Construction Materials

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ice | proceedings

Proceedings of the Institution of Civil Engineers

http://dx.doi.org/10.1680/coma.11.00051
Paper 1100051
Received 11/09/2011 Accepted 07/11/2011
Keywords: bitumen/energy conservation/roads and highways

Literature review of lower temperature asphalt systems

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A selection of the available literature on warm mix asphalt and half-warm mix asphalt were reviewed in order to ascertain whether some or all of the currently available technologies have a potential use on the UK Highways Agency's network. The review looked at the various categories of the technology, the differences required in site practices, the performance of the resulting asphalt and the environmental and economic advantages of their use. However, because there is considerably more literature than that included in this study, the findings can only be tentative.

1. Introduction

Warm mix asphalt (WMA) and half- (or semi-)warm mix asphalt (HWMA) are groups of technologies that allow the asphalt mixtures to be produced and placed at lower temperatures. WMA is produced at temperatures of between 100 and 140°C, which is about 20 to 55°C lower than typical hot-mix asphalt (HMA), and HWMA is produced at the even lower temperatures of 70 to 100°C. The WMA mixtures are generally based on technologies involving chemical additives, organic additives and/or foaming techniques, primarily in order to reduce the binder viscosity through rheological modification while still providing for the complete coating of aggregates at these lower temperatures. The HWMA mixtures are generally based on technologies involving bitumen emulsion or foamed bitumen, the primary effects of which are to reduce the viscosity of the binder through emulsification and to reduce the viscosity of the binder through volume expansion (foaming), respectively. The first reported trials of WMA were undertaken in Germany and Norway between 1995 and 1999 (Croteau and Tessier, 2008) with the first road trial in Germany in 1999 using the Aspha-min zeolite system.

These technologies are designed to achieve the same goals of producing successful and durable asphalt at lower temperatures. The main benefits that are claimed to result from these various WMA and HWMA technologies include the items listed here.

(*a*) Reduced mixing and compaction temperature leading to less binder hardening, an extended paving window and lower fuel use.
(*b*) Environmental aspects and sustainable development concerns particularly the need to reduce energy consumption, fuel consumption and CO_2 emissions.
(*c*) Improvements in field compaction which can extend the laying window, allow early trafficking and increase the layer thickness for short possession work.
(*d*) Less plant wear.
(*e*) Similar or better performance, including improved compaction, similar mixture stiffness, similar rutting resistance, improved resistance to thermal cracking, similar or less moisture damage and greater durability, to HMA.
(*f*) Potential to extend the haul distances from the asphalt plant.
(*g*) Potential to increase the proportion of reclaimed asphalt (RA) that can be added to the mixture.
(*h*) Lower fumes and emissions that improve working conditions and enhance welfare.

2. Lower temperature technologies

2.1 Terminology

In conventional asphalt plants, heat is used to dry the aggregate and to reduce binder viscosity. However, for lower temperature asphalt, the viscosity is reduced by adding water, chemicals or wax as lubricants in the mixing process or by foaming the bitumen so that the heat required can be reduced (Al-Rawashdeh, 2008). The development of different technologies for asphalt production has created different categories of asphalt. The different types of asphalt mixtures are usually defined in relation with their coating temperature as listed (Olard *et al*., 2007).

(*a*) Cold mix asphalt (CMA) – usually manufactured at ambient temperature from asphalt emulsions or foams.
(*b*) HWMA – produced at temperatures below 100°C down to about 70°C (also known as semi-warm mix asphalt).
(*c*) WMA – manufactured above water vaporisation at temperatures ranging from 100 and 140°C.
(*d*) HMA – usually produced at temperatures in the range 140 to 180°C depending on the mixture type and binder grade.

The distinction is shown in Figure 1, a variant of which has been used in several of the papers reviewed. Of these, CMA, HWMA and WMA are regarded as lower temperature asphalts, although this review has been restricted primarily to WMA and HWMA.

2.2 Categories

These lower temperature asphalts can be further categorised into five main types: organic additives; chemical additives; bitumen emulsion-based processes; water-bearing additives; and water-based processes. Generally, the organic additive and chemical additive systems produce WMA, the bitumen emulsion-based processes produce HWMA and the other categories vary.

