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Towards a sustainable paving technology

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Review of warm mix rubberized asphalt concrete: Towards a sustainable paving technology

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Abstract:

In recent years, transportation agencies and the general public alike are demanding increased considerations of sustainability in transport infrastructure. Warm mix asphalt (WMA) is developed for reducing energy consumptions and emissions in asphalt paving industry. In addition, the use of rubberized asphalt concrete (RAC) has proven to be economically and environmentally sound and effective in improving the performance of pavements around the world. The combination of WMA and RAC, namely WarmRAC, is a novel and promising paving technology that can realize pavement sustainability from principles to practices. This study summarizes the best practices and recent research findings on warm mix rubberized asphalt concrete, including mix design, construction techniques, performance evaluation, feasibility of recycling, and environmental and economic benefits. Although most research findings to date about WarmRAC are positive, it still has a long way for WarmRAC to be fully adopted worldwide. Therefore, life cycle assessment including environmental and economic impacts, and long-term performance of WarmRAC need further research with involvement of transportation agencies, industry and academia.

Keywords: Warm mix asphalt; Asphalt rubber; Rubberized asphalt concrete; Sustainability; Mix design; Construction

Contents

1 Introduction

1.1 *Background*

The Paris Agreement on climate change, which entered into force on 4th November 2016, is the world's first comprehensive climate agreement. Most governments, including the EU, the US, China and India, have ratified the accord to keep global warming well below 2 °C above pre-industrial levels (Rogelj et al., 2016). The agreement aims to strengthen the ability of countries to deal with the adverse impacts of climate change, foster climate resilience and support sustainable development in parallel (Schleussner et al., 2016).

Among the transportation infrastructure, the road construction, especially the construction of asphalt pavements, is always a large consumer of energy and resource (Romier et al., 2006). In this respect, developing environmental friendly and energy efficient asphalt paving technologies appears to be of great importance. This also coincides with the concept of global sustainable development (Mebratu, 1998; Schleussner et al., 2016). According to a report from the Modified Asphalt Research Centre (Miller and Bahia, 2009), a sustainable pavement may be defined as "*a pavement that minimizes environmental impacts through the reduction of energy consumption, natural resources and associated emissions while meeting all performance conditions and standards*." However, sustainable considerations in paving industry are not new, but in recent years, significant efforts are being made to realize the sustainability of pavement engineering in a more systematic and scientific way.

1.2 *Reasons for coupling warm mix asphalt with rubberized asphalt*

The vast majority of highways and roads are constructed with hot mix asphalt (HMA). It is a consensus that the temperatures for the production of HMA, including manufacturing, transport and laying, should be roughly above 140 °C (Hurley and Prowell, 2006). In order to reduce the emission of greenhouse gases (GHG) and the consumption of fossil fuels during the whole production and construction of asphalt concrete mixes, warm mix asphalt (WMA) has been proposed and implemented in asphalt paving technology without compromising the workability and mechanical performance of the material in comparison to HMA (Prowell D. et al., 2012). WMA are mixes that are manufactured and constructed at lower temperatures (100-140 °C) than HMA varying depending on the different utilized techniques. Besides the benefits of reduced emissions and energy consumption, WMA technologies also provide better working conditions, longer hauling distances, quicker turnover to traffic, an extended paving window, and less restrictions in non-attainment areas, as well as improved workability and compaction efficiency (Rubio et al., 2012).

Compared to WMA, rubberized asphalt has been widely applied in asphalt pavements since as early as the mid 1960's in Arizona (USA) (Epps, 1997). According to the different wet processing technologies (Lo Presti, 2013), rubberized asphalt has various technical terminology, such as Crumb Rubber Modified Binder (CRMB), Asphalt Rubber (AR), Terminal Blends (TB), etc. Specifically, CRMB refers to a general term to identify any bituminous binders that are modified by Crumb Rubber Modifier (CRM). AR is defined as the "wet processed" blend of asphalt cement, recycled tire rubber and certain additives in which the rubber content is at least 15 percent by weight of total blend. TB actually represents a unique mixing technique. TB rubberized binder is typically blended at the asphalt refinery or the "terminal" using finely ground (less than 40 mesh) CRM. On one hand, incorporating crumb rubber from end of life tyres into asphalt for paving applications makes contributions to the disposal of large amounts of scrap tyres, which may lead to potential environmental risks if not disposed properly (Sienkiewicz et al., 2012). On the other hand, rubberized asphalt concrete (RAC) has been proved to have improved aging and oxidation resistance, greater resistance to fatigue/reflection cracking and rutting, lower noise generation, and high skid resistance. The above improved engineering performance eventually leads to improved durability and lower maintenance costs of asphalt pavements (Lo Presti, 2013; Shu and Huang, 2014).

However, due to the incorporation of crumb rubber modifier (CRM), the viscosity of rubberized binder becomes much higher than the conventional binder, leading to higher production and compaction temperatures to achieve the desired workability and density of asphalt mixture (Abdelrahman, 2006; Abdelrahman and Carpenter, 1999). The increased temperature levels will result in not only higher energy consumption but also more asphalt fume and odour emissions, leading to compromised working conditions(Maupin Jr., 1996; NIOSH, 2001). Furthermore, if the compaction temperature is not high enough due to uncertain factors, the use of rubberized mixes will result in inadequate volumetric properties (i.e., higher air voids and uneven density distribution) and poor short-term and long-term performance (Akisetty, 2008). Under these circumstances, coupling rubberized asphalt with warm mix technology will be of great significance. WMA technology is supposed to decrease mixing and compaction temperatures of the rubberized asphalt, making them comparable to or even lower than those of conventional HMAs (Gandhi et al., 2014; Hicks et al., 2010; Oliveira et al., 2013). With synthesized properties of WMA and RAC, warm mix rubberized asphalt concrete (WarmRAC) is supposed to be a sustainable paving technology that integrated of energy conservation, environmental protection, performance optimization and durability extension. This paper summarizes the best practices and the recent research findings on warm mix rubberized asphalt concrete, including mix design, construction techniques, performance evaluation, recycling feasibility, and environmental and economic benefits.

2 Mix design

Currently, the typical mix design methods widely implemented around the world includes the Marshall, Hveem and Superpave methods (Roberts et al., 2002). Asphalt mix design and analysis methods generally consists of four major steps (Wang et al., 2016; Widyatmoko, 2008): (1) materials selection, (2) design of aggregate gradation, (3) binder content and additive dosage (if required) selection, (4) asphalt mix performance evaluation, such as water sensitivity, mixture modulus, rutting resistance, resistance to fatigue and thermal cracking. Steps 2 and 3 are accomplished through various studies of volumetric properties. Most agencies have specific criteria for steps 1 through 3, but specifications of mixture performance vary with the type of mix and geographic location. Based on the literature review (Bonaquist, 2011; California DOT, 2003; D’Angelo, 2008; Rubber Pavements Association, 2012), it can be stated that the majority of both WMA and RAC studies carried out have used mix design processes similar to those of conventional HMA. Notwithstanding, slight modifications may be needed to address the wide range applications of WMA and RAC technologies.

2.1 *Materials selection*

This part focuses on the selection of asphalt binder and aggregates, while the detailed requirements and strategies for selecting crumb rubber and warm mix additives can be found in (Lo Presti, 2013) and (Rubio et al., 2012) respectively.

