Innov. Infrastruct. Solut. (2017) 2:10
DOI 10.1007/s41062-017-0058-7

REVIEW

Use of reclaimed asphalt pavement (RAP) in warm mix asphalt (WMA) pavements: a review

Mohammad Adnan Farooq[1] · **Mohammad Shafi Mir**[1]

Received: 20 January 2017 / Accepted: 1 April 2017 / Published online: 10 April 2017

Abstract The limit in the use of reclaimed asphalt pavement material (RAP) proportion is restricted due to stiffness and workability issues related to RAP. This problem is addressed with the help of warm mix asphalt (WMA) which increases the proportion of RAP used by producing mixes having same/better properties viz., better workability, reduced viscosity than hot mix asphalt (HMA) at lower temperatures. This paper reviews research conducted on the use of RAP material in WMA pavements. It presents and discusses work done with regard to different recycling methods and on conversion of RAP into HMA. It analyzes the benefits/need of using RAP in WMA in light of previous research findings and the influence on engineering properties of WMA due to RAP introduction. This paper also discusses field performance, environmental/economic impact and some limitations of these mixes.

Keywords Recycled asphalt pavement material · Warm mix asphalt · RAP · WMA · Evotherm · Recycling

Introduction

Construction of bituminous pavements has attained tremendous growth during the past decades, leading to scarcity and increasing the price of virgin material viz., aggregates and bitumen. Using reclaimed asphalt pavement (RAP) not only helps in utilizing waste RAP material but also decreases the demand for virgin material leading to overall saving in cost. This less demand for virgin material also leads to a lesser impact on the environment along with savings in energy [1, 2]. As raw material and petroleum extraction involves huge cost, lot of study is being conducted across the globe to search for new materials which are durable and show good performance at low cost [3]. Using RAP to produce cold or hot mix asphalt is one of the methods which aims at cost reduction [4]. The re-use of aggregates and bitumen present in RAP aids in saving natural resources, money and is eco-friendly [5]. Recycling of pavements has become one of the most attractive pavement restoration alternatives over the years and it will continue to be the most appealing rehabilitation technique on the basis of continuous field and laboratory assessment [6]. The choice of restoration technique should be based on energy conservation, economic and engineering consideration, and environmental effects.

Asphalt production is a threat to environment. Various studies suggest using another technology called warm mix asphalt (WMA) which reduces the production and compaction temperatures of asphalt mixes [7]. WMA helps in producing asphalt mixes which have strength and durability equal to or better than HMA [8]. WMA mixes are produced using additives which facilitate in lowering the production temperatures by either lowering the viscosity and/or increasing the volume of the binder [9, 10]. As a result of this, aggregates are completely coated with the binder at a lower temperature than required for HMA. RAP–WMA mixes utilize lesser virgin material and result in reduced CO_2 emissions and this makes it environment friendly [4, 11]. WMA mixes prepared with RAP show similar properties to conventional HMA mixes [12].

✉ Mohammad Adnan Farooq
adnannit@yahoo.com

Mohammad Shafi Mir
shafi@nitsri.net

1 Civil Engineering Department, National Institute of Technology, Srinagar, Jammu and Kashmir 190006, India

Organic additives aid in reducing the viscosity of bitumen leading to increased flow of bitumen [13]. The organic additives undergo crystallization which increases the stiffness of the bitumen and its resistance to deformations [14]. Chemical additives, on the other hand, are a combination of emulsification agents, polymers, and additives which improve workability, compaction, and adhesion of bituminous mixes. These additives help in reducing the production and placement temperatures of a mix without the addition of water. The amount of chemical additive to be added is usually based on previous studies and supplier recommendations [15–18]. Unlike chemical and organic additives, water-based additives require an addition of water for the formation of foam which helps in decreasing the viscosity and increasing the volume of bitumen. If the use of water causes some stripping problems, use of anti-stripping agents is suggested. These anti-stripping agents aid in reducing moisture susceptibility and improve chemical adhesion between bitumen and aggregate surfaces [19].

Recycling methods

RAP recycling methods are broadly classified as central plant recycling and in situ recycling. In central plant recycling, RAP is modified away from the site at a plant and in situ recycling involves modification of RAP at the construction site. They are further classified as hot or cold recycling depending whether heat is applied or not. In cold recycling, recycling agents (emulsion or cutback) are used [20, 21]. Recycling methods are also classified on the basis of the depth of old pavement removed. It is termed as surface recycling if upper layer of pavement is removed and re-laid and is termed as full-depth reclamation if pavement layers up to base layer are removed and re-laid [22].

Hot in-place recycling involves heating of pavement and then scarifying the pavement to the required depth. Depending on the properties of milled RAP material, fresh aggregates and bitumen are added and the resulting mix is laid and compacted. This method consumes less time, causes the least disruption to traffic and reduces the transportation cost but involves bulky machinery [23]. In cold in-place recycling, no heat is applied and instead of bitumen, emulsion or cutback are used as a binder. It needs sufficient time for aeration and curing of the freshly laid layer. Additives like, cement, quick lime or fly ash may be used in this process. It reduces emission of harmful gases [24, 25]. Hot central plant recycling involves the addition of fresh aggregates and bituminous binder to RAP material in hot mix plant away from the site. The properties and performance of mix prepared using this process are similar to that of virgin hot mix [25]. This is due to better quality control achieved in central plant recycling [21]. However, due to susceptible nature of RAP material towards moisture, proper care should be taken for storing it. This method is suitable for places where sufficient space is not available at the site [26, 27]. Unlike hot central plant recycling, in cold central plant recycling no heat is applied in the plant and emulsion or cutback are used as a binder. Mixing time is a very important consideration in this process as over-mixing may cause premature breaking of emulsified binder and under-mixing may result in the insufficient coating of aggregates [20].