2.2.1 Organic additives

The processes that use organic additives waxes, amides and sulfur show a decrease in viscosity above the melting point of the admixture (D'Angelo *et al.*, 2008). At temperatures above the melting point, they reduce the viscosity of the binder to make it possible to reduce the production temperature whereas, below the melting point, they tend to increase the stiffness of the binder (Perkins, 2009). Organic additives are often referred to as 'intelligent fillers' because they provide reduced viscosity at mixing/placement temperatures and increased viscosity at service temperatures, which is an added benefit specific to this type of WMA system (Croteau and Tessier, 2008).

Products available in this category include

(*a*) Asphaltan-B
(*b*) Cecabase RT
(*c*) Ecoflex
(*d*) isomerised paraffin
(*e*) Licomont BS 100
(*f*) Sasobit
(*g*) Shell Thiopave
(*h*) Sübit.

2.2.2 Chemical additives

Chemical additives, such as surfactants, are a relatively new, emerging group of additives for WMA (Anderson and May, 2008). These surfactants improve the ability of the bitumen to coat the aggregate particles at lower temperatures rather than reduce the bitumen viscosity. Certain chemicals are added to the binder in a manner similar to anti-stripping agents in a concentration as low as 0·3% by mass of the bitumen (Croteau and Tessier, 2008).

Products available in this category include

(*a*) HyperTherm
(*b*) Low emission asphalt
(*c*) Qualitherm
(*d*) Rediset WMX
(*e*) REVIX.

2.2.3 Emulsion-based processes

The bitumen emulsion technique was developed in North America and it consists of mixing a specific high residue bitumen emulsion with hot aggregate at a reduced mixing temperature of between 85 and 115℃. As the emulsion is mixed with the hot aggregate, the water flashes off as steam. The bitumen emulsion is specifically designed for the HWMA process and includes additives to improve coating, workability and adhesion. It has been reported that mixture workability remains excellent at relatively low temperatures (< 80℃), which is a specific benefit of this system (Croteau and Tessier, 2008).

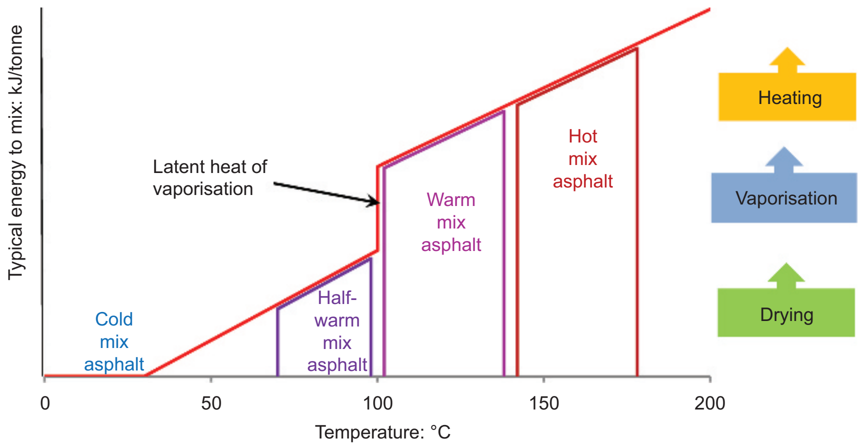

Figure 1. Classification by temperature range

Products available in this category include

(*a*) Evotherm DAT
(*b*) warm recycling.

2.2.4 Water-bearing additives

Water-bearing additives rely on a foaming action when water is introduced into a warm mixture. When small amounts of water are added to a warm mixture, the water vaporises and is encapsulated into the binder (Perkins, 2009). Small amounts of water can be added into hot asphalt via a foaming nozzle or expansion chamber, by incorporating a hydrophilic material such as zeolite or by having damp aggregate (D'Angelo *et al.*, 2008). When the hot bitumen makes contact with water, steam bubbles are forced into the continuous phase of the bitumen, which then expand until a thin film of bitumen holds the bubbles intact through their surface tension (Artamendi *et al.*, 2011). The volume of water expands by a factor of 1673 when it turns to steam at atmospheric pressure (Middleton and Forfylow, 2009). Therefore, the dispersion of the water in hot asphalt results in an expansion of the binder phase and a corresponding reduction in the mix viscosity and improvement in the workability. The amount of expansion depends on a number of factors, including the amount of water added and the temperature of the binder. The thin-film bitumen bubbles filled with water vapour are referred to as foamed bitumen (Croteau and Tessier, 2008). In a foam state, the viscosity of the bitumen is reduced which allows aggregate particles to be fully coated at lower mixing temperatures.