Generally, the asphalt binder grade is chosen according to the local climate and traffic level without or with less considerations on CRM and warm mix additives. That means using the same graded binder as conventional HMAs. In some asphalt rubber mix plants, proper proportions of extender oil (highly aromatic oil) were added to reduce binder's viscosity and promote mixture's workability (Peralta et al., 2011). It can be deduced that soft base asphalt with higher proportion of aromatic oils conduces to the interaction of rubber and asphalt. However, some research findings (Chowdhury and Button, 2008) recommended to use one grade harder binder with WMA than that normally used with HMA to counteract any tendency for reduced stiffness and increased rutting due to less aging during lower temperature plant mixing and construction. Arega et al. (2011) also suggested the strategy of using recycled asphalt to compensate the reduced stiffness of warm binders. It should be noted that this effect may be also offset by the addition of CRM for its improvement of rutting resistance (Akisetty et al., 2011; Rodriguez-Alloza et al., 2014). Therefore, one should not arbitrarily increase the binder grade in WarmRAC.

Aggregate property requirements for both WAM and RAC will not be different from the requirements for conventional hot mix except for the water absorption of aggregates. Due to the lower production temperature of WMA mixes, the drying of aggregates with high water absorption values may be incomplete (D'Angelo, 2008). It is strongly suggested that asphalt mixing plants adopt stricter limits for water absorption of aggregates to guarantee the construction quality and mixture performance.

2.2 *Mix gradation*

Most utilization of asphalt rubber in hot mixes in the USA and Europe is limited to gap and open gradations (Anderson et al., 2008; California DOT, 2003; Pasquini et al., 2011; Richard et al., 2014). Use of asphalt rubber is not recommended in dense-graded mixtures because there is insufficient void space to accommodate enough modified binder to significantly improve the performance of the resulting pavement to justify the added cost of the asphalt rubber binder. However, with the development of new mixing technique, such as TB, rubberized asphalt binder behaving like polymer modified binder can be applied in various mix gradations. Recently, more and more agencies choose open graded asphalt mixture with rubberized asphalt to obtain a “super quite” and good skid resistance pavement (Partl et al., 2010).

In terms of WMA, almost all types of asphalt mixture (dense graded, stone mastic, porous, mastic asphalt) have been manufactured using WMA technologies (Mansfeld et al., 2009; Prowell D. et al., 2012; Zaumanis, 2010). Most commercial WMA technology companies and highway agencies, who have evaluated any of the WMA technologies in the laboratory and field, have applied them in conventional dense-graded mixtures. However, researchers have made a consensus that WMA processes should be equally applicable to typical types of asphalt mixtures other than dense graded mixes, which have already been proved feasible. Based on previous studies, there were no noticeable differences in the aggregate gradation of WMA and HMA (Hicks et al., 2010; Prowell D. et al., 2012).

According to existing projects that implemented warm mix rubberized asphalt concrete, the main choices of aggregate gradation were open graded and gap graded (Hicks et al., 2010).

2.3 *Optimum bitumen content selection*

In order to achieve WarmRAC with performance characteristics comparable to conventional HMA, it is important to use the same volumetric criteria in the design process of both mixtures. National Centre for Asphalt Technology (NCAT) in the US recommended determining the optimum bitumen content (OBC) using standard HMA design procedures without inclusion of the warm mix additive (Hurley and Prowell, 2005). This is because the WMA additives can enhance the compaction of asphalt mixture effectively, resulting reduced OBC if following the same design procedure of HMA. Reduced OBC brought concerns regarding durability, permeability, water susceptibility and compaction of the resulting asphalt mixture. However, the OBC of RAC was normally slightly higher than that of control HMA. In California, the OBC of rubberized asphalt concrete was determined by a multiplication factor of 1.25-1.4 to the OBC of control HMA without considering warm mix additives

(Hicks et al., 2010). Therefore, the OBC of WarmRAC should be determined using rubberized binder without warm additives.

2.4 *Laboratory performance evaluation*

Although the test and analysis of WarmRAC should follow the same test routines and criteria of conventional HMA, some modifications should be made for the laboratory specimen preparation due to the potential complex components of rubber and warm mix additives which may be sensitive to temperature or other environmental conditions.

2.4.1 Conditioning/curing of test samples

Conventional HMA samples are often reheated for a variety of volumetric acceptance and performance evaluation tests. In NCHRP reports (Bonaquist, 2011; NCHRP, 2012, 2014), it was found that reheated samples of WMA mixtures can be used for mechanical tests as HMA. However, it was not recommended to use reheated WMA samples for volumetric acceptance due to potential irreversible components in warm mix additives or foamed asphalt. In terms of RAC, it is well known that the interaction between asphalt and rubber is time and temperature dependent. Reheating samples of RAC may cause potential physical and chemical reactions of rubberized binder, such as swelling, devulcanization and depolymerisation (Billiter et al., 1997; Zanzotto and Kennepohl, 1996), which may influence both mechanical and volumetric properties. As with conventional HMA, reheating times and temperatures for both WMA and RAC should be limited to minimize the additional aging and interaction effect.

2.4.2 Adjustment of testing equipment

The Superpave performance grade system brought new testing equipment and procedures for asphalt binder testing and specification, which were not originally developed to evaluate asphalt modified with particulate matter such as crumb rubber (Bahia et al., 1998). For example, the Dynamic Shear Rheometer (DSR) test procedure requires a maximum particulate size less than one quarter of the gap size (FHWA, 2014). That means the typical crumb rubber particle size used in asphalt binder should be less than 250 μm for DSR tests with 1 mm gap between plates. Otherwise, the rubber particles with larger sizes may touch the top or bottom plate, which will not represent the real properties of rubberized binder. Hopefully, the Federal Highway Administration (FHWA) has undertaken some work on developing new testing geometries that will allow evaluation of asphalt binders with even larger particulate sizes. Baumgardner and D'Angelo (2012) developed a new DSR testing geometry-a "cup-and-bob" geometry that uses a 27-mm cup and 14-mm bob to give a 6.5 mm effective gap size. A photograph and a graphic drawing of the testing geometry are shown in Fig. 1. This gap size is more than enough to accommodate the swelled crumb rubber particles. Their preliminary results indicated that the cup-and-bob geometry can replace the Superpave 1-mm gap parallel-plate geometry and accommodate large CRM particles, providing similar results for Superpave test. Besides, due to potential segregation of the rubber particles, especially for coarse rubber particles, it is difficult to prepare test samples with the same proportion and identical dispersion of crumb rubber (Bahia and Davies, 1994). According to the authors' experience, it is difficult to take the representative CRM modified binder after Rolling Thin-Film Oven (RTFO) aging from the jar. Therefore, it is of great importance to stir the liquid asphalt rubber uniformly before pouring and moulding samples to minimize the variability. Duplicate test samples are highly recommended.