Use of RAP in HMA

Most studies suggest 50% as the practical limit for using RAP material. The disposing of the remaining 50% RAP material poses a problem. The factors which pose the restriction on increasing the amount of RAP material are ambient temperatures of the materials, the rate of production, moisture content, discharge temperatures, allowable moisture content in the final mix and, the build-up of fine aggregates and asphalt binder on metal flights in drum [21]. Different studies conducted on RAP material reveal that RAP helps in increasing the stiffness of the mix. Studies also showed that RAP binder has a superior aging index in comparison to the original binder. The mixtures produced using RAP exhibited higher modulus [28–36]. In Europe, studies have been conducted to stimulate the use of up to 60% RAP material [37–39].

As RAP percentage increases, the required amount of front-end preparation and type of plant equipment needed will also change. The five stages of RAP injection for different percentages of RAP are explained as under [40]. In Stage One (0–10% RAP) the percentage of RAP is so low that it has little effect on the aggregate gradation and asphalt content in the mix. Parallel flow drum mixer, parallel flow drum mixer with a coater, counter-flow drum mixer, counter-flow drying drum with a coater, or a double RAP™ dryer can be used for processing up to 10% RAP material. In Stage Two (10–20% RAP) as the percentage of recycling in the mix increases, it is difficult to maintain the gradation and asphalt content in the final mix. Telescoping stackers help in producing better quality mix when up to 20% RAP is used. Stage Three (20–30% RAP) involves crushing, screening, and separation of RAP into the same sizes as the virgin aggregate that is used in the mix. Larger impact crushers should be used for larger sizes and quantities of RAP. For Stage Four (30–40% RAP) and Five (40–50% RAP) recycling, continuous mix plants with the double barrel dryer/mixer are most desirable. A counter-flow dryer with an outer aggregate blending chamber, like the double RAP dryer, is the best option for batch plants producing high RAP content mixes [40]. Use of High RAP proportion reduces the workability and increases the compactibility requirement of the mix due to stiff aged binder associated with RAP [41, 42]. This problem can be addressed by softer bitumen, the addition of rejuvenator and use of WMA additives [43, 44].

Use of RAP in WMA

The increase in demand for environmental friendly pavement material and rising cost of raw material are the two major problems which are confronted by the asphalt pavement industry. Use of RAP thus becomes inevitable to cope with the above problems. WMA additives help to incorporate increased proportion of RAP to produce bituminous mixes at a lower temperature than the conventional mix, leading to overall saving in energy and money [9, 10]. The most desirable feature of RAP–WMA mixes is the reduction in production temperatures without compromising on the properties of the bituminous mix [12]. Use of foamed bitumen to produce RAP–WMA mixes helps in increasing more RAP content as compared to other WMA technologies [43, 44]. An experimental study found that the aging of the binder decreases if the binder is aged at a lower temperature. In warm mixes as the mixing and compaction temperatures are less, the aging in the binder also decreases. It was also found out that this change in temperatures had not much effect on the binder's $G^*/\sin\delta$ value. Hence the reduction in the temperatures will not have much effect on the rutting resistance of the binder. Moreover, the presence of aged binder in form of RAP binder will compensate for this soft warm mix binder [45]. Aged RAP binder in the RAP–WMA mix decreases its fatigue life. Aging of the virgin binder produced at lower temperatures in WMA will be less than that of a virgin binder produced at higher temperatures in HMA. So a balance is required between these two aspects to using RAP materials and WMA technology together as both these technologies are aimed at saving resources and lowering the energy required for production [46, 47]. Although most of the work on WMA has involved dense-graded mixtures, however, in principle, WMA technology is equally applicable to other types of asphalt mixtures (e.g., open-graded, gap-graded, and stone mastic asphalts). WMA technology can be used for conventional asphalt mixing plants as well as traditional paving equipment and techniques [48]. The Maryland State Highway Administration produced an asphalt pavement section of the road using 45% RAP in the base course, SMA in the intermediate course, and 35% RAP in the surface course with 1.5% Sasobit by weight of total binder as a modifier. The stiffness of the WMA and HMA control mixes were found to be statistically similar [49].

Engineering properties of WMA–RAP

Various studies have been carried out across the world using RAP to produce WMA Pavements. The various properties affected are:

Mixing and compaction temperatures

The WMA additives allow producers to reduce the mixing and compaction temperatures of asphalt production [50]. The WMA technology helps in reducing mixing temperatures by about 20–30 °C as compared to HMA due to chemical composition changes during the mixing process [51, 52]. Improved compaction was noted at temperatures as low as 190 °F (88 °C) for mixes produced with Evotherm® [53]. The reduction in compactibility temperatures for production of RAP Incorporated WMA using surfactant additive was only 10 °C but the heating temperatures of virgin aggregates reduced by 40 °C, leading to overall saving of energy [54].

Air voids

The addition of Evotherm® (Chemical WMA additive) lowers the measured air voids in the gyratory compactor for a given asphalt content [53]. Pavement air voids were slightly lower for the WMA mixes on average and the foamed asphalt mixture showed the largest difference out of three WMA additives viz. a chemical modifier, wax additive and foaming additive which were used in multiple pavement projects. Statistics indicated an average reduction in air voids up to 1.4% [50]. Air void in mixtures produced using organic, chemical and water containing additives were all within specified limits [55]. The binder source and related WMA technology play an important role in determining the air voids of the Superpave mix design required to achieve optimum asphalt content [56].