Products available in this category include

(*a*) Advera WMA
(*b*) Aspha-min
(*c*) ECOMAC
(*d*) LEAB
(*e*) LT asphalt.

2.2.5 Water-based processes

HWMA can be produced by modifying the binder/aggregate mixing process to achieve the lower mixing and placement temperatures as well as by applying additives of various types, as was the case for the previous categories. Several proprietary processes have been developed, either based on mixing the binder (in foam or liquid state) with coarse and fine aggregates sequentially or based on mixing the aggregate with two different binders (again in foam or liquid state) sequentially (Croteau and Tessier, 2008). These processes are relatively inexpensive, provided that plant modifications are minor.

Products available in this category include

(*a*) Eco-Foam II
(*b*) Accu-Shear Dual WMA System
(*c*) Aquablack WMA
(*d*) Double Barrel Green
(*e*) Green Machine
(*f*) Half-warm foamed bitumen process
(*g*) HGrant Warm Mix System
(*h*) Low emission asphalt (LEA)
(*i*) Low energy asphalt
(*j*) Meeker warm mix
(*k*) Terex WMA system
(*l*) Ultrafoam GX
(*m*) WAM foam.

3. Construction

3.1 Mixing

Trials of WMA laid in Canada (Davidson, 2008) had no issues with mixing, laying or compaction, with the physical properties of the WMA being equivalent to HMA in all respects and performing as well as the HMA sections after 3 years of service. This experience seems to have been replicated elsewhere, with no reported experience of an inability of the plant to produce the mixtures successfully. Generally, WMA can be produced without significant changes at the asphalt production plant (Manolis *et al.*, 2008), although some of the systems do require plant modification. Even where no modification is necessary, there can be additional costs in producing lower temperature asphalts in terms of royalties (from the producer to the developer of the particular system, if different) and the cost of additives (which will be influenced by the dosage rate required).

For many WMA and HWMA systems, slightly longer mixing times are required, but the need varies depending on the system. For LEA, where the key is the different sequencing of adding the components, the addition time is reported to be about 5 to 10 s (L. Cowley and G. Evans, personal correspondence, Petroplus Bitumen, 2011).

3.2 Transport

Although WMA and, particularly, HWMA, mixtures are at lower temperatures than HMA mixtures, it is still important that any heat losses during transport are kept to a minimum. Therefore, such mixtures still require trucks that are covered and insulated. For some of the systems, the truck bottoms and associated equipment remain very clean so as to negate the requirement for release agents in order to avoid the material sticking (L. Cowley and G. Evans, personal correspondence, Petroplus Bitumen, 2011).

One of the advantages of WMA over HMA is that is can be taken for longer haul distances (Davidson, 2008). One reason that the longer distances come about is because the mixing temperature can be increased (but still below the HMA mixing temperature) to compensate for the extra time in transport without that extra temperature damaging the binder (Croteau and Tessier, 2008). An alternative reason that has been proposed (D'Angelo *et al.*, 2008) is that there is a reduced rate of cooling for WMA with the lower temperature as well as a reduced viscosity of WMA.

3.3 Laying and compaction

The laying and compaction of WMA and HWMA do not differ from that of HMA other than the temperature at which these operations occur, so the same equipment can be used. It is possible to meet the required volumetric properties when laying and compacting WMA using standard paving machinery and rolling patterns (Manolis *et al.*, 2008). This view is supported by there being no issues with mixing, laying or compaction trials of different WMA systems laid in Canada (Davidson, 2008). However, there may be some minor differences in their use, such as reducing the screed temperature on the conventional paver and the need for a minimum mass of rollers, which for LEA would be down to between 100 to 140°C and 8 t, respectively (L. Cowley and G. Evans, personal correspondence, Petroplus Bitumen, 2011).