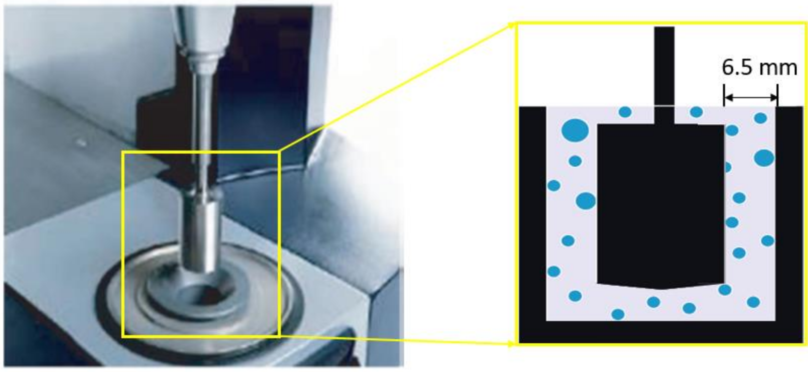

Fig. 1. Cup-and-bob setup geometry (Baumgardner and D'Angelo, 2012)

2.4.3 Additional workability tests

It has been shown that viscosity reduction is not the primary mechanism of WMA allowing for the reduced asphalt paving temperatures (Hanz et al., 2010). Reinke et al. first introduced the concept of binder lubricity and internal friction reduction as the fundamental mechanism of WMA technologies (Baumgardner and Reinke, 2013; Reinke et al., 2010, 2014). The WMA additives increase the lubrication properties of binder to reduce the efforts required for aggregates to move past each other during compaction. The lubrication effects of WMA technologies on asphalt binder were investigated through a novel use of conventional DSR with a newly designed testing fixture (Hanz et al., 2010) according to ASTM D5183-05, which is called asphalt lubricity tester as shown in Fig. 2. Another tribology fixture set-up for thin-film asphalt testing was developed by Baumgardner and Reinke based on the ball-on-pyramid principle (see Fig. 3). Above two asphalt tests will provide a more mechanistic understanding of the mechanism and workability of warm asphalt binder. Eventually, asphalt lubricity test can be used for warm-mix additives selection and estimation of the temperature reduction for a specific content of additive (Bennert et al., 2010; Hanz and Bahia, 2013).

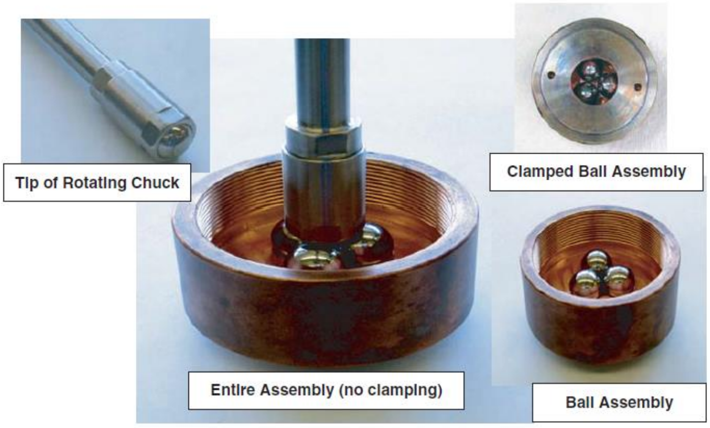

Fig. 2. Photographs of asphalt lubricity tester (Hanz et al., 2010)

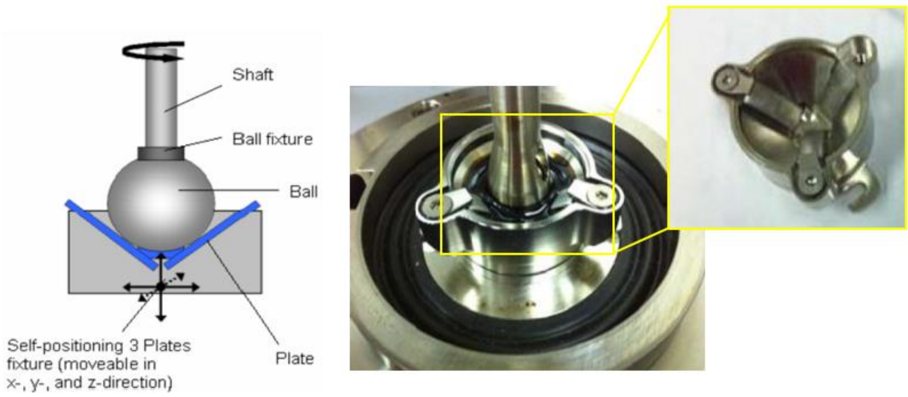

Fig. 3. Cup and plate assembly for the tribology fixture (Baumgardner and Reinke, 2013)

Since viscosity-temperature relationship used in the design of HMA cannot be used with the wide range of WMA processes currently available, additional design procedures should be carried out to evaluate the workability of WMA mixtures (NCHRP, 2012). Aggregate coating at the planned production temperature should be conducted following the standard AASHTO T195 procedure. In terms of compactability or workability of WMA mixtures, gyratory compaction indices at planned compaction temperature (Hanz et al., 2010), including gyrations required to reach 92% theoretical maximum density (G_{mm}) (N92) and construction force index (CFI) using the pressure distribution analyser (PDA) plate on top of the mixture, were adopted as the workability indicators. Besides, a torque tester (Tao and Mallick, 2009), which can determine the required torque to move a paddle through mix inside a bucket at different conditions, was also verified as an efficient tool to evaluate the workability of mixture.

2.5 *Summary*

Generally, the same mix design methodology and evaluation criteria of conventional HMA should be implemented to WarmRAC. However, these rules are not necessarily suitable for every WarmRAC product. Slight modifications should be made based on the used specific technology and material.

3 Construction techniques

3.1 *Temperature issues*

Production and construction temperatures are of foremost importance for both WMA and RAC. Rubberized asphalt materials need higher production and construction temperatures due to higher viscosity. Surface and probe type thermometers and heat guns are recommended for the plant and field inspectors to measure ambient and inside temperatures of rubberized asphalt mixtures (California DOT, 2003). Since temperature is one of the crucial factors that influence the storage stability of asphalt rubber (Ghavibazoo et al., 2013), the temperature of asphalt rubber blending and storage tanks should also be monitored with readily accessible thermometers.

In terms of WMA, there are increasing evidences that viscosity reduction of binder is not the only mechanism that allows for reduced production temperatures for mixtures (Baumgardner and Reinke, 2013; Hanz et al., 2010). Binder lubricity is also a crucial factor that influences the asphalt mixing and compaction temperature. Therefore, instead of using viscosity based temperatures, the optimum production and compaction temperatures should be determined directly with the aim of achieving a full coating of the aggregates. In addition, in some foaming processes, it is very difficult to directly measure the viscosity of the binder. Accordingly, the German Asphalt Pavement Association (Mansfeld et al., 2009) developed a method through comparing the bulk density of WMA to the reference HMA to determine the optimal production and compaction temperatures.

Apart from these, it is important to keep baghouse temperature high enough to prevent condensation in WMA production. Condensation causes corrosion of the baghouse and formation of damp baghouse fines or clogging. Several strategies suitable for increasing baghouse temperatures were summarised by NAPA (Prowell D. et al., 2012), including removing veiling flights, increasing air flow, using duct heater, installing variable frequency drive, insulating dryer shell, baghouse and ductwork, and reducing stockpile moisture content.

When producing WarmRAC in plants, rubberized asphalt binder was prepared first at high temperatures before it was added to the mixing drum. Then warm mix additives were mixed with aggregates and rubberized asphalt binder. According to limited documentations (Hicks et al., 2010), warm mix additives were not involved in the production of rubberized asphalt binder. However, warm mix additives reduce the production and compaction temperatures of WarmRAC. Field attempts to incorporate warm mix additives in the phase of preparing rubberized binder are highly recommended (Yu et al., 2017).

3.2 *Production rate*

Both WMA and RAC encounter reductions of production rates in asphalt plants. As mentioned in above section, condensation may happen during the WMA production, lowering the maximum production rate. In addition, it was reported that when adding chemical foaming additives, there were problems with the nozzles plugging, which in turn limits the production to a low rate (Chowdhury and Button, 2008). Comparing to conventional HMA rates, RAC production rates may be reduced somewhat due to increased plant mixing time (higher binder content) and additional asphalt rubber binder production time. Fortunately, proper planning and coordination between the material supplier and the asphalt plant operator can minimize the impacts on asphalt concrete production rate.