Resilient modulus

At a given compaction temperatures, the addition of Evotherm® increases the resilient modulus of an asphalt mix compared to control mixtures having the same PG binder [53]. The resilient modulus increases with the increase of RAP proportion for foamed warm mix asphalt [57]. The stiffness modulus of WMA mixes produced using RAP was higher than the conventional mixture. The use of the additive associated with the reduction in temperatures showed no influence on the stiffness and phase angle results of both RAP incorporated WMA and conventional WMA mixtures [58].

Rutting potential and complex shear modulus

The rutting performance of warm mix recycled asphalt was similar to that of HMA [59]. The use of surfactant additive showed improved rut resistance of WMA mixes produced with and without RAP, although the additive was more efficient with RAP–WMA mixes [54]. The addition of Evotherm® significantly decreased the rutting potential of the asphalt mixes evaluated as compared to control mixtures produced at the same temperatures. The rutting potential increased with decreasing mixing and compaction temperatures, and this is believed to be related to the decreased aging of the binder [53]. The rutting resistance increased with the increase of RAP proportion with different WMA additives (Evotherm 3G, Rediset LQ, Sasobit, and Advera). However, RAP–WMA mixes prepared with Sasobit (Organic additive) performed best among all due to the stiffening characteristics of this particular organic additive [60]. The rutting resistance of both HMA and WMA mixes increases with an increase of RAP proportion (up to 30%) irrespective of WMA technology and structure layer. Although WMA mixes with high RAP content showed lower rutting resistance than HMA mixes with low RAP content but still it was better than WMA mixes with low RAP content. However, there may still be concern regarding WMA–high RAP mixtures [61]. The dynamic stability was improved with the addition of 40% RAP in WMA mixture depicting improved rut resistance [52]. The addition of RAP binder increases rutting resistance of asphalt binder. However, it was found that the WMA additive could offset these properties of the combined binder [62]. An experimental study showed that the viscosity of recycled binder at 60 °C increased when Sasobit® was added to it, and hence demonstrated better resistance to rutting [63]. The relations for $G^*/\sin\delta$ for Evotherm DAT, Evotherm 3G and HMA mix, respectively, for RAP proportion up to 60% are given in Eqs. 1–3 [64]

$$G^*/\sin\delta = 0.346(\%\text{RAP}) - 0.048(\text{Dry ITS}) + 10.16 \quad (1)$$

$$G^*/\sin\delta = 0.323(\%\text{RAP}) - 0.024(\text{Dry ITS}) + 6.56 \quad (2)$$

$$G^*/\sin\delta = 0.346(\%\text{RAP}) - 0.022(\text{Dry ITS}) + 6.75. \quad (3)$$

Workability

The addition of WMA additive in RAP improves the workability of RAP [50, 53]. The addition of Sasobit H8 or Advera zeolite helps in lowering the viscosity of the 100% RAP, thus improving workability at temperatures as low as 110 °C [5]. PTI Foamer mixtures showed more workability than Evotherm 3G additive. The workability decreased as the RAP content increased [65]. Most WMA technologies aid in the temporary reduction of bitumen viscosity and/or improve lubrication that allows to sufficiently coat the aggregates and improve the workability without raising the temperatures [66, 67].

Creep deformation

The utilization of RAP with WMA exhibits high stability values with low flow values resulting in high marshall quotient (MQ) values, indicating a high stiffness mixture with a greater ability to spread the applied load and resist creep deformation [55, 68]. The inclusion of RAP leads to reduced disk-shaped compact tension and indirect tension creep compliance [60]. The creep compliance values were lower for Sasobit®-modified recycled binders than for the recycled binders without Sasobit®. The recycled binders in which Sasobit® was added showed lower phase angles and higher complex moduli than the normally recycled binders in the frequency sweep test [63].

Compactibility

Pavement densities for HMA and WMA prepared from RAP were comparable. The foamed asphalt pavement sections exhibited the highest pavement density indicating improved compactability [50]. Evotherm® improved the compactability of the mixtures in both the SGC and vibratory compactor [53]. For 40% RAP mixtures, the compactability for HMA mix improved when a softer grade binder, PG 58-28 was used. The 40% RAP–WMA mixtures did not show much difference in compactability with the change of binder [65]. A study conducted on porous asphalt mixture revealed that the energy required during construction by WMA with 0.25% Advera WMA was lower compared with the control mixture (HMA). The mixtures containing RAP were also found to have a higher compaction energy index [69].

Moisture susceptibility

Moisture susceptibility is an important issue for WMA mixtures including RAP that enable low mixing, laying and compaction temperatures compared to conventional HMA [55]. The lower compaction temperatures used when producing WMA with any such WMA additive may increase the potential for moisture damage [53]. The WMA–RAP mixture showed better results in terms of moisture sensitivity than HMA mixture [70]. WMA–high RAP surface mixtures showed better resistance to moisture regardless of WMA technology. Results of both tensile strength ratio (TSR) and resilient modulus ratio tests showed that the moisture susceptibility still remains a big concern in foamed WMA paved in base layer [61]. The chemical additive performs best because of the inherent antistripping capabilities. Increase in RAP proportion increases the resistance to moisture damage [57, 60]. The warm mixes produced using RAP showed the value of TSR above the minimum required 80%, indicating good resistance towards moisture damage of these mixes [71]. The WMA additive does not impart any detrimental impact on the water sensitivity of WMA mix materials [54]. The short term aged RAP–WMA mixtures showed higher TSR moisture resistance than corresponding virgin WMA mixture. However, TSR values were drastically reduced after long-term aging [52].