The paving-related benefits of using these mixtures include the ability to pave in cooler temperatures and still obtain density; the ability to have the workability to lay and compact the mixture after longer haul distances; reduced effort needed to compact the mixture; and the ability to incorporate higher proportions of RA at reduced temperatures (D'Angelo *et al.*, 2008).

WMA technologies are designed to act as compaction aids and reduce the required compactive effort (D'Angelo *et al.*, 2008). Some of the technologies (Sasobit and Licomont BS 100) were initially used for their stiffening effect at high in-service pavement temperatures. During this use, the materials reduced viscosity at compaction temperatures, particularly when compared with other types of modifiers. Therefore, it is not surprising that two of the advantages of WMA over HMA are as a compaction aid for stiff mixtures and improved compaction on site (Davidson, 2008). There is also a belief that a more uniform compaction can be achieved with WMA because its operating temperature allows the roller train to be better spaced so as to ensure proper mat coverage (Anderson and May, 2008). Improvements in workability will ultimately improve build-ability and increase the levels of compaction and, hence, ultimately affect longer-term durability (Self, 2006).

Another advantage of WMA over HMA is an extended paving season into cold weather (Davidson, 2008). Case studies in Europe have indicated that WMA has been produced, placed and properly compacted at ambient temperatures as low as −3°C (Anderson and May, 2008) while HyperTherm field trials in Ottawa demonstrated that WMA technology can be used to extend the paving season when it is necessary to do so (Manolis *et al.*, 2008).

With lower mixing temperatures, the temperature of the asphalt at the end of compaction should be lower with WMA and, particularly, HWMA than with HMA and, hence, closer to the service temperature at which it can take traffic without damage. Therefore, WMA and HWMA can be opened to traffic sooner and, for the same reason, multiple lifts with WMA can be overlaid sooner (Croteau and Tessier, 2008). It has been found that a reduction in laying temperature by 20°C will allow opening to traffic between 20 and 40 min earlier (Nicholls *et al.*, 2011). However, there is a counter view. The possible changes in the stiffness of the asphalt due to lower operating temperatures have been cited as a concern in that the workability would not dissipate prior to being opened to traffic, thus creating the potential for rutting (Hurley and Prowell, 2006).

4. Performance

4.1 Overall

A US study tour of Europe obtained laboratory and short-term field performance (with up to 3 years in service) data from three of the countries visited (D'Angelo *et al.*, 2008). The data indicated that WMA mixtures provide the same or better performance than HMA. It has been found (Diefenderfer and Hearon, 2010) that HMA and WMA sites perform similarly for at least the first 2 years of service, although noting that any improved WMA performance (as compared to HMA) will depend on the technology used to produce the WMA. Field densities had been found that appeared to be similar (Anderson and May, 2008), with slightly easier compaction being noted for WMA mixtures, while performance testing indicated that lack of age hardening may have caused the WMA mixture to be initially more susceptible to rutting if not allowed for in the selection of bitumen grade (and the use of RA). The same lack of plant age hardening should improve the initial cracking resistance of WMA in comparison with HMA. Controlled vehicle load tests and falling weight deflectometer tests conducted on site and in an accelerated pavement loading facility have shown that WMA and HMA mixtures behaved similarly (Al-Rawashdeh, 2008).

4.2 Durability

Over 5 Mt of LEA mixtures have been installed across Europe and the USA in all road layers including enrobé à module élevé (EME) binder course and polymer-modified binder (PMB) surface course on motorways and non-trunk roads under different climatic conditions from the warm South of France and Spain to parts of the world which experience both extremes of hot and cold weather conditions, such as the French Alpine region and New York State, USA. Since early trials in 2003 and commercial supply started in 2005, the materials have demonstrated acceptable in-service performance in that they continue to perform as would be expected from the HMA equivalent (L. Cowley and G. Evans, personal correspondence, Petroplus Bitumen, 2011). This type of experience has been found for other systems, but most WMA and HWMA systems have not been in general service for long enough to assess their actual long-term durability.

Test results from the saturated ageing tensile stiffness conditioning test for foamed HWMA and HMA had retained stiffness values in the region 0·8 to 1·2, indicating good durability (Artamendi *et al.*, 2011).

