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Warm asphalt rubber: A sustainable way for waste tire rubber recycling

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Abstract: Recycling end-of-life tire rubber as asphalt modifier is known as a sustainable paving technology with merits including enhanced pavement durability, waste tire consumption and noise reduction. However, the criticisms on the high construction emissions of asphalt rubber (AR) have limited its application. Warm mix asphalt (WMA) effectively reduces the mixing and compaction temperatures of conventional hot mix asphalt mixtures. The combination of AR and WMA, called warm asphalt rubber (WAR), is a promising paving material which achieves pavement sustainability from principles to practices. Many studies have demonstrated that WMA technologies work effectively with AR pavement in different ways, alleviating the concerns of potential higher emissions of AR by decreasing mixing and paving temperatures. A comprehensive literature review about WAR brings a better understanding of this promising paving technology. The findings of 165 publications were summarized in this review. It summarized the recent developments of WAR in various aspects, including rheological properties, mix design, mixture mechanical performance, field application, construction emission, and asphalt-rubber-WMA additive interaction. It is expected that this review is able to provide extensive information to explore further research development and application of WAR.

Key words: asphalt rubber; warm mix asphalt; workability; interaction; performance

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1 Introduction

Asphalt concrete (AC), the most frequently used paving material for highway construction, is conventionally prepared by blending aggregates, asphalt binder, and fillers together in elevated temperature with tremendous heat energy [1, 2]. While offering indispensable contribution to society, asphalt pavement significantly influences environment in all periods including construction, operation, and maintenance [3]. Since nowadays sustainability has attracted a lot of interest worldwide, the construction of infrastructures, including asphalt pavement, are suggested to follow reclaim, recycle and reduce (3R) principles [4]. Generally, reclamation in pavement engineering refers to the process of reclaiming road materials from loss or from a less useful condition; recycling involves processing waste materials from other fields into useful pavement products; and reduce means consuming less energy and bringing less

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pollutants to environment during the life cycle period. In recent years, many sustainable asphalt paving technologies fitting "3R" were developed and applied (Table 1). Besides, novel asphalt pavements with additional functions may also be beneficial to energy harvesting and environmental protecting, such as hydronic asphalt pavement [24, 25], photocatalytic pavement [26, 27], quiet pavement [28, 29], cool pavement [30] and self-healing asphalt pavement [31, 32].

Table 1 Available technologies of sustainable asphalt pavement design

Policy	Technology
Reclaim	Using certain percentage of reclaimed asphalt pavement (RAP) when constructing new asphalt pavement [5, 6]
Recycle	Recycling waste materials as aggregate/filler/modifier for pavement construction, such as scrap tires [7, 8], glass [9, 10], plastic [11, 12], steel slag [13−15], fly ash [16, 17], packing tape [18, 19], metal waste [20], etc.
Reduce	Applying cold or warm mix asphalt (WMA) technology for less energy consumption [21], and reducing traffic noise through asphalt rubber or porous asphalt pavement technologies [22, 23]

Recycling waste vehicle tires into asphalt pavement meets both the "recycle" and "reduce" principles (consuming waste tires and alleviating traffic noise). In addition, the incorporation of crumb rubber from waste tires makes asphalt pavement more durable. The waste tires, from either passenger cars or trucks, are shredded into small particles, which are labeled as crumb rubber modifier (CRM) in pavement engineering field [33]. The size of CRM particles ranges from −10 mesh (2 mm) to −80 mesh (0.18 mm). To incorporate CRM into asphalt mixtures, two major processes have been developed, namely dry process [34] and wet process [35]. The dry process defines method that adds CRM directly into asphalt mixture to replace part of aggregates or fillers [36]. In the case of dry process, the CRM particles were supposed to have limited interaction or component exchange with the hot asphalt binder during the blending process. However, the interaction of CRM and asphalt in dry process can be observed after long storage and service periods [37]. The wet process refers to the method that modifies bitumen with CRM first, making the modified binder well blend and then mix with aggregates and mineral fillers [34]. It should be noted that the overall engineering performance of wet process prepared AR mixture is better than that with dry process, as wet process not only utilizes the resilient particle effect of CRM like dry process, but also uses its polymer components as asphalt modifier to enhance binder's rheological properties [38−40].

Asphalt rubber (AR) belongs to rubberized asphalt binder produced by wet process. It is a blend of asphalt cement, reclaimed tire rubber, and certain additives in which the rubber component is no less than 15% by weight of the total blend and has reacted in the hot asphalt cement sufficiently to cause swelling of the rubber particles [41]. Terminal blended (TB) rubberized asphalt is also produced by wet process. The difference between AR and TB rubberized asphalt technique is that the production temperature of TB rubberized asphalt is 50−100 °C higher than AR. In addition, the interacting period of TB rubberized asphalt is much longer than that of AR. In the case of TB rubberized asphalt, the crumb rubber particles are fully digested into the asphalt.

In asphalt rubber, the incorporation of CRM reduces the temperature sensitivity of binder behavior, which effectively increases high-temperature performance and decreases low-temperature stiffness, helping to protect pavement from high-temperature rutting and low-temperature cracking [7, 42−47]. In addition to the superior mechanical properties, the noise reduction effect of AR mixture is also attractive, especially in urban areas [28]. The insoluble CRM particles provides a "cushion" effect on the noise generation from vibration source, which leads to a noise reduction of 3−5 dB in comparison with conventional asphalt pavements [48−50]. However, one major concern which obstructs the widespread application of AR is the poor workability [51]. Due to the incorporation of crumb rubber, AR is much more viscous than conventional asphalt binders. Therefore, the blending and compacting temperatures of AR and aggregate should be 35−60 °C higher than those of conventional asphalt mixture, resulting in poorer construction environment, more energy consumption and hazardous emissions [52, 53]. Regarding this concern, warm mix asphalt (WMA) technology, which meets the "reduce" principle, has been proposed to enhance the workability of AR pavement by researchers and engineers in different regions [54]. WMA technology is proven to lower the construction temperatures of traditional hot-mix asphalt (HMA) mixes without significantly weakening their engineering performance [1]. Given this, combining WMA technology and AR is an ideal approach to address the high construction emission concern of AR mixtures and produce durable and low-noise pavement.

Most available studies about warm asphalt rubber (WAR) pavements are original research articles, emphasizing one or several typical properties of AR binder and mixture. However, a comprehensive literature review about this sustainable paving material, which holistically presents its development and current state of art, is still limited. To fill this gap, this study aims to present and analyze the recent developments of WAR in various aspects, including rheological properties, mix design, mixture mechanical performance, field application, construction emission, and asphalt-rubber-WMA additive interaction. This review is expected to serve as the cornerstone of further research, development and application of WAR.