Thermal cracking and fatigue

The addition of chemical additive improves the fracture resistance of WMA mixtures as compared to control HMA. The presence of RAP may lead to increased thermal cracking potential for all types of WMA additives (Evotherm 3G, Rediset LQ, Sasobit, and Advera) [60]. The fatigue resistance of warm mix recycled asphalt was similar to that of HMA [70]. The WMA additive and lower production temperatures show no effect on the fatigue life of WMA mixes. The fatigue resistance of the RAP–WMA mix was found better than WMA mix produced from virgin materials [54]. The increase in RAP proportion may increase the cracking and fatigue resistance of WMA but decreases that of HMA. WMA–high RAP mixtures generally perform similarly or better in cracking and fatigue resistance than HMA–low RAP mixtures, which indicates that cracking and fatigue may not be a major concern when it comes to WMA–high RAP technology [61]. The addition of RAP decreases low temperature cracking resistance. The Evotherm-DAT WMA virgin mixture showed higher low temperature cracking resistance than S-I WMA virgin mixture. The low temperature cracking resistance of the WMA–RAP mixtures was not sensitive to the used WMA additives [52]. The addition of RAP binder reduces fatigue resistance of asphalt binder [62].

Field performance of RAP–WMA mixes

Many field tests have been performed using different percentages of RAP and various WMA additives. The Maryland State Highway Administration paved a section of road using 45% RAP in the base course, HMA in the intermediate course, and 35% RAP in the surface course; with 1.5% Sasobit by weight of total binder. The stiffness of the WMA and HMA control mixes were statistically similar [72]. A demonstration project was constructed in Orlando, Florida using 20% RAP and Zeolite. The Zeolite reduced production and compaction temperatures by 19 °C (39 °F) and resulted in in-place densities similar to control RAP produced at HMA temperatures [73].The air voids analysis of three field mixes viz., 15% RAP–HMA (175 °C), 15% RAP–WMA (150 °C) and 15% RAP–WMA (120 °C) showed that the WMA technology helps in reducing air voids even after reduction of mixing and compaction temperatures [74]. RAP, milled from State Route 11 in Deland Florida, was used with virgin material in 45:55 proportion to produce RAP–HMA and RAP–WMA (Foaming additive) mixes. Performance grade, Flow value and Dynamic modulus test results indicated that the high RAP–WMA mix is softer than the high RAP–HMA control mix. However, there is uncertainty about incomplete blending of RAP and virgin binder in high RAP–WMA mixes [75]. Lab analysis of four mixes viz., 20% RAP–HMA, 20% RAP–WMA, 28% RAP–WMA and 35% RAP–WMA, which were used in Route 44 Missouri, showed that the reduced oxidation of WMA binder allowed higher RAP contents than HMA control mixes at same binder stiffness. The case study also showed that ignoring other costs (milling, WMA additive, etc.), every 1% RAP lowers cost by $0.35/ton [76]. A number of field trials with Sasobit® have been constructed in the United States. The mix properties of such two test sections, constructed with Sasobit® in Milwaukee and St. Louis, were identical or improved in comparison to the virgin controls. The exception being a possibly increased susceptibility to moisture damage as indicated by laboratory tests run on the field mixed asphalt [77]. Test results of two other trial sections placed in Virginia, which were prepared using 1.5% Sasobit with 10 and 20% RAP, showed that there was no significant change in the volumetric properties or rut measurements. However, one trial section did not fulfill the TSR requirements, which may be due to high stockpile moisture conditions and lower mix temperatures during production [78].

Environmental and economic impacts

The adverse impacts on environment and high cost involved with asphalt mix production are attributed to the high energy requirement for asphalt production and high ingredient material costs [79]. The high energy consumption and the release of pollutant gases are the consequence of drying and heating mineral aggregate and bitumen at temperatures above 140 °C [80, 81]. Due to high heating temperatures, bitumen fumes are generated during HMA production which contains carcinogenic polycyclic aromatic hydrocarbon (PAH) compounds [82]. The production of these PAH compounds can be reduced up to 50% using

WMA technology, thereby reducing worker exposure to aerosol/fumes and PAHs [83]. Using RAP to produce WMA mixes are the most emerging sustainability practices which are being used worldwide these days. Using RAP to produce bituminous mixes can result in up to 23% energy savings [79]. However using RAP in higher proportions, to produce HMA, can lead to increased stiffness and reduced crack resistance [84, 85]. WMA technology on the other hand, when incorporated with RAP, results in reduced ageing of bitumen due to lower production temperatures of WMA mixtures, allowing for incorporation of higher RAP proportions. This leads to lesser use of virgin material along with reduced fuel consumption up to 35% due to lower production temperatures [46]. The decreased fuel consumption also lowers the fumes and greenhouse gas emissions produced during asphalt production, making it more environmental friendly [57]. Research conducted across Europe and Canada reveal that a 15–70% reduction in CO_2, SO_x, NO_x, and volatile organic compounds (VOCs) emissions are generally realized with the use of WMA [51]. One other study showed that WMA technology results in reduction of CO_2 by 30–40%, reduction of SO_2 by 35%, reduction of volatile organic compounds (VOCs) by 50%, reduction of CO by 10–30%, reduction of NO_2 by 60–70%, and reduction of dust by 20–25%. Measurements of WMA mixtures have shown up to 40% lower fuel costs when compared to comparable HMA mixtures, but this reduction is directly dependent upon the WMA production temperatures [86].