4.3 Deformation resistance

The deformation resistance for WMA and HWMA is generally acceptable and often better than HMA mixtures, but the performance does depend on the system.

A detailed analysis that was undertaken for Evotherm WMA (Hurley and Prowell, 2006) found that the bitumen grade had the largest influence on asphalt pavement analyser (APA) rut depth followed by compaction temperature, but with the presence of Evotherm significantly decreasing the rutting potential of an asphalt mixture.

For organic additive systems, gel permeation chromatography (GPC) analysis indicated that Sasobit lowered the large molecular sizes of one binder significantly, which suggests that mixtures with that binder will be more prone to rutting. However, Sasobit WMA, when compared to HMA, has shown significantly lower permanent deformation in repeated creep-recovery tests (Biro *et al.*, 2009) and greater resistance to densification under simulated trafficking, again indicating increased resistance to permanent deformation (Kantipong *et al.*, 2008). The deformation resistance was also enhanced with the inclusion of Shell Thiopave (Nicholls, 2009).

For water-bearing additives, the resistance to deformation of mixtures was generally improved with the addition of Advera WMA, even when mixed and compacted at lower temperatures (Nicholls *et al.*, 2011). Meanwhile, the addition of Aspha-min showed a higher potential for rutting from dynamic shear rheometer (DSR) test results but Aspha-min WMA had higher rutting resistance than HMA and the rutting resistance increased when the compaction temperature for the WMA increased (Goh and You, 2008). The reduction in the permanent deformation as identified from binder tests was different with different binders (Biro *et al.*, 2009), with GPC analysis indicating that Aspha-min, which is inorganic, had no significant effect on the binder (Biro *et al.*, 2009).

Results from both the Hamburg wheel tracking device and asphalt pavement analyser for foamed asphalt indicated that rutting should not be an issue (Hodo *et al.*, 2009) while wheel tracking test results at 60℃ on foamed HWMA indicated a similar performance to HMA in one test but a poorer performance in another (Artamendi *et al.*, 2011).

Overall, the deformation resistance appears to be dependent on the system, with some showing greater and others less than the equivalent HMA.

4.4 Stiffness

As with most of the other physical properties, the performance of lower temperature mixtures will depend on the particular system being used. However, there is inherently nothing that should reduce the stiffness of a mixture specifically because it is WMA or HWMA provided it has been adequately compacted.

For water-bearing additive systems, the stiffness of mixtures mixed and compacted at lower temperatures was found to be reduced with the inclusion of Advera WMA compared to HMA, but not to the same extent as mixtures mixed at those lower temperatures but without Advera WMA (Nicholls *et al.*, 2011). Similarly, WMA made with 0·5% Aspha-min and compacted at 120℃ showed a higher performance for dynamic modulus than when the mixture was compacted at 100℃ (Goh and You, 2008). These findings indicate that stiffness is lost when the mixing temperature is reduced for HMA, but that this loss can be minimised by using WMA and HWMA systems.

With the water-based processes, the conditioning of LEA samples prior to compaction provided higher wet and dry strengths when compared to the unconditioned samples, although the conditioning had no effect on tensile strength ratios. The dynamic modulus results indicate slightly less age hardening of the asphalt binder when using the LEA process but not significant enough to justify changing the grade of the binder (Harder, 2007).

The stiffness values of foamed HWMA and HMA were very similar in one trial and slightly lower in a second, although the value obtained, 2·9 GPa, is generally considered a typical value for a 20 mm dense macadam (asphalt concrete) (Artamendi *et al.*, 2011).

All these results show that stiffness is likely to be slightly lower for WMA and HWMA than for the equivalent HMA, but the difference should not be significant with a suitable choice of material.

4.5 Fatigue resistance

Results from dynamic mechanical analyses of mortar mixtures indicated that, for a given material combination, the fatigue cracking resistance typically decreased when the mixing and compaction temperatures were decreased (Vasconcelos *et al.*, 2010). However, results from a micro-calorimeter demonstrated that, for non-porous aggregates, lower aggregate temperatures within the range 90 to 150°C did not significantly impact on the total energy of adhesion and, therefore, did not significantly contribute to any reduction in fatigue cracking resistance (Vasconcelos *et al.*, 2010).