2 AR and WMA

With increasing vehicles and the rapid development of transportation, the amount of waste tires is growing significantly all over the world. Known as “black pollution”, waste tires are quite difficult to be degradated in natural environment. The landfill of waste tires occupies valuable lands, and brings environmental concerns including global warming, soil pollution, water pollution and potential fire risks. On the other hand, tire rubber is composed of precious polymer like nature rubber and synthetic rubber [55]. Crumb rubber particles are derived from end of life scrap tires of passage cars and truck. Their properties including components, gradation, surface texture, etc. are believed to strongly affect the properties of AR. The processing methods including the processing equipment and processing temperature affect the surface texture, dimension and gradation of crumb rubber particles. Ambient grinding refers to a mechanical grinding method that is able to process scrap tires (with the removal of steel and fabric components) into particles at ambient temperature [33]. Cryogenic grinding freezes the scrap tires before shattering the freeze tire rubber into particles. Compared with the ambient crumb rubber particles, cryogenic crumb rubber particles show smoother surface. This reduces the reaction between asphalt binder and crumb rubber and worsts the elastic properties of the mixture [56]. Therefore, ambient grinding is mostly used to produce crumb rubber modifiers for asphalt industry. The components of crumb rubber particles depend on the source of crumb rubber. Previous studies documented that crumb rubber particles derived from truck tires consist higher mass percentage of natural rubber than those derived from passenger car tires [33, 57, 58]. But chemically, regardless of the source types, crumb rubber particles consist of elastomer, carbon black, ash, and tetrahydrofuran with the average proportions of 50%, 32%, 5% and 13%, respectively [59]. Applying the crumb rubber produced from waste tire rubber is a promising and applicable approach to consume the black pollution in a sustainable and eco-friendly approach.

As mentioned, AR is a type of CRM binder prepared by “wet process-high viscosity” system. It is prepared by mixing crumb rubber particles with virgin asphalt binder by high shear mixing. AR has been developed and applied in pavement construction around the world since 1960s [33]. In addition to the contribution in waste management, AR exhibited superior engineering performance in high-, intermediate- and low-temperature compared to virgin bitumen. The enhancement of rheological performance of AR is attributed to both the polymer modification and the particle effect of crumb rubber [39]. On one hand, CRM desulfurizes and degrades during the mixing process, releasing some soluble polymers like synthetic and natural rubber to modify the raw asphalt binder like SBS [60, 61]. On the other hand, the bulk of CRM particle enlarges by absorbing light components of asphalt, which reduces the free space between particles and stiffens the binder [62]. However, the poor workability and storage stability have been the obstacle for the wide application of AR.

Although the workability of AR binder may be influenced by factors including crumb rubber source, rubber size/content, properties of base asphalt, blending temperature/time, etc., the incorporation of CRM should bring a dramatical increment of binder viscosity [63−66]. To ensure adequate interaction between rubber and asphalt, some government specifications required that at blending temperature, the rotational viscosity of AR should be over 1.5 Pa·s (Table 2). Several studies have proven that the viscosity of AR binder increased with the CRM content [67]. Since binder viscosity has significant influence on the compatibility of the mixtures, to achieve qualified volumetric property, higher production temperature is required for AR, bringing higher energy consumption, worse working condition and more odors. In some regions, asphalt rubber mixture production has been limited to 1000 t per day because of the restriction for the maximum allowable emissions [68].

Table 2 Required rotational viscosity of AR

Specification	Requirement
Jiangsu, China	1.5−4.0 Pa·s at 177 °C
Ontario, Canada	1.5−4.0 Pa·s at 191 °C
California, US	1.5−4.0 Pa·s at 191 °C
Arizona, US	1.5−4.0 Pa·s at 177 °C
Texas, US	1.5−4.0 Pa·s at 175 °C
Florida, US	>1.5 Pa·s at 177 °C
New Jersey	2.0−4.0 Pa·s at 177 °C
ASTM D6114	>1.5 Pa·s at 175 °C

In recent decades, the WMA technology, which is developed and applied at lower temperatures (100−140 °C) in comparison to the HMA (140−220 °C), has been developed to reduce energy consumption throughout the manufacturing and construction process of asphalt pavement [1]. WMA also allows asphalt mixtures to be constructed in cooler climates, extending the paving season [51]. Especially, the reduction in hazardous construction is an obvious advantage associated with WMA technology. The greenhouse gas emission during WMA production reduce was reported to be ranged from 25% to 50%, compared to HMA production.

Based on the working mechanism, WMA technologies and the associated additives can be divided into three categories: i) foaming processes (subdivided into mechanical foaming process and addition of foaming additives); ii) addition of organic additives (e.g., Fischer-Tropsch synthesis wax (FT-wax), fatty acid amides, and Montan wax); iii) addition of chemical additives (usually emulsification agents or polymers). Foaming process refers to the process that uses foaming machine or water-containing zeolite to cause volume expansion of hot bitumen during the blending at elevated temperature [69, 70]. It makes use of the evaporation of water, from liquid to gas/steam, which enlarges the bitumen volume and therefore leads to lower binder viscosity. The organic additive, with melting point lower than bitumen, acts as flow improver during the blending process. When temperature exceeds the melting point of wax, the melting of wax makes modified bitumen more flowable, allowing for easier coating and mixing. Meanwhile, the physical properties of wax also influence the binder rheological performance at certain level [71]. Chemical additives generally do not reduce the viscosity value of bitumen. They are liquid surfactants, acting as lubricating agent to reduce the friction between bitumen and aggregate during the blending process [72].

Nowadays, there are over 40 commercially available WMA products. Table 3 lists some typical WMA products that have been widely applied in field projects. The selection of WMA products is decided by many influencing factors like the quantity of WMA mixture and the designed producing temperature of WMA mixture. Some WMA processes may need higher material cost or special blending equipment. A holistic literature review about WMA products has been conducted by RUBIO et al [1], where the performance, benefits, drawbacks of different WMA technologies

Table 3 Typical types of WMA technologies

Category	WMA additive	Company	Recommend dosage
Organic	Sasobit	Sasobit	2%−3% by binder
	Asphaltan	Romonta	2% by binder
	Licomont DS-100	Clariant	3% by binder
Chemical	Evotherm-DAT	MeadWestVaco	5% by binder
	Evotherm-3G	MeadWestVaco	0.5% by binder
	Rediset	Akzo Nobel	0.4%−0.75% by binder
	Cecabase RT	Ceca	0.2%−0.5% by binder
Foaming	Advera	Eurovia	0.3% by total mix
	Aspha-Min	PQ corporation	0.3% by total mix
	Double-Barrel Green (DBG)	Astec	Water foaming, N/A

were thoroughly introduced [1]. Regarding the negative effects, WMA mixtures were reported to be more susceptible to moisture damage (stripping) because aggregates may not be completely dried at lower WMA temperatures [73]. In addition, the insufficient hardening effect caused by the lower WMA temperatures may compromise with the high temperature performance of some WMA mixtures [74].