Limitations and specifications for using RAP–WMA mix

One of the biggest concerns with pavement performance, whether it is hot mix, warm mix, or RAP, is moisture susceptibility [87]. Moisture damage can be adhesive failure (between the binder and aggregate) and cohesive failure (reduced strength of the binder through moisture damage) [88]. The possibility of moisture damage in case of RAP–WMA mixtures is increased due to lower mixing and compaction temperatures of WMA which leads to incomplete drying of aggregates [89]. One other limitation in the use of RAP with WMA is that it does not result in any significant enhancement in the resistance to low temperature cracking after long-term aging as compared to the use of RAP with a conventional HMA [90]. Although WMA additives improve fatigue resistance but these reduce rutting resistance of RAP–WMA mixes [91]. Chemical and Organic WMA additives perform well in terms of moisture susceptibility except foaming additive, hence, there is a need to use antistripping agents with foaming additives.

Untill 2009–2011, most Departments of Transportation (DOT) in the US viz., California DOT, Florida DOT and the like did not permit use of RAP with WMA, especially in the frictional courses. Florida DOT does not treat WMA differently from HMA and has no additional restrictions for RAP use in it. RAP limits across various DOTs in US are 10–25 percent for wearing courses, 35–40 percent for binder layers, and 40–50 percent for the base layers. Texas DOT has constructed many projects with RAP/WMA, mostly with 20 percent RAP with chemical WMA additives. The only change in using RAP with WMA was the increase of dwell time in the drum, to ensure proper coating and mixing [92]. Currently, the maximum amount of RAP material allowed in the surface course by the Iowa DOT is limited to 30% of the virgin binder replacement by Classified RAP materials [93]. Some standards dealing with mix design of RAP are: AASHTO M323: Superpave Volumetric Mix Design; ASTM D 3515: Standard Specification for Hot-Mixed, Hot-Laid Bituminous Paving Mixtures; and ASTM D 4887: Standard Practice for Preparation of Viscosity Blends for Hot Recycled Bituminous Materials. Up to 15% RAP content, AASHTO M323 ignores the effect of RAP; and above 15%, use of softer binder is recommended. At intermediate (up to 40%) RAP content, use of blending charts is recommended [94] whereas above 50%, more understanding and control is required.

Conclusions

RAP is being used all over the world to produce HMA. However, there is a limit to the maximum amount of RAP that can be used to produce HMA. Different processes are available to prepare HMA from RAP depending on the percentage of RAP. Depending on the feasibility at site, i.e., whether the adequate right of way and heat treatment is available or not, various recycling methods are available. Use of warm mix technology helps in increasing RAP proportion. The problem of increasing price of raw materials and release of harmful gases in the environment during HMA production is also solved by RAP to produce WMA pavements. It helps in creating better working environment for the workers and reduction of fuel costs. Using RAP to produce WMA mixes helps in improving various engineering properties viz., workability, creep deformation, rutting potential, low temperature cracking and fatigue failure. Field performance of these mixes is also comparable to HMA mixes. However, due to lower production temperatures, it becomes important to check for moisture susceptibility, especially for long-term aged binders.