3.3 *Compaction*

In general, the same compaction equipment and procedure used for HMA are suitable for WMA. Also, it is easier to obtain target compaction density of WMA mixes compared to HMA mixes, even with less compaction effort. During compaction of RAC mixes, rubber-tired rollers are not allowed because asphalt binder tends to stick to cold tires severely. Rollers for RAC compaction must be steel-wheeled (drum) and equipped with pads and a watering system releasing agents to prevent excessive pick-up (asphalt binder sticking to tires) (Maupin Jr., 1996; Rubber Pavements Association, 2012).

3.4 *Summary*

Specific addition technologies and plant modifications of WMA are rather dependent on the specific products, which can be found in Zaumanis's thesis (Zaumanis, 2010) and (Prowell D. et al., 2012). From the construction standpoint, WMA is an aid to RAC regarding production and construction temperatures, and compaction efficiency to achieve desired mixture density. Construction techniques for WarmRAC should be integrated of concerned modifications of both WMA and RAC.

4 Performance of WarmRAC

Although there is not a standard practice addressing performance testing of asphalt concrete, several performance tests have been developed and have received high level of acceptance by both academia and industry. Performance tests are available for measuring mixture stiffness/modulus, water sensitivity, rutting resistance, and resistance to fatigue cracking and thermal cracking (McCarthy et al., 2016). Since WMA is a relative new technology, and combination of WMA and RAC only happened in most recent years, little is known about the long-term performance of WarmRAC. In this regard, most of the performance evaluation tests came from laboratory tests, few full-scale accelerated pavement tests and practical trial projects.

4.1 *Laboratory tests*

4.1.1 Warm rubberized asphalt binder

In the previous studies, the individual effect of crumb rubber modifier (CRM) and warm-mix additives on the asphalt has been extensively investigated. It was shown that the interactions of asphalt and rubber and their effects on the final properties of crumb rubber modified asphalt (CRMA) depend on the raw material parameters (e.g., asphalt composition, CRM type, particle size and dosage) and interaction conditions (e.g., mixing temperature, time and rate, energy type of the mechanical mixing exerted) (Abdelrahman, 2006; Airey et al., 2011; Shen and Amirkhanian, 2007). The interaction mechanisms involved in the production of CRMA binders are generally categorized as two types: rubber particle swelling and degradation (devulcanization and/or depolymerization) in the binder matrix (Abdelrahman and Carpenter, 1999). The incorporation of CRM into asphalt binders was reported to improve the overall pavement performance, e.g., higher resistance to rutting, ageing, fatigue and thermal cracking (Shu and Huang, 2014). It also increases the skid resistance of pavements and reduces the traffic noise (Rymer and Donavan, 2005), which provides a safe and comfortable driving condition. The effect of WMA technology on the performance of asphaltic materials varies with the type of WMA technology used. WMA technologies can be categorized as three main types (Rubio et al., 2012): foaming processed, organic (wax-based) additives and chemical additives. However, the influence of WMA additives on the crumb rubber modified asphalt binders has not yet been clearly identified. The interactions between asphalt and rubber as well as the WMA additives have a significant impact on the mechanical performance and durability of warm-mix rubberized asphalt pavements. Because of the complicated relationship between the individual components of warm-mix rubberized asphalt mixture, it is essential to understand their interactions in the rubberized binders before applying them to the mix design level. The interaction between asphalt, rubber and warm-mix additives will be discussed from the aspects of rheology and chemo-physical characterization.

4.1.1.1 Rheological properties

Akisetty et al. (2011); Akisetty et al. (2010); Xiao et al. (2009) did very comprehensive laboratory tests of warm CRM binders. The rubberized binders were produced using PG 64-22 binder with ambient ground rubber of 40 mesh size and 10% by weight of binder. Then two types of warm mix additives (Aspha-min, Sasobit) were added to the rubberized binders to prepare warm CRM binders. They found that the addition of WMA additive into rubberized binder is beneficial for improving the rutting resistance of both the unaged and aged binders based on increased G*/sinδ values, while adverse to the fatigue cracking resistance based on higher G*sinδ values. Moreover, the rubberised binders with Sasobit were found to have significantly higher stiffness and lower *m*-value properties, which relate to a negative effect on the low-temperature cracking resistance. However, the addition of Aspha-min did not statistically affect the low temperature performance of rubberised asphalt binders. In terms of viscosity, different warm additives have different effects on the viscosity of rubberized binders. For instance, viscosity was increased at both 135 °C and 120 °C with Aspha-min, and decreased with Sasobit compared to control binders (Akisetty et al., 2009). This is mainly due to the different components of various additives. Rodríguez-Alloza et al. (Rodriguez-Alloza et al., 2013; Rodriguez-Alloza et al., 2014) further verified this conclusion that the incorporation of any of the four used organic additives reduces the viscosity of the CRM binder.It is noteworthy that CRM binders with organic WMA additives have a peculiar and complex mechanical response, which is related to the changeable crystalline properties of the wax at different testing temperatures (Rodríguez-Alloza et al., 2016). Therefore, some contradictory results of CRM binders with wax may be found in previous studies. In contrast to the finding that most wax-based warm additives can increase the rutting performance of binders, Yu et al. (2017) found asphalt rubber binders with chemical additive Evotherm-DAT provided poor high-temperature performance but similar intermediate and low-temperature performance compared to control asphalt-rubber binders.

University of California Pavement Research Center (UCPRC) evaluated the binder field aging properties of hot and warm mix rubberized asphalt. Through DSR and BBR tests of extracted and recovered binders from field-aged pavements, it was found that the warm mix technology chemistry had insignificant effects on the test results (Farshidi, Frank et al., 2013). However, the binders containing organic wax additive consistently showed better rutting resistance, and this was attributed to the residual crystallization wax structure in the binder. BBR results indicated that the WMA technologies tested did not result in a grade change with respect to thermal cracking properties at low temperatures. The warm-mix additives and associated lower production and placement temperatures generally had limited effect on aging kinetics with respect to long-term field aging, except for the organic wax.

The degree to which each of above mentioned properties are changed depends on the amount of crumb rubber, rubber size, warm additives type and content, and asphalt binder source. Therefore, Yu et al. (2012) suggested that the tailored parameters of preparing warm mix rubberized asphalt product should be determined based on the specific environmental and project condition.

4.1.1.2 Chemo-physical characterization

Yu et al. (2014) analysed the rheological modification mechanism of warm mix additive Evotherm-DAT on CRM asphalt binder using a series of advanced testing equipment. Through microscopic and chemical component analyses, no complex chemical reaction was found between Evotherm-DAT and CRM binder. However, the colloidal structure and rheological properties of CRM binder were changed by Evotherm-DAT through affecting the aggregative state and intermolecular forces of rubber particles within the CRM binder. Rodríguez-Alloza et al. (2016) found that the addition of organic WMA additive (wax) makes CRM binder more elastic, as displaying decreased phase angles in DSR tests. They also pointed out that there is a quite complex reaction between CRM binders and waxes, which relates to the melting/crystallizing properties of the wax and the residual crystallinity into the binder blend. Through thermal analysis, Yu et al. (2016) found that n-alkanes from wax-based warm mix additives not only interact with asphalt components to reduce viscosity but also penetrate into CRM particles during the mixing process. Moreover, the conventional wax (56# paraffin) with shorter carbon chain has better interactions with CRM than the commercial wax-based additive (Sasobit), which can promote the release of synthetic rubber from rubber particles. Based on the above findings, it is recommended to incorporate warm mix additives especially the wax-based additives at an earlier stage. This will not only promote the component exchange (interaction) between rubber and asphalt, but also has the potential to reduce energy consumption through decreasing the interaction temperature and time between rubber and asphalt. However, this statement needs to be verified with field practice.