The production temperature of AR mixture is 165−200 °C and a 20−45 °C reduction can be achieved by using WMA technologies [75]. Generally, warm mix asphalt refers to asphalt with production and construction temperatures in range from 85 °C to 135 °C [51]. Although the production temperature of WAR was still outside of WMA definition, one of the most serious concerns of conventional WMA, moisture susceptibility, can be well addressed. In addition, the incorporation of CRM is able to compensate part of negative effect (on rutting and cracking performance) from some WMA technologies. Hence, it is a win-win combination to use AR and WMA together.

3 Production of WAR binder and mixtures

3.1 Binder preparation

In laboratory, AR is generally produced by using high shearing mixer (blending speed: 1000−4000 r/min) at a mixing temperature of 175−200 °C [76], while in field AR binders are produced by mixing conventional asphalt and CRM at or near the job site by special blending equipment. In most cases, longer blending time can compensate the lower mixing rate of blending machine. The reacting time should be limited to less than one hour to prevent further devulcanization and depolymerization of CRM [68, 77, 78]. Generally, it is recommended to use soft virgin asphalt (superpave PG64 or lower) and smaller crumb rubber particles (smaller than 20 mesh) to promote the component interaction [79, 80]. The blending condition is designed to allow adequate interaction between crumb rubber and asphalt fractions. After interaction with bitumen, every crumb rubber particle should have its elastic cores, while the edge part turns to colloid materials due to component exchange with asphalt fractions. It has to be mentioned that with extremely long blending time or high blending temperature, the rubber particles can be totally dissolved into asphalt fractions. In this case the modified asphalt is called “terminal blend (TB) rubberized asphalt” [81]. By comparison, there is no “particle effect” of crumb rubber in terminal blend rubberized asphalt. TB rubberized asphalt exhibited superior storage stability compared to AR. However, AR significantly outperformed TB rubberized asphalt in terms of rutting resistance and the function of noise reduction [82, 83].

In most available studies, the WAR binder is prepared by adding WMA additives into hot AR and mixing together for several minutes at the same or slightly lower temperature [67, 84−86]. By conventional mixing procedure, the effect of WMA additives can be easily evaluated, and the field quality control should be simpler since there are many AR production guidelines available. Another potential mixing procedure is to directly mix the WMA additive, base asphalt and CRM together. Since all components can be put into the blending tank together in one time, the direct mixing method is believed to be more convenient and more energy efficient [87]. The direct mixing method is not allowable for WAR with foaming additive, due to the limited foaming time of zeolite [88]. Especially, for WAR with liquid WMA additive, another possible mixing sequence called pre-treating method is available. In this method, the rubber particles are soaked in liquid surfactant to make the liquid WMA additive absorbed by crumb rubber. And then use the modified crumb rubber to be blended with hot asphalt. However, whether WMA additives can be added during or before the prepare process of AR is still under discussion. Previous studies showed that the earlier incorporation of Evotherm-DAT (both direct mixing and pre-treating method) reduced the production temperature of AR by 16 °C without significantly disrupting the rheological properties of WAR binder [89]. However, directly mixing wax additive, base binder and CRM together achieved similar mechanical properties compared to the traditional method, but it was found that directly mixing method leads to slightly poorer workability [90]. Since the adding timing of WMA additive influences the rheological properties of WAR binder, using WMA additives to control and optimize the blending condition of WAR binder is a promising topic which deserves further investigation.

3.2 Mix design and mixture preparation

The mix design of WMA is speculated to be compatible to HMA procedures [90]. Currently, the mix design of AR is also applicable for WAR, regardless of the type and incorporation timing of WMA [67, 84, 92−94]. In available studies, AR and WAR are considered conventional polymer-modified asphalt binders like SBS modified asphalt. The mix design methods, specifications and construction procedures used for conventional asphalt binders can be used with AR and WAR binders. Standards or guidelines in designing AR mixtures have been developed by several agencies [95−97]. Marshall (applied in most regions) and Hveem (applied in California) methods with slight modifications were suggested to be used for dense-graded and gap-graded AR mixtures while the design procedure in FHWA-RD 74-2 was recommended to be used for open-graded AR mixture design) [98]. All procedures essentially contain five steps, namely, aggregates and binder selection, mixes compaction (with various binder contents), air voids measurement of compacted mix samples, mechanical testing, and finally optimum binder content determination.

In general, as a portion of the asphalt is replaced by rubber in AR binder, the AR/WAR binder content should generally be higher than the corresponding mixture containing virgin bitumen. An empirical method is that the increased binder content should be the same as the content of crumb rubber used in AR binder [99]. A practical experience in California indicated that the optimum asphalt content (OAC) of WAR should be 1.2−1.4 times that of the OAC with neat binder [100]. Because of the swelling property of CRM and the increased binder content, gap- and open-graded mixes are more preferable for AR/WAR than dense-graded. Gap-graded is speculated to be a variation of dense-graded in which the aggregate gradation is coarsened to provide a greater amount of mixture voids. The increased amount of voids allows for higher AR/WAR binder content and provides rooms for potential swelling of crumb rubber. Open-graded mix can definitely accommodate higher amount of AR binder. Correspondingly, the use of viscous AR and high binder content leads to thicker binder films, improved anti-aging property and better durability. It has to be mentioned that the OAC of asphalt mixture depends on the designed air voids content, aggregate source, compaction method, service condition of the corresponding asphalt pavement, etc. Based on available studies, the OACs of dense-graded, gap-graded, and open- graded asphalt mixture are around 4.4% to 5.5%, 4.5% to 6.2%, and 4.3% to 6.5%, respectively [101−110].

Since WMA additives are either solid or liquid at ambient temperature, they are pre-blended with hot AR a few minutes prior to mixing with aggregates. In some cases, the WMA additives can also be directly added to the mixture in the mixing bowl, just after addition of AR. Or the WAR binder can be prepared by direct mixing method and then blended to aggregate and fillers. Nearly no changes to the asphalt plant should be made except the installation to incorporate WMA additives and decreased production and compaction temperatures [85].

It has to be mentioned that although the design and application of AR and WAR pavement has been a practice-ready technology, some limitations still need further investigation. The most outstanding one is the neglect of rubber’s volume effect in current design specifications of AR. In wet process, the volume of crumb rubber can expand by two to three times. The diameter of swelling rubber reaches about 1 mm, which is larger than mineral fillers and some fine aggregates. Additionally, crumb rubber accounts for 1%−1.5% of the total mass of mixture. The density and modulus of swelling rubber are distinct from that of aggregate, which may have significant influence on the mechanical system of WAR mixture. Therefore, a more specific evaluating on the volume effect of swelling rubber in AR mixture design is recommended.

4 Interaction among components of AR and WAR

4.1 Interaction between crumb rubber and asphalt

Crumb rubber, shredding from passenger car tires or truck tires, mainly comprises nature rubber, synthetic rubber, carbon black and fillers [111].