References

1. Feih S, Boiocchi E, Mathys G, Z M, Gibson A (2011) Mechanical properties of thermally treated and recycled glass fibres. Compos. B 42 350–358. Elsevier
2. Chang C, Tseng L, Lin T, Wang W, Lee T (2012) Recycling of modified MSWI ash-mix slag and CMP sludge as a cement substitute and its optimal composition. Indian J Eng Mater Sci 19:31–40
3. Sengupta S, Pal K, Ray D, Mukhopadhyay A (2011) Furfuryl palmitate coated fly ash used as filler in recycled polypropylene matrix composites. Furfuryl palmitate coated fly ash used as filler in recycled polypropylene matrix composites. Compos. B 42 1834–1839. Elsevier
4. Mallick R, Kandhal P, Bradbury R (2008) Using warm mix asphalt technology to incorporate high percentage of reclaimed asphalt pavement (RAP) material in asphalt mixtures. J Transp Res Board 2051:71–79
5. Tao M, Mallick RB (2009) Effects of warm-mix asphalt additives on workability and mechanical properties of reclaimed asphalt pavement material. Transp Res Rec J Transp Res Board 2126(1):151–160
6. Shahadan Z, Hamzah M, Yahya A, Jamshidi A (2013) Evaluation of the dynamic modulus of asphalt mixture incorporating reclaimed asphalt pavement. Indian J Eng Mater Sci 20:376–384
7. Wasiuddin N, Selvamohan S, Zaman M, Guegan M (2007) Comparative laboratory study of sasobit and aspha-min additives in warm-mix asphalt. J Transp Res Board 1998:82–88
8. Newcomb D (2007) An introduction to warm-mix asphalt. Report, Natl. Asph. Pavement Assoc
9. Button JW, Estakhri C, Wimsatt A (2007) A synthesis of warm-mix asphalt. Report,Texas Transp. Institute, Texas A&M Univ. 7
10. Hurley G, Prowell B (2005) Evaluation of sasobit for use in warm mix asphalt. Report, US Natl. Cent. Asph. Technol. Auburn
11. O'Sullivan K, Wall P a. (2009) The effects of warm mix asphalt additives on recycled asphalt pavement. B.Sc project report. Worcester polytech inst. Project number: MQPRBM0903
12. Mallick RB, Bradley J, Bradbury R (2007) Evaluation of heated reclaimed asphalt pavement material and wax-modified asphalt for use in recycled hot-mix asphalt. Transp Res Rec J Transp Res Board 1998(1):112–122
13. Jamshidi A, Hamzah M, Aman M (2012) Effect of sasobit content on the rheological characteristics of unaged and aged asphalt binders at high and intermediate temperatures. Mater Res 15:628–638
14. Zaumanis M (2010) Warm mix asphalt investigation. M.Sc. Thesis, Tech. Univ. Denmark, Kongens Lyngby
15. Xiao F, Punith V, Amirkhanian S (2012) Effects of non-foaming WMA additives on asphalt binders at high performance temperatures. Fuel 94:144–155
16. Zaumanis M (2014) Warm Mix Asphalt. In: Clim. Chang. Energy, Sustain. Pavements. pp 309–334
17. Chowdhury A, Button JW (2008) A review of warm mix asphalt. Report, Texas A&M Univ Syst Coll Station Texas Transp Inst 7:75
18. Jones D, Tsai B, Signore J (2010) Warm-mix asphalt study: laboratory test results for Akzonobel Rediset WMX. Univ. Calif. Pavement Res. Cent
19. Button J, Alvarez A (2010) Field and laboratory investigation of warm mix asphalt in Texas. Texas Transp. Institute, Texas A&M Univ
20. Aravind K, Das A (2006) Bituminous pavement recycling. Dep Civ Eng IIT Kanpur 1–3
21. Kandhal P, Mallick R (1997) Pavement recycling guidelines for state and local governments-participant's reference book. Auburn, AL Natl. Cent. Asph. Technol. Rep. Number FHWA-SA-98-042
22. Epps J, Terrel R, Little D, Holmgreen R (1980) Guidelines for recycling asphalt pavements. In: Guidel. Recycl. Asph. pavements. In: Proc. Assoc. Asph. Paving Technol. p vol. 49, pp. 144–176
23. Jones G (1979) Recycling of bitumenous pavements on the road. In: Proc. Assoc. Asph. Paving Technol. p vol. 48, pp. 240–251
24. Mosey J, Defoe J (1979) In-place recycling of asphalt pavements. In: Proc. Assoc. Asph. Paving Technol. p Vol.48, pp. 261–272
25. Mallick B (2005) lecture notes. In: A 3-day Work. Recycl. other pavement Rehabil. methods, IIT Kanpur. pp 8–10, pp. 58–350
26. Wolters R (1979) Bituminous hot mix recycling in Minnesota. In: Proc. Assoc. Asph. Paving Technol. p vol. 48, pp. 295–327
27. Betenson W (1979) Recycled asphalt concrete in Utah. In: Proc. Assoc. Asph. Paving Technol. p vol. 48, pp. 272–295
28. Chaffin J, Liu M, Davison R, Glover C, Bullin J (1997) Supercritical fractions as asphalt recycling agents and preliminary aging studies on recycled asphalts. Ind Eng Chem Res 36(3):656–666
29. Daniel J, Lachance A (2005) Mechanistic and volumetric properties of asphalt mixtures with recycled asphalt pavement. Transp. Res. Rec. J. Transp. Res. Board, No. 1929, Transp. Res. Board Natl. Acad. Washington, DC, 28–36
30. Kandhal P, KY (1997) Designing recycled hot mix asphalt mixtures using Superpave technology. Natl. Cent. Asph. Technol. New Orleans, 101–117
31. Lewandowski L, Graham R, Shoenberger J (1992) Physico-chemical and rheological properties of microwave recycled asphalt binders. In: Proc., Mater. Eng. Congr. ASCE, New York. pp 449–461
32. McDaniel R, Shah A, Huber G, Gallivan V (2007) of Properties of Plant-Produced RAP Mixtures. Transp Res Rec J Transp Res Board, No 1998, Transp Res Board 103–111
33. Peterson R, Soleymani H, Anderson R, McDaniel R (2000) Recovery and testing of RAP binders from recycled asphalt pavements. In: Assoc. Asph. Paving Technol. Proc. pp 69, 72–91
34. Terrel R, Fritchen D (1978) Laboratory Performance of Recycled Asphalt Concrete. ASTM Spec Tech Publ 104–122
35. Yamada M (1984) Characterization of recycled asphalt mixes and their pavement performance. In: Doboku Gakkai Rombun-Hokokushu/Proc. Japan Soc. Civ. Eng. p (348), 51–60
36. Yamada M, Ninomiya T, Mise T (1987) Recycled asphalt mixtures in Osaka and their performance. Mem Fac Eng Osaka City Univ 28:197–201
37. Celauro C, Bernardo C, Gabriele B (2010) Production of innovative, recycled and high-performance asphalt for road pavements. Resour Conserv Recycl 54(6):337–347. doi:10.1016/j.resconrec.2009.08.009
38. Dinis-Almeida M, Castro Gomes J, Antunes M, Vieira L (2013) Mix design and performance of warm-mix recycled asphalt. Proc ICE Constr Mater. doi:10.1680/coma.12.00054
39. Silva HMRD, Oliveira JRM, Jesus CMG (2012) Are totally recycled hot mix asphalts a sustainable alternative for road paving? Resour Conserv Recycl 60:38–48. doi:10.1016/j.resconrec.2011.11.013
40. Brock J, Richmond J (2007) Milling and Recycling. Tech. Pap. T-127, ASTEC Inc., Chattanooga, USA
41. Artamendi I, Phillips P, Allen B (2009) Workability of bituminous mixtures incorporating reclaimed asphalt. 6th Int. Conf. Maint. Rehabil. pavements Technol. Control (MAIREPAV6), 8–10 July Turin, Italy. Turin Politec. di Torino
42. Mogawer W et al (2012) Performance characteristics of plant produced high RAP mixtures. Road Mater Pavement Des 13(1):183–208. doi:10.1080/14680629.2012.657070