Nevertheless, there was an increase of about 10% in the slope and a commensurate reduction of 5% in the relative strain for a lifetime of 10^6 cycles for the fatigue curve with the addition of Shell Thiopave to one mixture (Nicholls, 2009). Similarly, the addition of Aspha-min showed a higher potential for fatigue cracking through the DSR test when compared to the control binder (Goh and You, 2008).

Overall, there appears a small decrease in fatigue resistance when moving from HMA to WMA and HWMA, although the actual situation will depend on the selected system.

4.6 Cracking

In a trial with Sasobit, no differences in surface condition were observed between the HMA and WMA sections during the first year of service although cracking along the centreline of the pavement was observed during the 2 year visit (Diefenderfer and Hearon, 2010). This cracking was primarily located in the HMA section, although some was observed in the WMA section, but the presence of cracking in both sections indicated that the cracking was unlikely to be materials related. Similarly, visual assessments performed during visits to different sites with Sasobit and Evotherm did not indicate any difference in performance between the HMA and WMA sections over a 2 year evaluation period (Diefenderfer and Hearon, 2010).

Route 11 in New York State was laid with a single lift overlay of 9·5 mm either with LEA or HMA to a compacted depth of 25 mm in July 2006 in the rain (Harder, 2007). A site inspection the following spring showed that the HMA section exhibited approximately seven times the amount of cracking as that of the LEA section.

4.7 Air voids content

In a site trial (Schmitt *et al.*, 2009), there was no statistical difference in the average density readings behind the roller between WMA and HMA, although the standard deviation of WMA was higher because of decreasing density values as the amount of RA increased. Separately, the air voids contents were determined for cores from four different asphalt mixtures (Sasobit, Evotherm, Aspha-min and HMA) taken in the wheel-path at construction and both 3 and 20 months after the construction of the road (Al-Rawashdeh, 2008). The air voids content increased during the first 3 months for the Sasobit and Aspha-min mixtures, which is surprising, but overall the WMA mixtures had lower air voids contents than the HMA mixture, with all the positive implications for durability.

Similarly, statistical analysis from three WMA trials, two with Sasobit and one with Evotherm, each with HMA controls, showed minor differences in the change in air voids contents with time in service between the HMA and the WMA, but there was no overall trend (Diefenderfer and Hearon, 2010).

Overall, suitable low air voids contents can be achieved with WMA and HWMA systems, although more care is needed with some systems.

4.8 Sensitivity to moisture

In WMA and, to a greater extent, HWMA the heat during mixing is less likely to completely dry out the aggregate than in HMA. Therefore, there are concerns that the potential for inherent dampness will make such mixtures more sensitive to moisture. This phenomenon has been found (Vasconcelos *et al.*, 2010) with the lower compaction temperatures used to produce WMA increasing the potential for moisture damage because of the incomplete drying of the aggregate at these lower temperatures. Testing has indicated that HMA mixtures tend to be less moisture susceptible than mixtures containing WMA additives (Austerman *et al.*, 2009). However, the effect of using WMA on stripping has been shown to be dependent on the system used (Croteau and Tessier, 2008), with some reports indicating a slight decrease in stripping resistance whereas others show no significant trend. Therefore, the addition of anti-stripping agents may be necessary when using certain WMA additives. Furthermore, water-sensitivity testing may be an integral step when developing a mix design procedure for mixtures with WMA additives.

4.9 Binder properties

The effect of the various additives and processes used for WMA and HWMA on the full spectrum of binder properties will be dependent of the selected system. Nevertheless, one of the advantages of WMA and HWMA over HMA is the reduced age hardening of mixtures that should occur at the lower mixing temperatures, with the resulting potential for longer service lives (Davidson, 2008). The penetration and softening point of the binders recovered from foamed HWMA has been found to show less hardening than similar HMA due to lower mixing temperatures (Artamendi *et al.*, 2011). However, the reduction is likely to be related to the technology chemistry and production temperatures and thus is somewhat project dependent, and further evaluation throughout the life of any mixture is necessary to validate this conclusion (Diefenderfer and Hearon, 2010).