According to the different polarities, asphalt can be separated into four fractions, which can be distinguished by their polarity. Highly polar asphaltene micelles are dispersed in a viscous phase of saturates, aromatics and resins (maltene phase) [112]. The interaction mechanism within AR has been extensively investigated by many previous studies [113−117]. Especially, WANG et al [118] have comprehensively summarized the available chemical methods used for characterizing the interaction among components in AR binder. The interaction between crumb rubber and asphalt happens during the high shear blending in evaluated temperature. During the interaction, the crumb rubber changes by two stages: swelling and dissolution. And the swelling and dissolution of crumb rubber happens simultaneously [118].

The production of AR is far more complicated than simply mixing and dispersing CRM into hot asphalt binder fractions. As depicted in Figure 1, once mixed with hot asphalt, the outer part of CRM dissolves with mixing time, releasing natural rubber, synthetic rubber and other components into asphalt fractions. In addition, the light components of asphalt, including saturates and aromatics, are absorbed into CRM polymer chains, forming a thin gel layer around the elastic rubber core of CRM. A study about four fractions analysis of AR binder proved that compared to raw asphalt, AR had higher percentage of heavy fractions (asphaltenes and resins) and lower percentage of light components (aromatics and saturates), which should be attributed to the “absorbing effect” of CRM [90]. In addition, the peak at 1012 cm^{-1} in Fourier transform infrared spectroscopy (FTIR) spectrum of AR binder is ascribed to the loss of light components of asphalt binder after the incorporation of CRM [35]. The swollen CRM plus gel layers are two to three times larger than the original CRM. Meanwhile, some polymer chains in CRM, including natural rubber and synthetic rubber, are released, and mixed with asphalt fractions.

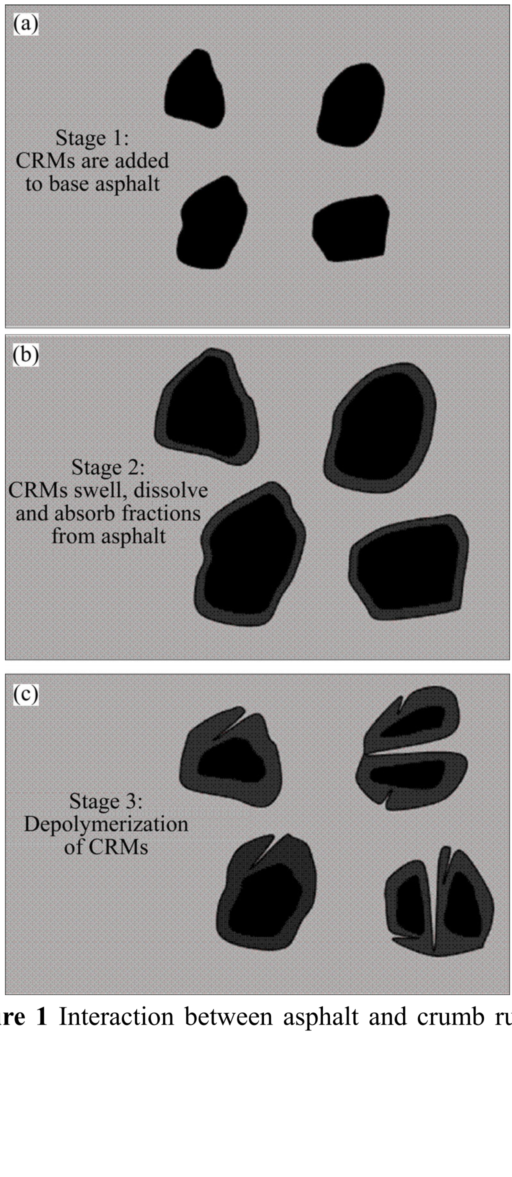

Figure 1 Interaction between asphalt and crumb rubber [63]

The dissolution of CRM has been demonstrated by YU et al [119] through thermal analysis. As shown in Figure 2, the dissolution of CRM can be indicated by the higher amount of final residual mass and the disappearance of natural rubber’s endothermic peak. Compared to the original CRM, the extracted CRM shows a similar pattern in the thermogravimetric (TG) curve but a different shape in the differential scanning calorimetry (DSC) curve. The main weight loss of the extracted CRM still occurs from 300 °C to 500 °C. However, the final residual mass fraction of the extracted CRM (about 26 wt%) is higher than that of the original CRM (17 wt%), indicating that the interaction of rubber with base asphalt may have consumed part of the decomposable polymers. Besides, the DSC curve of the original CRM has two clear endothermic peaks from 300 °C to 500 °C, while the extracted CRM only has one, indicating that the components in the original CRM are more complicated. The peak within the range of 300−400 °C is due to the nature rubber component of CRM while the one within the range of 400−500 °C is related to the synthetic rubber. The disappearance of nature rubber’s endothermic peak is caused by its partial dissolution during interaction with asphalt fractions.

In addition to thermal analysis, results of gel permeation chromatography (GPC) test also

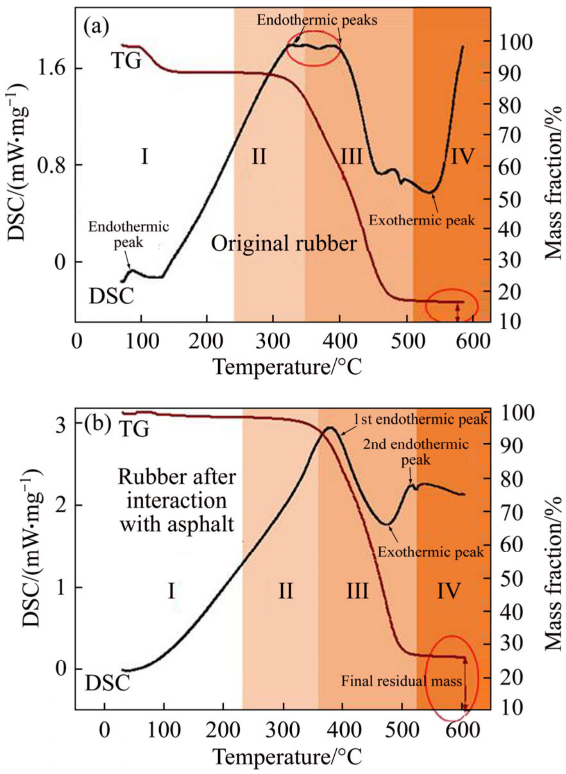

Figure 2 Thermal analysis of CRM before (a) and after (b) being mixed with asphalt fractions [119] (I, II, III and IV refer to oil and plasticizer, natural rubber, synthetic rubber, carbon black and other fillers respectively)

demonstrated the component exchange process between CRM and bitumen fractions. The interactions between CRM and virgin asphalt binder resulted in a higher large molecule content due to the release of polymers from CRM [120]. In general, the component exchange process between asphalt and CRM is considered as physical reaction. The strong attractive interactions among the asphaltene particles lead to the dramatically increased viscosity of asphalt and strengthen the network structure formed by asphalt molecules.