4.1.2 Warm mix rubberized asphalt concrete

Although the increase in the mixing and compaction temperatures due to the addition of crumb rubber can be offset comparable to conventional HMA by adding the warm asphalt additives, different warm-mix additives exhibited inverse effects on the long-term fatigue performance. The fatigue life of the mixtures made with crumb rubber and Sasobit® is greater than the control mixtures, while rubberized mixtures containing Aspha-min® has a lower fatigue life in terms of beam bending fatigue tests (Xiao et al., 2009).

Akisetty (2008) found that regardless of aggregate source, the addition of warm mix additives into rubberized mixtures increased the percentage of voids filled with asphalt (VFA) and decreased the percentage of voids in the mineral aggregate (VMA). This finding indicates the incorporation of warm-mix additives increase the density or compaction degree of the rubberized mixtures. Furthermore, results in his research showed that the engineering properties, such as indirect tensile strength, rutting depths, resilient modulus, of rubberized mixtures containing the warm-mix additives are not significantly different from control rubberized mixtures. This conclusion verifies that it is possible to incorporate WMA technologies into crumb rubber modified asphalt mixtures without having a negative effect on the mixture properties. Oliveira et al. (Oliveira et al., 2013) also obtained similar results that the production temperatures of rubberized mixtures can be reduced by 30 °C with the incorporation of small amounts of a surfactant based warm mix additive. In addition, mixtures with surfactant additives have comparable performance as traditional rubberized asphalt mixtures and show lower water sensitivity through increasing the bonding between asphalt and aggregates. Rodríguez-Alloza and Gallego (2017) manufactured asphalt rubber mixtures with two organic waxes (Sasobit® and Licomont BS100®) at temperature that are 10~30 °C lower than control asphalt rubber mixtures. Mechanical performance evaluation of asphalt mixtures showed that waxes enhanced the permanent deformation resistance and maintain the fatigue performance, but slightly decreased the moisture damage resistance. Yang et al. (2017) conducted a comprehensive evaluation on the mechanical performance of crumb rubber modified WMA with Evotherm and crumb rubber modified HMA. Results from both laboratory compacted samples and field collected samples showed that rubberized WMA had equivalent rutting resistance and low temperature performance compared to rubberized HMA. However, due to the anti-stripping agents in WMA additive Evotherm, rubberized WMA exhibited better fatigue performance and moisture damage resistance than rubberized HMA.

4.2 *Full scale accelerated pavement tests*

California probably did the most comprehensive research on the full-scale trial tests regarding WarmRAC (Hicks et al., 2010). The test tracks located at the University of California Pavement Research Center in Davis, California, were designed and constructed using gap-graded rubberized asphalt concrete with various WMA technologies (Jones, 2013; Jones, David et al., 2011; Jones, David et al., 2011). Accelerated load testing with a Heavy Vehicle Simulator (HVS) was used to assess rutting behaviour and long-term performance. In addition, laboratory tests on specimens sampled from test tracks to assess rutting, fatigue cracking performance and water sensitivity were carried out. Through nuclear gauge determined density measurements, it was confirmed that adequate compaction can be achieved on WarmRAC at lower temperatures. However, roller operators were recommended to adjust rolling operations and patterns according to the different rolling responses between warm mixes and conventional hot mixes. HVS tests showed that WarmRAC has equal and potentially better rutting performance than hot mix. Laboratory test results indicate that WMA technologies had insignificant effect on the mixture performance when compared to control specimens. In view of the above findings, they concluded that there are no results to suggest WarmRAC should not be used in California.

4.3 *Practical trial projects*

From 2007 to 2010, various warm-mix asphalt test sections were constructed in California to assess long-term performance under specific climate and traffic conditions. Table 1 lists the main projects using WMA technologies with asphalt rubber in California and other states (Hicks et al., 2010).

Table 1 Selected warm mix rubberized asphalt concrete projects constructed in the USA

Location	Paving date	WMA technology	WMA additive content (by mass of binder)	Mix type	Production temperature (°C)	Placement temperature (°C)
Santa Clara	March 2006	Sasobit	-	Gap graded	138	-
Massachusetts	August 2008	Advera	3.85%	OGFC	143-149	135-143
Santa Nella	September 2008	Astec DBG & Evotherm	-	Gap graded	132	-

Orland	May 2009	Evotherm	0.5%	OGFC	143	120
San Diego	June 2009	Advera, Evotherm, Sasobit	-	OGFC	-	132
Marysville	July 2009	Evotherm	0.5%	OGFC	150	130
Humboldt	September 2009	Evotherm	-	Gap graded	121	-
Sutter County	November 2009	Evotherm	0.5%	OGFC	-	110
Auburn	August 2010	Evotherm	0.5%	OGFC	150	135

Monitoring included a visual assessment from the road shoulder and a photographic record without any physical measurements. According to the observation results, the road shoulder still looked good after 2-4 years' service, and most of the sections performed well with no sign of distress. Some early minor rutting of the warm mix section was found in the first half year in Orland due to less binder aging. However, rut depths on both warm-mix and control sections were almost identical after one year traffic loading since the oxidation had stabilized (Jones, 2013). Warm-mix technologies provided improved workability of the mix and better compaction, which could prevent early ravelling and improve durability eventually. Besides, Warm mix technologies extend the application range of rubberized asphalt concrete in terms of extended paving season, longer hauling distances and less geographical restrictions of asphalt plants. Many contractors stated that they were eager to continue using WarmRAC in the future projects (Hicks et al., 2010).

4.4 *Summary*

From both laboratory and full-scale tests, the performance of WarmRAC is comparable to conventional HMA, and even better in terms of rutting resistance and fatigue performance. However, long-term performance of WarmRAC should be monitored and evaluated with the cooperation and coordination of different agencies, industry and academia.

5 Feasibility of recycling WarmRAC

Apart from in-service performance and durability, related transportation agencies and contractors also concern a lot about the recyclability of the constructed roads. Since warm mix rubberized asphalt concrete is a relatively new technology, currently, there is no related literature about the recycling of WarmRAC. As mentioned before, WMA technologies are mainly used for lowering the production and construction temperature of asphalt mixes, and they don't contain any potential hazardous or intractable components during the traditional recycling process. Therefore, the main concern about feasibility of recycling WarmRAC should be laid on the recyclability of crumb rubber modified paving materials.

In 1993, a report (USDOT and USEPA, 1993) to U.S. Congress mentioned that the New Jersey Department of Transportation conducted a study incorporating recycled dry process CRM asphalt pavement into a paving project to assess the concern of the recyclability of asphalt pavements containing ground tire rubber. The report acknowledged that no modifications were required to the drum plant and all production procedures were normal from producing the recycled rubberized mixtures. In addition, air quality testing performed for this project shows that materials can be recycled within current air quality standards.

In 2005, California DOT surveyed several DOTs that had recycled rubberized asphalt concrete in limited and valuable experiments or demonstration projects (California DOT, 2005). The respective studies included different types of RAC (i.e. wet process and dry process). Some common featured findings of these experiments included:

• Reclaimed RAC could be used in plant mixing to produce recycled mixes.

• The recycled RAC mixtures could be placed and compacted using conventional equipment and practices without any problems.

• The recycled RAC pavements typically have comparable performance to virgin pavements.

• Results of tests on AC plant emissions and worker exposure conducted during production and placement of recycled mixes including reclaimed RAC paving materials do not indicate adverse impacts on health and safety.