4.10 Compositional analysis

Little was found about any problems with assessing the compositional analysis for WMA and HWMA. However, the bitumen contents of LEA mixtures determined by means of an ignition oven appeared to be higher than for equivalent HMA mixtures (Harder, 2007), which may be the result of very fine particles remaining in the LEA mixture and not going to the baghouse.

5. Environmental and economic issues

5.1 Energy savings

One of the advantages of WMA over HMA is lowering of overall energy costs (Davidson, 2008). The primary reason is that, in a traditional HMA process, a great deal of energy is spent drying aggregates by evaporating water with the latent heat of evaporation of water representing five times the energy required to raise the same mass of water from 0 to 100℃, allowing substantial energy savings if the mixing temperature remains below 100℃ (Romier *et al.*, 2006). Furthermore, reducing temperatures by 10℃ can produce savings of about 3 to 4% (Anderson and May, 2008; Self, 2006), which equates to around 0·25 kg fuel per tonne of asphalt produced, which is increasingly significant with the increasing cost of fuel.

The decrease in fuel use is affected by (Anderson and May, 2008; Harder *et al.*, 2008)

(*a*) type of equipment
(*b*) the type of dryer
(*c*) the exhaust systems of different pieces of equipment to the dust collector
(*d*) the amount of moisture in the aggregate requiring evaporation to achieve less than 0·5% by mass of the mixture
(*e*) the dryer exhaust temperature
(*f*) the entry temperature of the aggregate
(*g*) the type of fuel used
(*h*) the volume of air used in the plant operation in excess of the volume necessary to burn the fuel
(*i*) the plant elevation.

Estimates of the savings vary. It has been reported (Harder *et al.*, 2008) that the mixing of asphalt at 160℃ with an ambient temperature of 15℃ causes heat losses which are nearly twice those if the asphalt was mixed at 90℃. It has been reported (Hassan, 2009) that WMA provides a reduction of 18% on fossil fuel consumption in comparison with HMA. Energy-savings ranging from 20 to 35% at the plant have been reported on WMA trials (Croteau and Tessier, 2008). Others (D'Angelo *et al.*, 2008) have reported that burner fuel savings with WMA typically range from 11 to 35%, although fuel savings could be higher (possibly 50% or more) with processes such as low-energy asphalt concrete (LEAB) and LEA in which the aggregates (or a portion of the aggregates) are not heated above the boiling point of water.

However, a comparison of the materials and production costs indicates that, while WMA mixtures offer savings from reduced fuel consumption, it may not be enough to immediately offset the cost of the initial investment (in the case of the water-based process technologies) or the additives (in the case of the remaining WMA additives) (Anderson and May, 2008). However, other benefits, such as increased production or late-season paving, can provide additional economic incentives for WMA mixtures.

5.2 Carbon footprint

One of the advantages of WMA over HMA is reduced emissions of greenhouse gases (Davidson, 2008). Typical expected reductions are 30 to 40% for carbon dioxide and sulfur dioxide, 50% for volatile organic compounds (VOC), 10 to 30% for carbon monoxide, 60 to 70% for nitrous oxides and 20 to 25% for dust (D'Angelo *et al.*, 2008). Actual reductions will vary depending on a number of factors, but technologies that result in greater temperature reductions are expected to have greater emission reductions.

Although there are factors other than energy consumption that affect the carbon footprint, the reduction in greenhouse gas emissions is closely associated with the reduction in energy consumption (Croteau and Tessier, 2008), with 20 to 35% reduction in $CO_{2\text{-e}}$ equating to about 4·1 to 5·5 kg of $CO_{2\text{-e}}$ per tonne of asphalt. It has been estimated (Self, 2006) that 0·4 Mt less CO_2 would be produced annually if the entire 63 Mt of asphalt produced in Germany was all lower temperature asphalt, representing a potential reduction of approximately 25%.

However, despite these findings, the effect of using additives on the carbon footprint of an asphalt mixture often depends on the amount of $CO_{2\text{-e}}$ that is required to produce the additive and where it is produced. If the additive has to be transported half way around the world rather than locally, it can increase the $CO_{2\text{-e}}$ to change the effect from positive to negative (Nicholls, 2011). Therefore, the actual effect needs to be checked for each particular situation. For the analysis, the method preferred by the Highways Agency for use in the UK is Aspect (Wayman *et al.*, 2010).