4.2 Interaction among asphalt, crumb rubber and WMA additives

As mentioned, the term “interaction” in AR refers to swelling and dissolving of CRM plus diffusing of maltenes from the base asphalt into the crumb rubber [121]. It is known that the production of WAR binder does not simply mean mixing and dispersing CRM and WMA additive into asphalt fractions. The addition of WMA may either enhance or deteriorate the formed asphalt-rubber system, which mostly depends on the components and properties (both physical and chemical) of WMA additives. By measuring the final residual weight of CRM extracted from AR and WAR binders, YU et al [119] found that both organic and chemical additives had a positive effect on the dissolution of CRM in asphalt fractions.

Figure 3 presents the schematic diagram of swelled CRM interacting with asphalt fractions and WMA additives. During blending, both components from WMA additives and asphalt fractions are absorbed into the rubber-asphalt interacting area. YU et al [120] divided the interaction area of swelled CRM into four layers by staged extraction method. They found that the effect of wax additive on the absorption preference of swelling rubber is limited. Conversely, chemical surfactant was reported to significantly decrease the large molecule content and obstruct the formation of C—O bond. In terms of the final status of WAR binder, environmental scanning electron microscope (ESEM) observation suggested that AR has a single-phase continuous structure with particles not uniformly distributed in base asphalt [122] and Evotherm-DAT is capable to make the rubber-asphalt system more homogeneous [66]. Fourier transform infrared spectroscopy (FTIR) studies demonstrated that there is no complex chemical reaction between Evotherm-DAT/Sasobit/56# paraffin wax and AR. The emerging peaks in WAR’s spectrum were attributed to the chemical components of each WMA additives [85, 111]. GPC study showed that WMA additives obviously influence the molecular weight distribution of AR because of their own components [123]. Thermogravimetric (TG) and differential scanning calorimetry (DSC) analysis illustrated that the incorporation of WMA additives can promote the component exchange between CRM and asphalt, and the wax-based additives penetrate into CRM

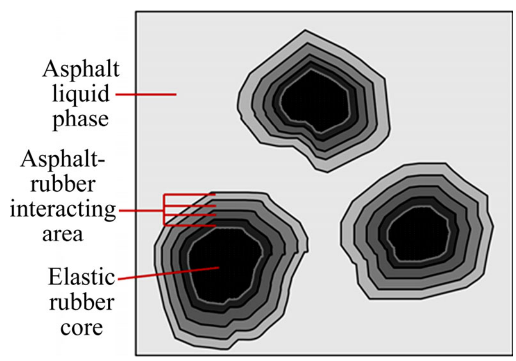

Figure 3 Schematic diagram of swelled CRM in WAR binder

particles during the mixing process of WAR. AFM investigation showed that CRM decreased the dimension but increased the quantity of the typical bee-like structure of asphalt. However, the incorporation of organic WMA additive enlarged the size of bee-like structure, resulting in stiffer rheological behavior [124].

In addition to the type of WMA additive, the mixing procedure also influences the interaction in WAR system. YU et al [89] found that using same dosage of wax additive, direct mixing CRM, WMA and asphalt together leads to fewer wax content in liquid asphalt phase of WAR binder than conventional procedure. That means that during the reacting process, both light fractions of base asphalt and wax molecules are absorbed by CRM. Therefore, when direct mixing method is applied to prepared WAR with wax additive, more wax dosages are required. In a study of WAR with Evotherm-DAT, it was found that the liquid Evotherm-DAT can be well absorbed by rubber particles. FTIR results showed that certain reaction happens between them at room temperature [90] (Figure 4), indicated by the new generation of hydrogen bond between O—H/N—H group of crumb rubber and —COO— of Evotherm-DAT. The earlier incorporation of liquid additive also promotes the interaction between rubber and raw bitumen. Therefore, it is possible to reduce the reacting time when preparing WAR with Evotherm-DAT as the WMA agent, also as interaction promoter in rubber-asphalt system. Based on above-mentioned literatures, it is believed that research on interaction mechanism among components within WAR binders provides

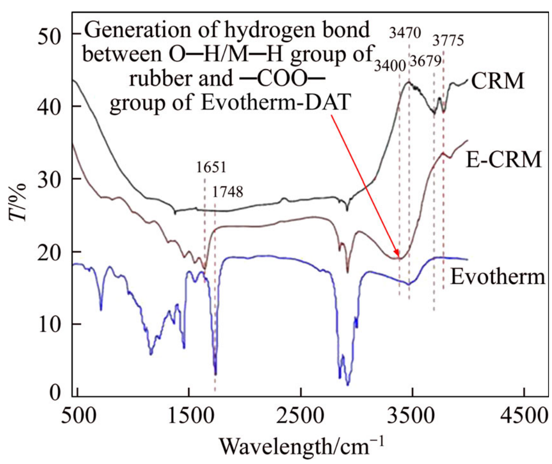

Figure 4 FTIR spectra of CRM, Evotherm-DAT and E-CRM (CRM after soaking into Evotherm-DAT)

information to optimize the materials and blending condition design of WAR, which helps to produce this sustainable paving material in a more efficient and effective way.

5 Engineering performance and recycling potential of WAR

5.1 Rheological properties of WAR binders

Interaction between CRM and base asphalt results in superior performance of AR at high, intermediate and low temperature. The dissolution and swelling of CRM also dramatically increase the viscosity of asphalt binder. Meanwhile, the storage stability of AR binder is poorer compared to raw asphalt due to the density difference between CRM and asphalt. WMA additives are able to alleviate the workability concern of AR. Because of their various physical natures and working mechanisms, WMA additives exert different influences on the rheological and mechanical properties of AR binder and mixture.

When CRM is incorporated into base asphalt, the penetration value, ductility and phase angle of asphalt binder decrease, whereas its softening point, elastic recovery, viscosity and complex shear increase [76]. In other words, compared with raw bitumen, AR binder is stiffer and more elastic, but less consistent and flowable. Then enhanced rheological performance of AR binder is indicated by higher Superpave rutting factor ($G^*/\sin\delta$), lower non-recoverable compliance (J_{nr}), more loading cycles to fatigue failure and lower stiffness at low temperature [35, 125, 126]. WANG et al [39] evaluated the rheological properties of liquid asphalt phase extracted from AR and WAR binders. They found that the enhanced rutting resistance of AR is ascribed to the polymer modification and particle effect, while the extended fatigue life mainly can be attributed to CRM's particle effect.

