Jurnal Teknologi

Full paper

Warm Mix Asphalt Technology: A Review

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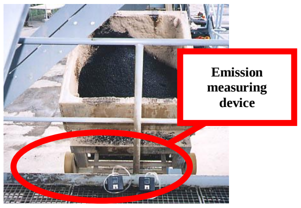
Article history

Received :5 June 2014
Received in revised form :
25 September 2014
Accepted : 16 October 2014

Graphical abstract



Abstract

Warm Mix Asphalt (WMA) represents the technologies that allow the reducing of asphalt binders' mixing and compaction temperatures by reducing its binders' viscosity. This paper gives a comprehensive chronological review from prior researches and practical experienced among researchers and industrial practitioners while implementing WMA technology including constituent materials, mix design and mechanical performance issues. Within this, the problems and benefits as well as different types of WMA additives were clearly identified as essential for a better understanding of the application of WMA technology in pavement constructions.

Keywords: warm mix asphalt, global warming, WMA additive, WMA performance

■1.0 OVERVIEW OF GLOBAL WARMING

The greenhouse effect can be considered as a condition where the short wavelengths of visible light of the sun passing through a transparent medium which is later absorbed and converted to heat energy. However, some of the heat that has been re-emitted from the heated objects is not capable to pass through that medium. The trapped heat by the greenhouse gases in the atmosphere leads to more heating and consequently, resulting higher temperature of the earth. Nevertheless, without this natural effect, the earth's surface temperature would dramatically decrease below freezing temperature. The study shows that this effect can be linked directly to the increasing of greenhouse gases such as carbon dioxide, methane and nitrous oxide from human activities. Hence, this will aggravate the global warming that causes climate change and rising of the sea levels. Global warming is primarily an important issue to be concerned of for the sake of us and our children in the future. This important issue has been identified internationally through the United Nations Framework Convention on Climate Change. Many countries are signatory to the issue and have agreed on the national targets for the reduction of greenhouse gas emissions in the Kyoto Protocol [1-3].

The Kyoto Protocol was completed on December 11, 1997 which comprised of 28 articles with the aim to decrease the growth of greenhouse emission in order to improve the global climate. The protocol had set up greenhouse gas emission targets for participating nations as a percentage of emission level in 1990. Canada was charged with reaching a level of 94% while the United States was required to reach a level of 93%. A credible long-term emissions reduction target is an important part of ensuring a certain country can make a smooth transition to a low-carbon future. Therefore, the national policies especially in the areas of energy efficient technologies, renewable source of energy, promotion of sustainable forest management practices and also the reduction of fiscal incentives in greenhouse gas emitting sectors of the economy must be well developed in each country. Additionally, the emission reduction can be implemented not only by using alternative energy production methods. It is desirable for all countries to encourage and reward credits based on the environment factors where the effort is coming from human initiative rather than natural occurring [4].

■2.0 GREEN TECHNOLOGY IN MALAYSIA

In simple words, Green Technology definition is a developed environmental friendly product and processed without disturbing the environment and conserves natural resources. The Malaysian government had identified green technology as the main growth area under the National Green Technology Policy in 2009. The implementation of Green Technology is expected to minimise and reduce the negative impact of all human activities towards natural environment and resources. According to the policy, major improvement of the Green Technology was established based on four key areas as the following [5]:

(i) Energy Sector
Green technology is applied in power generation and also in the energy supply side management that include co-generation by the industrial and commercial sectors. This policy has also emphasised all Energy Utilisation Sectors including the demanding side of the management programmes.
(ii) Building Sector
The Green Technology is adopted in the construction, management, maintenance and also the demolition of buildings.
(iii) Water and Waste Water Management Sector
Adoption of the Green Technology in the construction, management, maintenance and demolition of buildings.
(iv) Transportation Sector:
Incorporation of the Green Technology in the transportation infrastructure and vehicles, in particular, biofuels and public road transport.

In addition to the four key areas, Malaysian government had announced the National Green Technology Policy Strategic Thrusts in 2011 to strengthening the green technology adoption. The Strategic Thrust consists of five thrust as the following:

(i) Strengthen the institutional frameworks
(ii) Provide Conducive Environment for Green Technology Development
(iii) Intensify Human Capital Development in Green Technology
(iv) Intensify Green Technology Research and Innovations
(v) Promotion and Public Awareness.

Currently, many researchers are supporting the fourth thrust in order to help the government in achieving their goals towards implementing green technology in Malaysia. The fourth thrust claimed that the Research, Development, Innovation and Commercialisation (RDIC) is very crucial in creating new technologies, techniques and applications which would be able to reduce the cost of Green Technology and promote its usage. It is also stated that the Research, Development and Innovations (RDI) could be enhanced through [5]:

(i) Provision of financial grants or assistance to public and private sector in RDIC;
(ii) Implementation of Green Technology foresight;
(iii) Establishment of an effective coordinating agency for RDI and Centre of Excellence or new research institute for Green Technology development;
(iv) Enhancement of smart partnerships between the government, industries and research institutions; and
(v) Establishment of strong linkages between local research institutions and regional and international centers of excellence in Green Technology RDI.

As from the perspective of pavement technologies, warm mix asphalt (WMA) is one of the potential technologies that can be implemented by local authorities in supporting this green technology by replacing the conventional hot mix asphalt (HMA) practice. Some of the countries are also strictly practising environmental regulations to increase the awareness among the contractors to transform from conventional HMA to the new technology of WMA. Currently, local authorities and public users in Malaysia are concerned on the issues of global warming which can affect the surrounding environment in the near future. Therefore, researchers and pavement industries have put their energy and efforts in implementing the WMA technology in order to reduce energy requirements during pavement construction for environmental benefits.