Environmental testing did by Texas Transportation Institute (Crockford et al., 1995) also showed there was very little difference between the emissions from RAC and standard asphalt plants. Detailed information about environmental emission analysis will be discussed in the next section.

From above results, it can be found that the evaluation criteria of the recyclability of one paving material generally include: (1) whether the material can be produced and constructed using conventional production and paving equipment without major modifications; (2) whether the pavement performance containing recycled material meets the requirements of related standards; (3) whether the recycling of the material has negative environmental impacts. The results from respective DOT’s studies indicate that a wide range of RAC paving materials have been successfully recycled, which supports the feasibility of recycling WarmRAC.

6 Environmental analysis

6.1 *Potential environmental effects of RAC pavements*

As many documents demonstrate that incorporation of crumb rubber from scrap tires into asphalt pavements is an effective way to solve the disposal issue of used tires, it also brings potential environmental issues due to the complex components of waste tire and bitumen. Specifically, air quality and occupational exposure might be adversely affected during the production and construction process, and water quality might be affected by the leachates from RAC pavements. One should note that the environment here is a generalized concept, which contains both natural environment and human beings.

6.1.1 Air quality and occupational exposure

Every day there are millions of workers working with asphalt related materials, either in asphalt/roofing plants, or in the road paving sites. It was estimated that workers are exposed to asphalt fumes during almost 40% of their working hours, which may bring potential health concerns (USDOT and USEPA, 1993). The earliest systematic research on the health effects of occupational exposure to asphalt dates back to 1977. In 1977, the U.S. National Institute for Occupational Safety and Health (NIOSH) reviewed the available data on hazardous environmental effects during asphalt paving and recommended an exposure limit for asphalt fumes of 5 mg/m^3 measured as total particulates during any 15-minute period (NIOSH, 2000). With the massive applications of RAC pavements in U.S., both industry and labour have concerns over inadequate information on the environmental and human health effects resulting from RAC pavements. Driven by the U.S. Environmental Protection Agency (EPA), NIOSH cooperated with FHWA to evaluate occupational exposures of CRM asphalt and conventional asphalt among asphalt paving workers at seven paving projects from 1994 to 1997 (NIOSH, 2001).

Air samples from both area air (highway background) and personal breathing zone (paver hopper, paver screed and roller) were collected and analysed following specific NIOSH or EPA testing protocols. The sampling and analytical methods, as well as the findings in the evaluation are summarised in Table 2.

Only TP and BSP can be comparable to existing occupational exposure limits. Benzothiazole (Ghosh et al., 2003), an accelerator used in the vulcanization process for rubber, was found primarily during CRM paving. This chemical is also a useful indicator in the analysis of complex CRM asphalt fumes and leachates. Results from both area air and personal breathing-zone (PBZ) samples indicated exposures to a variety of analytes (TP, BSP, PACs, OSCs and benzothiazole) were generally greater during the rubberized asphalt paving than the conventional one. Among paving crews, truck dumpers, paver and screed operators suffer the highest PBZ exposures. Fortunately, as shown in Table 2, the concentrations of volatile organic compounds (VOCs, including toluene, xylene, MIBK) were generally less than 1 part per million (ppm), which means well below their respective occupational exposure limits (NIOSH, 1992). Overall, although test results showed that some analytes' concentrations of CRM exposures are higher than conventional exposures, there were no definitive results indicating that CRM exposures are more hazardous than conventional exposures. Therefore, this latest report does not recommend any changes to the 1977 NIOSH criteria for recommended exposure standards.

Table 2 Summary of sampling and analytical methods for characterizing asphalt fumes

Evaluation substance	**Analytical methodology**	**Findings**
Total Particulate (TP)	NIOSH Methods 0500 and 5042	Below 1.5 mg/m^3
Benzene Soluble Particulate (BSP)	NIOSH Method 5042	Below 0.5 mg/m^3
Respirable Particulate (BP)	NIOSH Method 0600	-
Polycyclic Aromatic Compounds (PACs), Organic Sulfur Compounds (OSCs), and Benzothiazole	NIOSH Method 5800	Higher concentrations than conventional exposure
Elemental/Organic Carbon	NIOSH Method 5040	Higher concentrations above the screed auger.
Volatile Organic Compounds	NIOSH Methods 1300, 1301,	Higher concentrations at CRM

(VOCs, including benzene, toluene, xylene, MIBK)	1501 and 1550 Tekmar thermal desorber Gas chromatograph/mass spectrometry (GC/MS) detector	asphalt paving site; Well below occupational exposure limits (except for benzene). Benzene concentrations ranged up to 0.77 ppm
H_2S, SO_2, CO, and ozone	Toxilog® diffusion monitors CEA® TG-KA Portable Toxic Gas Detector	Very low concentrations of H_2S, SO_2, and ozone at both CRM and conventional paving sites. Higher concentration of CO
Mutagenicity Assay	Teflon® sampling filter Tester strains TA98 and TA100	None of the asphalt fume samples are mutagenic.

6.1.2 Water quality

During the wet seasons, the rubberized paving materials have the potential to leach out complex chemical constituents, which would possibly be transported to adjacent water bodies (Azizian et al., 2003). Due to the constitutive complexity of crumb rubber and asphalt binder as well as the uncertain interaction between them, the leachates often contain a mixture of organic and metallic contaminants (Li et al., 2010). According to NCHRP Report 443 (NCHRP, 2000), leaching from a wide range of highway construction material use can be modelled as six different reference environments, including permeable highway surface, impermeable highway surface, piling, borehole, fill, and culvert. In order to evaluate the important processes that affect the chemical composition, aquatic toxicity, and fate of leachates from RAC in highway applications, Azizian et al. (2003) applied a validated chemical and toxicity evaluation methodology to assess the leaching behaviour of RAC pavements in highway environments. Through short-term and long-term batch leaching test, and flat plate leaching test, the information on the mobility of constituents in RAC materials under a range of conditions and further estimates of expected leachate chemical concentrations were obtained. After a series of laboratory tests, aluminium, mercury and benzothiazole, were detected in the leachates at concentrations of about 1.5, 0.02, and 0.54mg/l, respectively. However, these contaminants from leachates were proven to be degraded or retarded to completely nontoxic by some natural (removal/reduction/retardation (RRR)) processes during their transport through nearby soils and ground water due to mass transfer effects. Soil sorption is the most important removal/retardation process for benzothiazole, aluminium, and mercury. Volatilization and biodegradation have significant effects on the concentration reduction of benzothiazole by about 90%, while photolysis does not affect the benzothiazole concentration. After referring to some related environmental standards, they concluded that leachates from highway material (including RAC paving material) have little or no impact on the aquatic environment, which cannot be qualified to be hazardous (NCHRP, 2001). An independent environmental testing did by Texas Transportation Institute (Crockford et al., 1995) also showed that trace metals, volatile organics, and semi-volatile organics may be leached from asphalt rubber, but all at levels too low to be environmentally significant or hazardous under current guidelines.

6.2 *Environmental benefits of WMA technology*

Reduction in GHS emissions is the most significant benefit associated with WMA production. According to the different WMA application stages, environmental benefits from WMA production can be divided into two subcategories-direct and indirect emission reductions. The direct emission reduction comes from the energy savings in asphalt plants and paving sites due to the significantly reduced asphalt concrete production and construction temperatures offered by WMA technologies. A laboratory study on carbon dioxide emission (CO_2) from warm mix asphalt binder found that temperature is the only statistically significant factor on emissions (Mallick and Bergendahl, 2009). For the stack emissions sites, a 21% reduction in fuel usage and a 20% reduction in CO_2 emissions can be obtained through an average 52 °C reduction in asphalt mixture temperature (NCHRP, 2014). Therefore, it can be deduced that lowering the asphalt mix temperature is the most effective way to reduce CO_2 emissions. Results from Rubio et al. (2013) showed that half-warm mix asphalt (HWMA) which was manufactured at temperatures lower than 100 °C considerably reduce combustion gases emission (58% for CO_2 and 99.9% for SO_2) and particles emitted into the atmosphere. Regarding PAH (polycyclic aromatic hydrocarbon) and VOC emissions of HWMA, the concentrations of these compounds were very low or undetectable. Although this study is with respect to HWMA, it is also meaningful and valuable to WMA. Generally, the actual reduction depended on the condition of the plant, type of fuel, weather conditions during production, and the type of technology used (Zaumanis, 2010).