Many studies have investigated the influence of different WMA additives on several rheological properties of AR binders (as summarized in Table 4). Previous studies demonstrated that all WMA technologies, regardless of the working mechanism, are able to increase binder's workability by means of decreasing the viscosity of AR binder. However, compared to raw bitumen, the viscosity values of WAR binders were still much higher. The viscosity-reducing effect of organic

Table 4 Influence of WMA technologies on AR's main rheological properties

Category	WMA additives	Workability	Rutting resistance	Fatigue resistance	Low temperature cracking resistance
Organic additive	Sasobit	Enhanced	Enhanced	Deteriorated	Slightly deteriorated
	Licomont		Enhanced		Deteriorated
	Asphaltan		Enhanced	N/A	Deteriorated
Chemical additive	56# Paraffin wax		Insignificant effect	Deteriorated	Deteriorated
	Evotherm-DAT		Deteriorated	Deteriorated	Insignificant effect
	Bio-modifier		Deteriorated	N/A	N/A
Foaming additive	Aspha-min		Slightly Enhanced	Slightly deteriorated	N/A
	Advera		Insignificant Effect	N/A	N/A
Foaming process	Water foaming		Deteriorated	Enhanced	Enhanced

additives is constant, which is ascribed to their relatively lower melting point and higher flowability after melting. In terms of chemical additives, it is still unsure whether the enhancement is attributed to the surfactant effect or liquid physical nature. Foaming process and additives only enhance AR's workability during the foaming period. Using commercial foaming additive may finally lead to an increased viscosity as the residual zeolite particles act as fillers in WAR system [69].

The type and content of WMA additives exhibited significant effects on rheological properties of AR binder. Based on the Superpave rheological characterization, FT-wax was found to enhance rutting resistance but compromised fatigue and low-temperature cracking resistance [127]. However, liner amplitude sweep (LAS) test indicated that the effect of FT-wax on fatigue resistance is positive [128]. By comparing the fatigue performance evaluation of WAR binder, mortar and mixture, YU et al [128] proposed that LAS is a more reliable fatigue test than the Superpave fatigue factor test. The non-commercial additive, 56# paraffin wax, slightly worsens all rheological properties of AR. The negative effect of conventional wax additive on rutting resistance and low temperature cracking resistance is determined by its low melting point and glass transition temperature respectively. To ensure satisfing low temperature performance, the dosage of wax additive should be controlled. Various types of chemical additives were reported to bring negative effect on the anti-rutting performance of AR binder [66, 130]. Foaming additives have indistinct effect on rutting performance while foaming process brings slightly negative influence [45, 131]. Nevertheless, it is worthy mentioned that although some WARs may perform worse compared to AR, they are still much superior to the corresponding base binders.

5.2 Mechanical properties of WAR mixtures

The mechanical properties of asphalt mixture considerably vary in a large range depending on the specific asphalt binder, mixture gradation, aggregate type as well as blending condition [77, 78]. Consistent with the superior rheological properties of AR binder, the mechanical properties of hot AR mixture, including moisture sensitivity, stiffness modulus, resistance to cracking and permanent deformation, are obviously superior over that of conventional HMA, due to the increased binder viscosity and higher production temperature [132, 133]. The air voids content of Marshall samples and the numbers of gyrations of the SGC samples to achieve the same specimen height were employed by YU et al [75] as the measures of asphalt mixtures' compactability. It is found that WMA additives could reduce the production temperature of the AR mixture by at least 16 °C, without significantly compromising the compactability of mixtures. Other studies have also demonstrated that the use of WMA technologies achieves blending temperature reduction ranges from 20°C to 35°C with very limited influence on volumetric properties [93, 134].

Table 5 shows the effect of WMA technologies on the service performance of AR mixture. It is noted that the moisture damage resistance of WAR mixture is slightly poorer than that of hot AR mixture, as more moisture entraps in aggregate at lower production temperature [67, 86]. A surface

Table 5 Effect of WMA technologies on AR mixture performance (compared to hot AR mixture)

Performance	Sasobit	Aspha-min	Resiset	Surfactant	Foaming process
Moisture susceptibility	↑ [135] ↓ [67,87]	↓ [45]	↓ [87]	↑ [93] ↓ [135]	↓ [135]
Fatigue resistance	↑ [92] → [126]	↓ [92]	→ [135]	→ [135]	→ [135]
Rutting resistance	↑ [135]	→ [45]	→[135]	↑ [93] ↓ [135]	→ [135]

Note: ↑ means enhanced; ↓ means deteriorated; → means no obvious effect.

free energy study conducted by Habal and Singh drawn the same conclusion. It was found that AR with Rediset, Sasobit and Advera exhibit poorer moisture resistance compared with hot AR [87]. OLIVEIRA et al [93] hold the opposite view since they believed surfactant additive should result in less water sensitivity of AR mixture, because the adhesion between aggregates and binder was improved by surfactant. JONES et al [134] concluded that the warm-mix technology by itself is unlikely to influence moisture sensitivity; however, problems are likely to be attributed to aggregate condition and construction quality. By summarizing the available studies, the water based chemical additive (like Evotherm-DAT) should exhibit negative effect on moisture sensitively due to the incomplete evaporation of the liquid surfactant. In addition, WMA mixtures normally performed worse compared to corresponding HMAs caused by the lower heating temperature of aggregates. In terms of fatigue performance, XIAO et al [92] believed that among organic, chemical, and foaming additives, only aspha-min results in poor fatigue cracking resistance. The study conducted by JONES et al [134] showed that warm mix asphalt technologies exert limited effect on fatigue performance of AR mixture, since lower production temperature leads to lower binder oxidation. YU et al [128] study proposed that only WAR with organic additives exhibited longer fatigue lives than hot AR mixture. And the LAS, mortar shear fatigue test, and four-point bending beam test provided the same prediction of fatigue resistance on rubberized samples.

Regarding rutting resistance, WAR with FT-wax exhibited superior performance over hot AR, which is consistent with their rheological properties [78]. A minimal improvement was observed on rutting resistance with addition of surfactant by OLIVEIRA et al [93]. By comparison, the effects of foaming additives and foaming process on rutting resistance were both insignificant [67]. According to available studies, the mechanical properties of WAR mixtures were generally in good consistence with the rheological properties of their binders.

The effect of mixing sequence on mechanical properties of WAR mixtures is also noticeable. YU et al [128] tried to optimize the mixing sequence of WAR mixture with surfactant additive by analytic hierarchy process (AHP). According to their findings, it is suggested to make CRM absorb surfactant first followed by incorporating the CRM-surfactant mixture to raw asphalt binder and finally blending the modified binder to aggregates [135]. Similar findings were also obtained by WAR mixture with FT-wax. A recent study employed fuzzy comprehensive evaluation (FCE) method to quantify the performance grade of wax-based WAR mixtures prepared by six mixing sequences according to fuzzy logic. It is found that for regions with hot and humid climate, the optimal mixing sequence of WAR with FT-wax is to mix AR binder and Sasobit first followed by incorporating them into aggregates [136].