43. Karlsson R, Isacsson U (2006) Material-related aspects of asphalt recycling-state-of-the-art. J Mater Civ Eng 18(1):81–92. doi:10.1061/(ASCE)0899-1561(2006)18:1(81)
44. Al-Qadi I, Elseifi M, Carpenter S (2007) Reclaimed asphalt pavement: a literature review. Springf. Illinois Cent. Transp. Rep. Number FHWA-ICT-07-001
45. Wielinski J, Hand A, Rausch D (2009) Laboratory and field evaluations of foamed warm-mix asphalt projects. Transp Res Rec no. 2126:125–131
46. Prowell B, Hurley G (2008) Warm-mix asphalt: best practices. Quality Improvement Publication 125, 3rd edn. NAPA, Lanham, MD
47. Copeland A (2011) Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice. US Dep. Transp. Fed. Highw, Agency
48. Koenders B, Stoker D, Bowen C, de Groot P, Larsen O, Hardy D, Wilms K (2000) Innovative Processes in Asphalt Production and Application to Obtain Lower Operating Temperatures. 2nd Eurasphalt Eurobitume Congress Barcelona, Spain
49. Michael L (2005) Warm mix technology to improve compaction. NEAUPG Annual Meet, Burlington
50. Buss A, Williams RC, Schram S (2015) The influence of warm mix asphalt on binders in mixes that contain recycled asphalt materials. Constr Build Mater 77:50–58. doi:10.1016/j.conbuildmat.2014.12.023
51. D'Angelo J et al. (2008) Warm-mix asphalt: european practice. Rep. No. FHWA-PL-08-007. U.S. Department of Transportation. Federal Highway Administration, Washington, DC.
52. Guo N, You Z, Zhao Y, Tan Y, Diab A (2014) Laboratory performance of warm mix asphalt containing recycled asphalt mixtures. Constr Build Mater 64:141–149. doi:10.1016/j.conbuildmat.2014.04.002
53. Hurley G, Prowel B (2006) Evaluation of Evotherm for use in WMA. Rep. 06–02, June. NCAT
54. Oliveira JRM, Silva HMRD, Abreu LPF, Gonzalez-Leon JA (2012) The role of a surfactant based additive on the production of recycled warm mix asphalts - Less is more. Constr Build Mater 35:693–700. doi:10.1016/j.conbuildmat.2012.04.141
55. Oner J, Sengoz B (2015) Utilization of recycled asphalt concrete with warm mix asphalt and cost-benefit analysis. PLoS One 10:1–18. doi:10.1371/journal.pone.0116180
56. Xiao F, Hou X, Amirkhanian S, Kim KW (2016) Superpave evaluation of higher RAP contents using WMA technologies. Constr Build Mater 112:1080–1087. doi:10.1016/j.conbuildmat.2016.03.024
57. Shu X, Huang B, Shrum ED, Jia X (2012) Laboratory evaluation of moisture susceptibility of foamed warm mix asphalt containing high percentages of RAP. Constr Build Mater 35:125–130. doi:10.1016/j.conbuildmat.2012.02.095
58. Oliveira JRM, Silva HMRD, Abreu LPF, Gonzalez-Leon JA (2012) The role of a surfactant based additive on the production of recycled warm mix asphalts—less is more. Constr Build Mater 35:693–700. doi:10.1016/j.conbuildmat.2012.04.141
59. Dinis-Almeida M, Castro-Gomes J, Sangiorgi C, Zoorob SE, Afonso ML (2016) Performance of warm mix recycled asphalt containing up to 100% RAP. Constr Build Mater 112:1–6. doi:10.1016/j.conbuildmat.2016.02.108
60. Hill B, Asce AM, Behnia B, Buttlar WG, Asce M, Reis H (2013) Evaluation of warm mix asphalt mixtures containing reclaimed asphalt pavement through mechanical performance tests and an acoustic emission approach. J Mater Civ Eng 25:1887–1897. doi:10.1061/(ASCE)MT.1943-5533.0000757
61. Zhao S, Huang B, Shu X, Woods M (2013) Comparative evaluation of warm mix asphalt containing high percentages of reclaimed asphalt pavement. Constr Build Mater 44:92–100. doi:10.1016/j.conbuildmat.2013.03.010
62. Xiao F, Putman B, Amirkhanian S (2015) Rheological characteristics investigation of high percentage RAP binders with WMA technology at various aging states. Constr Build Mater 98:315–324. doi:10.1016/j.conbuildmat.2015.08.114
63. William R (2011) Influence of warm mix additives upon high RAP asphalt mixes. Univ, Diss
64. Crew E (2009) Warm Mix Plus RAP. MeadWestvaco Corp. NCAUPG 2009 Madison, WI
65. Kusam A (2014) Laboratory evaluation of workability and moisture susceptibility of warm mix asphalt technologies with reclaimed asphalt pavement material. Diss. North Carolina State Univ
66. Arnold C et al (2012) Unlocking the full potential of reclaimed asphalt pavement (rap): high quality asphalt courses incorporating more than 90% RAP: a case study. In: 5th Euroasphalt Eurobitume Congr. 13–15 June 2012 Istanbul, Turkey. Istanbul Eur. Asph. Pavement Assoc. p Paper No. 05EE–187
67. Zaumanis M, Olesen E, Haritonovs V, Brencis G, Smirnovs J (2012) Laboratory evaluation of organic and chemical warm mix asphalt technologies for SMA asphalt. Balt J Road Bridg Eng 7:191–197. doi:10.3846/bjrbe.2012.26
68. Sengoz B, Oylumluoglu J (2013) Utilization of recycled asphalt concrete with different warm mix asphalt additives prepared with different penetration grades bitumen. Constr Build Mater 45:173–183. doi:10.1016/j.conbuildmat.2013.03.097
69. Goh S, You Z (2012) Mechanical properties of porous asphalt pavement materials with warm mix asphalt and RAP. Journal of Transportation Engineering. J Transp Eng ASCE. doi: 10.1061/(ASCE)TE.1943-5436.0000307
70. Dinis-Almeida M, Castro-Gomes J, Sangiorgi C, Zoorob SE, Afonso ML (2016) Performance of warm mix recycled asphalt containing up to 100% RAP. Constr Build Mater 112:1–6. doi:10.1016/j.conbuildmat.2016.02.108
71. Dinis-Almeida M, Castro-Gomes J, Antunes MDL (2012) Mix design considerations for warm mix recycled asphalt with bitumen emulsion. Constr Build Mater 28:687–693. doi:10.1016/j.conbuildmat.2011.10.053
72. Michael L (2005) Warm mix technology to improve compaction. NEAUPG Annual Meet. Burlington Vt. U.S. Department of Transportation, Federal Highway Administration (FHA), Washington, D.C. USA
73. Hurley GC, Prowell BD (2005) Evaluation of aspha-min zeolite for use in warm mix asphalt. Natl Cent Asph Technol - Rep 05–04 35
74. Bentsen R (2008) RAP USE IN I-90 WMA PROJECT. Illinois Tollway, NCAUPG 2008 CASE Stud
75. Copeland A, D'Angelo J, Dongré R, Belagutti S, Sholar G (2010) Field evaluation of high reclaimed asphalt pavement-warm-mix asphalt project in florida. Transp Res Rec J Transp Res Board 2179:93–101. doi:10.3141/2179-11
76. Williams D (2008) MO DOT Materials Eng. MS&T 51st Asph. Conf
77. Hurley GC, Prowell BD (2008) Field performance of warm mix asphalt technologies. In: Proc Transp Res Board 87th Annu Meet Washington, DC. doi: 10.17226/22272
78. Diefenderfer SD, McGhee KK, Donaldson BM (2007) Installation of Warm Mix Asphalt Projects in Virginia. Virginia Transp. Res. Counc. Rep. No. FHWA/VTCR 07-R2
79. Chiu C-T, Hsu T-H, Yang W-F (2008) Life cycle assessment on using recycled materials for rehabilitating asphalt pavements. Resour Conserv Recycl 52:545–556. doi:10.1016/j.resconrec.2007.07.001
80. Capitão SD, Picado-Santos LG, Martinho F (2012) Pavement engineering materials: review on the use of warm-mix asphalt. Constr Build Mater 36:1016–1024. doi:10.1016/j.conbuildmat.2012.06.038