5.3 Improved worker welfare

Bitumen fumes produce emissions of VOCs, including polycyclic aromatic hydrocarbons (PAHs), which are present in small quantities and have an adverse impact on health. However, bitumen fumes are not listed as carcinogenic substances by the European Union and independent studies carried out by international scientific bodies have not found any causal link between bitumen fumes and lung cancer (Self, 2006). A reduction of 13°C in the manufacturing temperature of the mixture will halve the PAH emissions, which considerably reduces the health risks (Olard *et al*., 2007). A lower temperature reduces the amount of bitumen fumes and odour produced during construction, with the estimated range varying from 30 to 50% (Anderson and May, 2008; D'Angelo *et al*., 2008) and from 30 to 90% behind the paver (Croteau and Tessier, 2008).

5.4 Increased proportions of reclaimed asphalt

Increased use of RA has a potential economic benefit for the user and producer. The amount of RA has been limited in HMA by many US highway agencies because of concerns that at higher amounts of RA the asphalt mixture would be too 'aged' after production leading to a potential for early cracking (Anderson and May, 2008). In WMA, the lower mixing temperatures means that the virgin asphalt binder would not be as age hardened as in an HMA and, therefore, an increase in RA could be possible before the resulting mixture would be too stiff, leading to the potential of early cracking. The higher aggregate temperature needed for RA results in more complete removal of internal aggregate moisture in WMA production and it increases the temperature of the exhaust gas going into the baghouse for operational efficiency. Therefore, WMA allows for a higher rate of recycling because it may allow more conductive heat to be transferred between hot aggregates and reclaimed asphalt (Croteau and Tessier, 2008).

However, the recycling constraints for WMA may differ from those of HMA recycling (Croteau and Tessier, 2008). The decrease in mixing temperature also decreases the added binder ageing and, as a result, the properties of the blend of recovered binder may differ from the same blend of binder obtained through the HMA process, with the warm mix process helping the rejuvenation of the RA binder in a similar manner as if a softer binder was used in the HMA process.

6. Conclusion

The literature reviewed indicates that lower temperature asphalt can be produced that is equivalent to HMA in terms of the physical properties achieved but with environmental and, possibly, economic advantages. However, care must be taken to ensure that the aggregate particles are adequately coated and that excess moisture is removed. These potential disadvantages are, theoretically, more likely with the colder systems.

In particular, the review has demonstrated the following conclusions.

(*a*) There are a large number of WMA and HWMA systems that are based on very different technologies to reduce the temperature at which the mixtures are produced.
(*b*) The equipment used for producing, transporting and laying WMA and HWMA are basically the same as for HMA, although there may need to be some modification to the mixing plant dependent on the specific process.
(*c*) It is suggested that longer haul distances are possible.
(*d*) The workability of WMA and HWMA has to be better than HMA to make the reduced production temperatures viable.
(*e*) The time before opening to traffic or overlaying will reduce as the production temperature is reduced.
(*f*) The deformation resistance appears to be dependent on the system, with some showing greater and others less than the equivalent HMA.
(*g*) The stiffness was marginally lower for WMA and HWMA compared to HMA.
(*h*) The sensitivity to moisture appears to be dependent on the specific system and should be checked and corrected with the addition of adhesion agents if necessary.
(*i*) The bitumen will age harden less during construction with WMA and HWMA compared to HMA.
(*j*) The energy to produce WMA and HWMA is less than for HMA, but needs to be balanced against the one-off costs of any plant modifications necessary.
(*k*) The carbon footprint of WMA and HWMA should be less than HMA, but the actual advantage will be job specific.
(*l*) There will be less bitumen fumes and associated emissions with WMA and HWMA compared to HMA, with the associated improvement in the working environment.
(*m*) The proportion of reclaimed asphalt can be increased for WMA and HWMA compared to HMA.

These advantages and disadvantages tend to be greater for HWMA than WMA because of the temperature difference.

Acknowledgements

The work described in this paper was carried out by the infrastructure division of TRL Limited on behalf of the Highways Agency. This paper is published with the permission of the chief executives of all the organisations, whose support is gratefully acknowledged.

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