalt emulsion is very important for mix design and should be based on the minimum ISSA requirements, also taking into account the stress state of the pavement to be treated. In terms of performance characteristics, including surface friction, noise emission, and filling of minor ruts, the MS and SS mixtures with CR perform similarly or better than conventional mixtures.

(6) Overall, the amount of research on RWT-PPM and RAP-PPM is still very limited. Most studies have focused on modifying the mix design of PPM to incorporate recycled wastes, while others have investigated the mechanical performance of waste-treated PPM mixes. However, little or nothing is known about the constituent interaction behavior of waste-treated PPM mixes, microstructure and chemical changes due to aging, long-term performance, functional performance, cost-effectiveness, and environmental impacts compared to conventional PPM mixes. A comprehensive understanding of these aspects is crucial if this sustainable pavement maintenance method is to be promoted and supported by the various transportation jurisdictions around the world.

Data availability statement

Data included in this research is referenced in the article.

CRediT authorship contribution statement

Xia Chen: Project administration, Funding acquisition, Conceptualization. **Qiuping Li:** Project administration, Funding acquisition. **Taiwo Sesay:** Writing – review & editing, Writing – original draft, Conceptualization. **Qinglong You:** Visualization, Supervision, Project administration. **Ekeoma Bridget Chineche:** Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Qinglong You reports financial support was provided by Science and Technology Project of the Jiangxi Provincial Department of Transportation (Project No, 2022H0002).

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