5.3 Reclaiming potential of AR and WAR pavement

Several studies focusing on RAP-AR mixtures have been performed, and good compatibility was found between these two sustainable paving materials [137−139]. By comparison, available studies on reclaiming AR or warm AR are limited. The reclamation of rubberized asphalt pavement in field has not been a common practice yet. Early studies in US investigated the in-situ paving properties regarding the feasibility of recycling RAC [140, 141]. In those studies, the rubberized asphalt pavement was reclaimed as conventional asphalt mixtures, and the performance of reclaimed rubberized asphalt pavement was acceptable based on local specifications. For laboratory studies, LEE et al [142] found that the performance properties of the recycled aged CRMA, prepared by mixing virgin and aged CRMA, met the Superpave binder requirements. Besides, there was no significant difference between the control and the recycled rubberized mixes in moisture susceptibility and rutting resistance [143].

It is known that AR and WAR binders

exhibited superior aging resistance compared to unmodified asphalt binder, because the dissolution of natural rubber component of crumb rubber was reported to make the AR binders more flexible after aging [144, 145]. The crumb rubber modifier may also exhibit modification effect on rutting and fatigue performance in the reclaimed rubberized asphalt mixture. The key point to reclaim AR/WAR pavement is to analyze the blending efficiency between the new asphalt binder and the aged AR or WAR binder. In addition, how to select optimal rejuvenators towards highly efficient recycling for aged polymer modified asphalt remains a concern for pavement researchers.

6 Economic and environmental effects

6.1 Economic effects

The economic effects of AR and WAR pavement are related to raw material cost, blending temperature, equipment installation or modification fee and WMA additive dosage rate. In addition, long-term pavement performance influences future maintenance cost [146]. Life cycle cost analysis (LCCA) and life cycle assessment (LCA) studies demonstrated that with the use of recycled waste vehicle tires, AR pavement is beneficial in terms of energy saving, environmental impact, human health, preservation of ecosystems and minimization of resource depletion [147]. By constructing the same amount of mixes, AR should exert poorer economic and environmental effect due to its higher production temperature [148]. However, the AR technology may reduce construction cost due to the use of thinner asphalt layer and therefore to the reduced amounts of materials used and reduced amounts of milled materials that are transported and eventually disposed. These energy- and material-saving properties render the use of AR technology with an overall advantage in road construction [68].

In terms of the effect of WMA, some studies proved that significant benefit on energy saving can be achieved by incorporating WMA [149, 150]. Economic merits can be also obtained by the enhanced in-place density and smoothness. However, some publications proposed that the energy saving effect depends on the types of WMA technologies. Moreover, the benefits obtained from lower construction temperature may be offset by the greater impacts of the additional material cost [151]. WANG et al [152] believed that WAR requires higher initial cost compared to conventional HMA, but it is more cost-effective in life-cycle due to the enhanced engineering performance and lower maintenance cost. CAO et al [153] analyzed the long-term energy-reducing effect of different WMA additives in AR pavements by LCA framework incorporated with uncertainty analysis. They found that a noticeable energy saving can be obtained by the incorporation of WMA technologies during the construction period. Using FT-wax was proved to be the most economic choice considering the life-cycle energy consumption. Figure 5 shows the expected cost analysis of WAR pavement compared to HMA. It is noted that WAR should have long-term economic benefits. Nevertheless, compared to the abundant studies focused on engineering performance of WAR, research on economic effect of WAR is relatively limited.

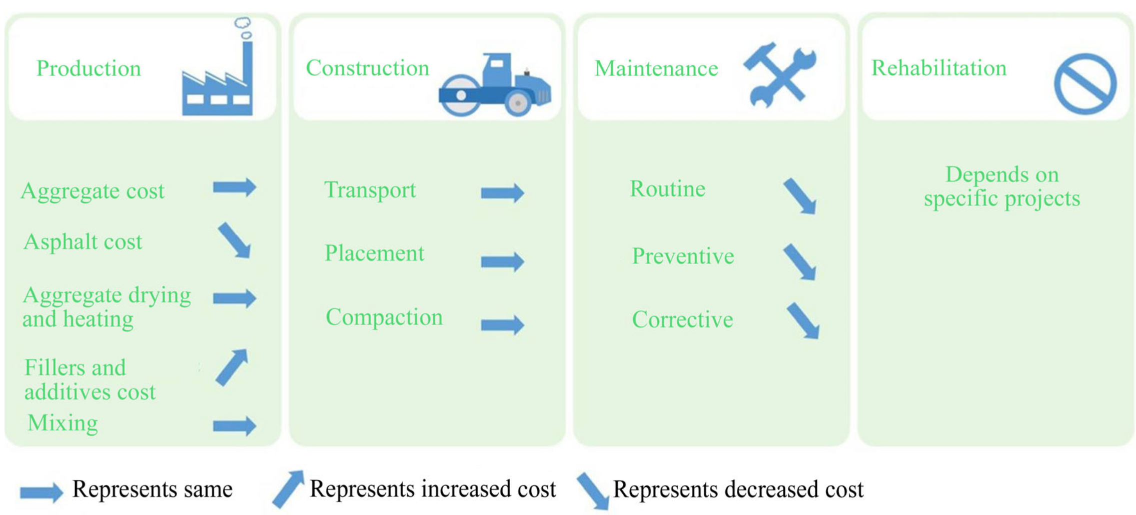

Figure 5 Cost analysis of warm asphalt rubber compared to hot mix asphalt

Future investigation is suggested on more comprehensive LCA on WAR to provide quantitative references for decision-making.

6.2 Environmental effects

In terms of the construction environment, it is known that construction odors during the production of asphalt pavement is highly dependent on the paving temperature [154]. Besides, the rubber particles itself could release some hazardous components (VOCs primarily BTEX (benzene, toluene, ethylbenzene, and xylenes) and sulfur compounds) at elevated temperatures [155, 156]. Therefore, emissions of hazardous organic chemicals from AR have been the longstanding environmental and occupational health concerns. Previous studies have shown that levels of pollutants (total suspended particles (TSP), volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs)) varied with the raw materials and blending/compacting condition. Odor of bitumen is one of the concerns influencing paving workers and residents living near the construction site, which is the resultant of interactions of certain VOCs with the sense of smell [157]. A study by the US National Institute for Occupational Safety and Health (NIOSH) concluded that exposure to emissions from asphalt containing CRM may be more harmful to workers than conventional paving materials [158]. However, a recent study indicated that both conventional and AR generated similar levels of particles and PAHs contributing to human exposure [159].

WMA has been reported to exert significant environmental benefits during the construction period [1]. For conventional HMA construction, WMA technologies generally reduce carbon dioxide (CO_2) and sulfur dioxide (SO_2) by 30%−40%, volatile organic compounds (VOC) by 50%, carbon monoxide (CO) by 10%−30% and nitrous oxides (NOx) by 60%−70%. Moreover, its environmental benefits lead to economic benefits. According to a European study, 20%−35% burner fuel can be saved by using WMA technology [160]. Studies on the environmental and impacts of WAR are relatively limited. A field investigation in California revealed that no smoke or haze was emitted when AR and surfactant additive were used together [62]. By both lab scale and full-scale emission analysis, GHIU et al [148] proved that the emission concern of hot AR pavement can be greatly alleviated when the paving temperature drops. WANG et al [161] proved that in comparison with traditional hot mixing process, warm mixing is able to reduce energy consumption and gas emissions by 18%−36% and 15%−87%, respectively. By comparison, chemical WMA additive conserved the most amount of energy and produced the least emissions. A comprehensive LCA conducted by Rodríguez-Alloza showed that with the aid of organic additives, the energy consumption and greenhouse gas (GHG) of hot AR production can be reduced by 18% and 20%, respectively.