Apart from the direct emission reduction during asphalt production, several other benefits of WMA technology promise indirect related emission reduction. For instance, less aging of asphalt binder during lower production and placement temperature tends to improve the resistance to fatigue and thermal cracking of asphalt pavements (Kristjansdottir, 2006). In addition, the lowering of bitumen viscosity enhances the workability and compaction of the mix, also thus allows the incorporation of a high percentage of Reclaimed Asphalt Pavement (RAP) (Doyle et al., 2011; Tao and Mallick, 2009), and wider applications of CRM asphalt pavement at relatively low placement temperatures (Oliveira et al., 2013). Adding both RAP and CRM into WMA mixtures will yield more significant environmental benefits.

More importantly, lower emissions of asphalt fumes/aerosols improve safety and working conditions for paving crews as shown in Fig. 4. The Ministry of Transportation of Ontario (Canada) (Politano, 2012) found that comparing to HMA, WMA technology reduces dust, benzene soluble fraction (BSF) behind the paver and at the location of the paver operator significantly, and increases the transparency value of paving sites to about one third of that of HMA at both locations. According to Olard et al. (2007), the proprietary low-energy asphalt techniques enabled a reduction of both energy consumption and GHG emissions to nearly 40%. For paving projects that are not in open air (e.g. tunnels), the decrease of occupational exposure to emissions is magnified. With better working conditions, labour productivity and retention will be improved.

Fig. 4. Fumes from HMA (left) and high transparency from WMA (right) (Jones, 2013)

6.2.1 Case study of WarmRAC

The most related study with respect to emission of WarmRAC was finished by UCPRC (Farshidi, F. et al., 2013). As reported by Kumar and Viden (2007), some personal sampling devices used for detecting TP and BSP did not reflect the actual paving conditions. Emissions from asphalt maybe influenced by passing traffic and paving equipment itself. To overcome these limitations, a portable flux chamber was designed and built by UCPRC for collecting emissions exclusively in the fields (Farshidi, F. et al., 2013). Through various laboratory tests on the asphalt fume extractions from samples, VOCs, SVOCs and PAHs were identified and quantified. Results show that in most instances, total alkane emissions produced in the warm mixes are significantly lower than that in the hot mixes (e.g., 117 $\mu g/m^3$ from WMA compared to 2,516 $\mu g/m^3$ from the HMA control). PAH concentrations is related to initial mix production temperature, with warm mixes produced at lower temperatures show lower PAH concentrations.

Yang et al. (2017) conducted the stack emission test which monitored six types of hazard emissions (formaldehyde, naphthalene, total xylene, ethylbenzene, toluene, and benzene) from control HMA, rubberized HMA and rubberized WMA. Results showed that rubberized HMA exhibited a visibly higher emission than control HMA due to the addition of CRM. Fortunately, some of the increased hazardous emissions were offset with the application of Evotherm WMA technology.

6.3 *Summary*

Application of rubberized asphalt mixtures in pavements can generate potential negative effects to both air and water quality, but all within the related environmental exposure limits. WMA technology can significantly reduce gas emissions during the production and construction. With the incorporation of WMA, the negative influence of RAC pavements to environment will be minimized. Temperature is the most significant factor that affects the emissions during construction. Therefore, determining the optimal temperature range will minimize emissions concentrations without undermining performance properties of WarmRAC. Besides, a multifunctional WMA product that incorporates asphalt fume retardant (Xiao et al., 2010; Xu et al., 2013) will have great market potentials.

7 Economic analysis

7.1 *Life-cycle cost of RAC technology*

Many documented publications reported concerns on the higher initial cost of crumb rubber modified asphalt pavements when compared to conventional ones, which stems from the add-on cost of scrap tires, manufacturing cost and potential equipment modification. However, it is more scientific and reasonable to analysis the cost effectiveness in a life-cycle manner instead of only considering the initial capital cost. The life cycle analysis (LCA) of asphalt pavements is usually divided into four phases (Huang et al., 2009): production of raw and mixed materials, placement and construction, maintenance and repair, and demolition or recycling. Studies show that RAC is more cost effective than conventional asphalt mix based on annual equivalent costs, capital costs and layer equivalencies (Hicks and Epps, 2000; McQuillen Jr et al., 1988). This conclusion is supported by the improved performances (e.g. higher stiffness, aging resistance, fatigue and thermal cracking resistance, etc.) of RAC, which in turn make rubberized asphalt pavement with reduced layer thickness, extended service life, and lower maintenance cost. According to McQuillen Jr et al. (1988), the required thickness of a RAC surface layer can be reduced by 1.2 to 1.4 times compared with the conventional mix if using the allowable tensile strain based equivalency factors. Furthermore, under the same life cost of conventional asphalt concrete surface which lasts 15 years, RAC pavements with equal layer thickness would have a life span of approximately 20 to 23 years. It should be noted that life-cycle costs here do not include potential intangible benefits of rubber-modified pavement system, such as value-added disposition of scrap tires, increased skid resistance and noise reduction. Nevertheless, RAC is not cost effective in all applications. Therefore Hicks and Epps (2000) suggested using life cycle cost analysis to determine where and when to use RAC in a more economical way.

7.2 *Fuel savings of WMA technology*

WMA also encounters similar dilemma of higher initial cost than HMA as RAC. The additional costs of WMA comparing to HMA come from costs of WMA additives, potential asphalt plant modification, and technology licensing costs (Kristjánsdóttir et al., 2007).

Studies show that energy savings has similar proportions as the reduction in GHG emissions during WMA production (Kristjansdottir, 2006). The degree of the reduction in energy consumption largely depends on how much the production temperature was lowered and the differential in moisture reduction in the aggregates. Theoretical calculations indicate that a temperature reduction of 28 °C should result in a fuel saving of 10~15 percent (NCHRP, 2014). Based on the rough relationship between mixing temperature and fuel consumption in Fig. 5, Yang et al. (2017) found that WarmRAC had a fuel savings of around 14% comparing to control rubberized HMA. In addition, a reduction in the amount of moisture that is removed from the incoming aggregates also reduces fuel consumption. For every 1% reduction in moisture, fuel consumption is reduced by approximately 10% (Prowell D. et al., 2012). However, the effects of reductions in production temperature and moisture content on the final fuel consumption are interrelated, which means the contributions of each effect to fuel savings should not be summed up simply. Based on the energy audits for several WMA projects, the following relationship (Equation 1) was built between energy savings for WMA production and temperature reduction:

$$Energy\ savings = T_R \times 1100\ Btu/ton \qquad (1)$$

Where T_R is temperature reduction (°F), Btu is an energy unit (British thermal unit). The above relationship shows that one-ton WMA mixes with one °F temperature reduction can save 1100 Btu energy.