81. Rubio MC, Martínez G, Baena L, Moreno F (2012) Warm mix asphalt: an overview. J Clean Prod 24:76–84. doi:10.1016/j.jclepro.2011.11.053
82. Ventura A, Jullien A, Monéron P (2007) Polycyclic aromatic hydrocarbons emitted from a hot-mix drum, asphalt plant: study of the influence from use of recycled bitumen. J Environ Eng Sci 6:727–734. doi:10.1139/S07-022
83. WAM-foam—An environmentally friendly alternative to hot-mix asphalt. WMA Scan Team, Nor. Public Roads Adm. Oslo, Norw
84. Xiao F, Amirkhanian S, Juang CH (2007) Rutting resistance of rubberized asphalt concrete pavements containing reclaimed asphalt pavement mixtures. J Mater Civ Eng 19:475–483. doi:10.1061/(ASCE)0899-1561(2007)19:6(475)
85. Behnia B, Dave E, Ahmed S, Buttlar W, Reis H (2011) Effects of recycled asphalt pavement amounts on low-temperature cracking performance of asphalt mixtures using acoustic emissions. Transp Res Rec J Transp Res Board 2208:64–71. doi:10.3141/2208-09
86. Vaitkus A, Čygas D, Laurinavičius A, Perveneckas Z (2009) Analysis and evaluation of possibilities for the use of warm mix asphalt in lithuania. Balt J Road Bridg Eng 4:80–86
87. Hunter ER (2001) Evaluating the moisture susceptibility of asphalt mixes. Thesis, Laramie
88. Zollinger CJ (2005) Application of surface energy measurements to evaluate moisture susceptibility of asphalt and aggregates. Texas A&M Univ
89. Hurley GC, Prowell B (2006) Evaluation of potential processes for use in warm mix asphalt. J Assoc Asph Paving Technol 75:41–90
90. Arega Z, Bhasin A (2012) Recommendations and guidelines for the use of wma mixtures. Center for transportation research. The University of Texas, Austin. TxDOT Project 0-6591
91. Sabouri M, Choi YT, Wang Y, Hwang S, Baek C, Kim RY (2016) Effect of rejuvenator on performanceproperties of WMA mixtures with high RAP content. In: Canestrari F, Partl M (eds) 8th RILEM international symposium on testing and characterization of sustainable and innovative bituminous materials. RILEM Bookseries, vol 11. Springer, Dordrecht, pp 473–484
92. Solaimanian M, Milander S, Boz I, Stoffels SM (2011) Development of guidelines for usage of high percent RAP in warm-mix asphalt pavements
93. Iowa DOT Standard Specifications, "Section 2303. Hot Mix Asphalt Mixtures"
94. McDaniel R, Soleymani H, Anderson R, Turner P, Peterson R (2001) recommended use of reclaimed asphalt pavement in the superpave mix design method. NCHRP Web Doc. 30, Final Rep. NCHRP Proj. 9–12