Another significant environmental effect of AR and WAR pavements is the noise reducing function. The resilient rubber particles provide a “cushion” effect on the noise generation from vibration source. AR pavements with the open- or gap-graded mixtures, have been reported reducing noise levels by up to 3−5 dB compared to traditional dense-graded asphalt pavements [99, 162]. A study by the Rubber Pavements Association (RPA) proved that the use of tire rubber in open-graded mixture reduced tire noise by at least 50% compared to concrete pavements [49]. SANDBERG [163] compared the old SMA16 to the new rubberized SMA11 and rubberized ARSMA8 by CPX. The rubberized SMA11 and SMA8 obtained a noise reduction of 2.3 dB and 3.9 dB, respectively. Since the noise reduction effect is mainly ascribed to the properties of rubber particles remaining in asphalt pavement, effect of WMA technologies on this function is limited.

7 Field application

As Table 6 shows, agencies in US, England, China and India have applied WAR for field application [85, 77, 164]. For example, one million tons of WAR mixtures were produced in California during the 2011 paving season containing Evotherm, Sasobit, Advera and Astec DBG additives [135]. It is reported that the paving temperatures of WAR were significantly lower compared to control AR, which in turn decreases the amount of fumes. Field evaluation in California showed that WMA technologies reduced the production temperatures by 19 to 45 °C [165]. Although the production temperatures were still outside the range of WMA definition, many contractors believed its work

Table 6 Typical field projects of WARs from different regions

Region	CRM content/%	Mix type	Mixing temperature/°C	Applied WMA additive
Rhode Island, US	20	Gap	143−150	Advera
Newcastle, England	20−25	Gap	150	Sasobit
Orlando, US	12	Open	143	DBG
			132	DBG
California, US	18.5−22	Open, Gap	143−160	Evotherm
			150	Sasobit
Jiangsu, China	20	Gap	150−160	Evotherm
Shanghai, China	18−22	Gap	170	Sasobit
Haryana, India	15	Dense	125−130	Surfactant additive
Hong Kong, China	18	Gap	145	Sasobit

environment of WAR was acceptable. Besides, the in situ density of WAR is reported to be closed to that of AR. The initial field performance of the warm AR pavements was “very good” and there was nearly no sign of distress after two years [85]. A field project evaluation in Hong Kong showed that the rubberized asphalt performed at least equivalent to the conventional HMA one year after construction. Moreover, the relatively rougher surface and higher surface permeability brings less hydroplaning and splashing problem during raining season [49].

It has to be mentioned that depending on the type of WMA additives, the asphalt plant may need little or many modifications. Usually it is decided project by project. Now regions like California (US) and Yunnan (China) have established practical standards for WAR pavement. With the increasing use of WAR and more report about the satisfied results, WAR will most likely be a standard mix for more regions.

8 Future research

Although the binder rheological properties, mixture mechanical performance and interaction mechanism of WARs were reported in the literatures, WAR still deserves further research, like how to recycle the WAR pavement, how to control the interaction of asphalt and rubber by WMA additives and how to optimize the combination of WMA and AR for specific regions. In turns of the control of the interaction between asphalt and rubber by WMA additives, an optimal blending parameter (materials dosage, mixing time/ temperature/rate/sequence) for a typical design of WAR should be developed. Besides, the interaction level among different components should be evaluated by both rheological properties and micro/chemical characteristics. For the combination optimization of WMA and AR for specific regions, decision support methods, such as analytical hierarchy process (AHP), fuzzy comprehensive evaluation (FCE), decision trees, could play a greater role. By these method, service condition of pavement in the specific regions and the effects of combination method on the properties of WAR can be taken into consideration. Furthermore, life cycle cost analysis (LCCA) and life cycle assessment (LCA) are suggested to be conducted to identify WAR pavement with balanced economic and environmental performance. It is also believed that the further investigations on construction technology, maintenance technology and operation parameters will have deeper theoretical and practical understandings for WAR, which could lead to more extensive applications of WAR.

9 Summary

WAR is an ideal paving material which alleviates the environmental concerns of conventional AR mixtures and reduces the tire-road noise. Below lists the noticeable findings of this overview:

1) Warm mix technologies can be used with asphalt rubber mixes. They offset the increase in the mixing and compaction temperatures due to the incorporation of CRM. By enhancing the workability of asphalt rubber mixes, better construction environment can be achieved.

2) WAR binders can be prepared by different

mixing procedures, which has slightly influence on component interaction and binder rheological properties.

3) The mix design of WAR is compatible to AR procedures. In field production, asphalt plants may need little or many modifications depending on types of WMA technologies.

4) Similar compaction levels can be achieved with hot AR and WAR mixtures. The warm mix technologies are unlikely to exert considerable negative influence on the mixture performance of AR.

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Contributors

YU Hua-yang provided the concept and edited the draft of manuscript. YU Hua-yang, DENG Guan-sen, and ZHANG Ze-yu conducted the literature review and wrote the first draft of the manuscript. DENG Guan-sen and ZHANG Ze-yu edited the draft of manuscript. WANG Duan-yi and OESER Markus performed the Project Administration, and Supervision.

Conflict of interest

YU Hua-yang, DENG Guan-sen, WANG Duan-yi, ZHANG Ze-yu, and OESER Markus declare that they have no conflict of interest.

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中文导读

温拌橡胶沥青：一种可持续回收利用废旧轮胎橡胶的途径

摘要：将废旧轮胎橡胶回收利用为沥青改性剂是建筑可持续路面结构的有效途径。该方法具有提高路面耐久性、减少废旧轮胎处理压力、降低路面噪音等优点。温拌沥青技术可有效降低常规热拌沥青混合料混合和压实时的温度。现有研究表明，将温拌沥青技术与废橡胶改性沥青通过不同的方式结合，可以有效降低沥青混合的施工温度，从而减少橡胶沥青在施工过程中的排放量。本文总结了 165 篇文献的研究结果，从流变性能、配合比设计、混合料力学性能、实际应用、施工排放以及橡胶沥青与温拌剂的相互作用等方面分析、比较、总结了近年来国内外对温拌橡胶沥青的研究进展。期望本综述能为温拌橡胶沥青的进一步研究，发展及推广应用提供借鉴。

关键词：橡胶沥青；温拌沥青；和易性；相互作用；力学性能