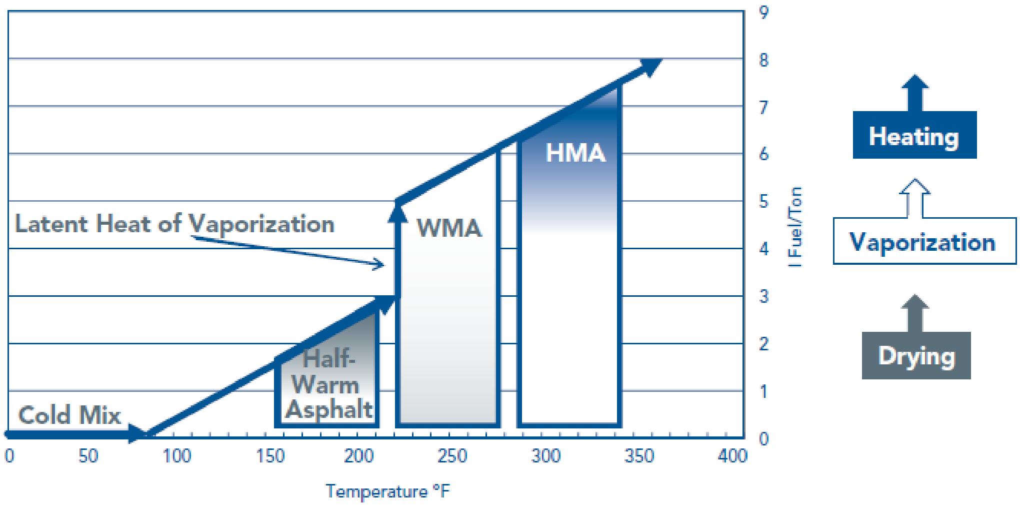

Fig.5. Asphalt mixture type classification based on the manufacturing temperature and fuel consumptions, adapted from (D'Angelo, 2008)

Depending on the burner fuel (e.g. recycled fuel oil, natural gas) asphalt plants used for drying and heating aggregates, the energy savings vary from \$0.16/ton to \$0.39/ton for a 25 °F drop from HMA to WMA, and vary from \$0.31/ton to \$0.79/ton for a 50 °F drop (NCHRP, 2014). With the increasing of energy cost, this fuel-saving benefit of WMA will be magnified. It was also reported by contractors that using WMA could have improved in-place density and smoothness, which will provide unquantifiable economic benefits.

7.3 *Comparative cost analysis of WarmRAC*

Decisions regarding when and where to use specific paving technology must be based on cost and expected performance. Transportation or highway agencies are advocating the use of life cycle cost analysis (LCCA) to assist in determining the most appropriate pavement design, rehabilitation and maintenance strategies for a given situation (Asiedu and Gu, 1998). For example, in terms of a highway pavement (Walls III and Smith, 1998), in addition to the initial construction cost (within agency cost), LCCA takes into account all the user costs, (e.g., vehicle operating costs (VOC), user delay costs, and accident costs.), and agency costs related to future activities, including future routine and preventive maintenance, resurfacing and rehabilitation. All the costs are usually discounted to a present day or year value known as net present value (NPV) for convenient comparison (Hicks and Epps, 2000). Since there is limited data regarding the entire life cycle cost of WarmRAC, this subsection is intended to give a brief qualitative cost analysis of WarmRAC at different stages compared to conventional HMA. Generally, the user costs of WMA and RAC have slight differences compared to conventional HMA according to previous studies. Additionally, normal travel costs are not dependent on individual project alternatives. As a matter of convenience, the user costs are assumed equal for HMA and WarmRAC. Therefore, the main cost differences locate at the production, construction, maintenance and rehabilitation stages. The impact assessment of different evaluation items is based on a rough estimate according to the advantages and disadvantages of WarmRAC discussed before, as shown in Table 3. From this preliminary analysis, it is obvious that WarmrRAC pavement system is more cost-effective than the conventional HMA one. However, detailed and systematic LCA and LCCA of WarmRAC should be carried out according to the following four steps (Butt et al., 2012): (1) Goal and scope definition; (2) Life cycle inventory; (3) Life-cycle impact assessment; (4) Life cycle interpretation.

Table 3 Agency cost analysis of WarmRAC compared to conventional HMA

Stage	Impact item	Impact assessment
Production	Aggregate production	/
	Binder production	+
	Aggregate drying and heating	-
	Fillers and additives feeding	+
	Mixing	-
Construction	Transport	/
	Placement	/
	Compaction	-
Maintenance	Routine	-
	Preventive	-
	Corrective	-
Rehabilitation		According to specific project type

Note: / represents the same, + represents increased cost, - represents decreased cost.

7.4 *Summary*

WarmRAC encounters a higher initial cost in comparison to conventional HMA, which is one of the main concerns of contractors when utilizing this technology. However, WarmRAC is believed to have long-term benefits, such as preserved ecosystem, improved durability and lower maintenance cost, which will be more cost-effective than conventional HMA in a life-cycle manner.

8 Conclusions and recommendations

WMA is developed in response to demands for reduced energy consumption and gas emissions. The incorporation of crumb rubber into paving technology can not only solve the disposal issue of waste tires, but also improve the performance of asphalt pavements. WarmRAC, which is the combination of WMA and RAC, is a novel paving technology that satisfy the environmental, economic and social requirements of current society. Based on the review and analysis of both WMA and RAC, WarmRAC can be considered as a type of sustainable pavement that, on a broader scale, (1) meets basic human needs, (2) uses resources effectively, and (3) preserves/restores surrounding ecosystems. Specifically, following conclusions and speculations can be drawn:

(1) Generally, WarmRAC can use the same mix design methodology of conventional HMA with slight modifications, such as aggregate gradation, bitumen content, etc., based on specific WarmRAC product.

(2) WMA technology is an aid to RAC pavement from the standpoint of construction. Construction techniques of conventional HMA with slight modifications can be successfully applied to WarmRAC.

(3) The performance of WarmRAC is comparable to conventional HMA. Although there are some uncertainties of WarmRAC, it still meets the requirements or standards for typical HMA.

(4) It is feasible to recycle WarmRAC using available technologies and equipment without adverse effects on environment and human beings.

(5) WarmRAC can significantly reduce the emissions and energy consumption with insignificant negative impact on environment. Moreover, it is speculated that WarmRAC will maximize the additional value of waste tires, eliminating the potential risks to environment under improper disposition.

(6) Although WarmRAC has a higher initial cost than conventional HMA, it is believed to be more cost-effective based on the preliminary life cycle cost analysis.

As mentioned before, WarmRAC is a relatively new paving technology. The research findings to date about WarmRAC are positive and encouraged. Contractors continue to find new benefits from the use of WarmRAC. However, there remain a number of areas where additional evaluation, development, and research regarding WarmRAC are required. Further considerations are recommended as follows.

(1) Both chemical and physical interaction mechanisms between bitumen and crumb rubber should be investigated for material selection and quality control.

(2) The interactions between crumb rubber and WMA technology chemistry should be further evaluated in terms of both performance and emission properties.

(3) Accurate identification, quantification and measurement of emissions and leachates of WarmRAC should be developed during asphalt paving operations and service period. Developing laboratory procedures are encouraged to simulate asphalt fumes and leaching in filed conditions.

(4) Long-term performance of WarmRAC should be documented and evaluated with the collaboration between different departments to realize its environmental, economic and social benefits. Accordingly, systematic LCA tools should be developed to quantify above environmental, economic and social impacts of WarmRAC.

(5) A closer involvement of local and national government bodies with policies or regulations supporting will stimulate the development of this sustainable paving technology in both industry and academia. Education and training for related researchers, designers and workers are also required for the successful application of WarmRAC in asphalt pavements.

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