■3.0 WARM MIX ASPHALT TECHNOLOGY

Asphalt mixture is the most popular paving material used all over the world and it is a uniformly mixed combination of asphalt binder, coarse aggregate, fine aggregate, filler and other materials depending on the type of asphalt mixture. The different types of asphalt mixtures implemented among contractors in pavement construction are HMA, WMA and cold mix asphalt [6]. HMA has been conventionally produced at a temperature of between 155 and 165°C, resulting in high energy (fuel) costs and generation of greenhouse gases [7]. Figure 1 shows the typical mixing temperatures for asphalt mixtures.

The WMA technology can reduce production temperatures, reduce odour emission from plants, longer paving seasons, longer hauling distances, earlier traffic opening, reduce binder aging, reduce cracking and minimise oxidative hardening, since the mixes are produced closer to the operating temperatures [8-10].

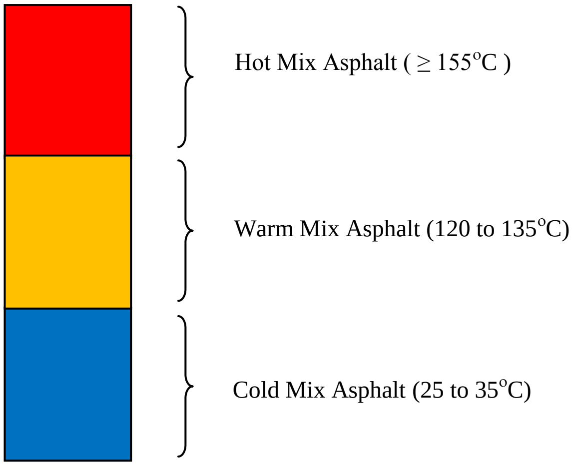


Figure 1 Typical mixing temperature range for asphalt mixtures [7]

Since pavement construction with warm asphalt mixes did not begin until the middle of the 1990's, little is known about the long-term mechanical performances of these mixtures. In this regard, most of the practical tests to assess the performance of this asphalt had been based on field trials. Such tests have been implemented throughout the USA. However, in Europe, the only countries that have performed this type of tests are Germany and Norway [11]. Therefore, most literatures present their findings based on the performance results obtained from the laboratory tests and there are limited publications explaining the findings according to the field performance.

3.1 The Advantages of Implementing WMA Technology

The advantages of implementing WMA technology have been constantly established among local authorities, pavement industries and researchers all over the world. It has been reported that the WMA technologies promised several advantages as compared to the conventional HMA. The detail advantages of this technology are described as follows:

(i) Environmental benefits
(ii) Economical benefits
(iii) Construction benefits
(iv) Recycling benefits

3.1.1 Environmental Benefits

In many countries, electricity, fossil fuels, mining, iron and steel, chemical industrial, paper and also asphalt mixing are considered as the energy-intensive industries. Among them, asphalt mixing contributes one of the most energy-intensive processes as compared to other industrial activities. During the mixing process, the energy consumed was about 60% of the total energy required for the construction and maintenance of a given road over a typical service life of 30 years. The process of WMA will produce temperature as low as 10 to 40°C which is lower than the typical HMA production temperatures. The advantage of this technique is not only towards the energy saving but also to the reduction of emissions. In addition, the electrical usage for mixing the material and also to move the material through the plant is also reduced due to the lower temperature usage during production [7, 12-15].

Based on the Bitumen Forum [16], there are virtually no asphalt emissions at temperatures below 80°C. At about 150°C, the emissions recorded were only about 1mg h-1 whereas significant emissions were recorded at 180°C. This shows that the temperature reduction in WMA produces a dramatically drop in fumes and several pollutants like CO_2, NO_x and SO_2 [11, 14, 16-17]. Table 1 shows the reduction of emissions due to implementation of WMA.

Table 1 Emission reduction when implementation of WMA [16]

Air Pollutant Gaseous	Reduction Measured as Compared to HMA
CO_2	15 to 40%
SO_2	18 to 35%
NO_X	18 to 70%
CO	10 to 30%
Dust	25 to 55%

Moreover, this reduction of emissions is also beneficial to the workers that will negatively be affected by exposure to the fumes which is produced during asphalt paving process. The less exposure will lead to the improvement of working conditions. Workers' exposure to emission is more critical for paving project in closed area like tunnels [7, 11-12, 18]. Figure 2 shows the measurement of emissions during the production of asphalt mixtures at plant.

Based on the study, hot asphalt fumes generated during asphalt mixing processes contain polycyclic aromatic hydrocarbon (PAH) compounds. Some of the compounds contain carcinogenic, mutagenic and teratogenic. Carcinogens are known as the agent that will cause cancer, mutagens will damage the genes causing heritable abnormalities in offspring while teratogens will produce abnormalities in the growing embryo or foetus. Currently in practice, the most common asphalt mixing process is HMA which can allow PAH emissions especially during the required warming and drying of the aggregate steps. Goh [7] had stated that the percentage of PAH reduction in WMA is between 30 to 50%. Hence, the use of WMA processes can effectively reduce the production of these fumes which consequently reducing exposure to many people especially the paving crews, contractors, local authorities and also the public [12, 16].

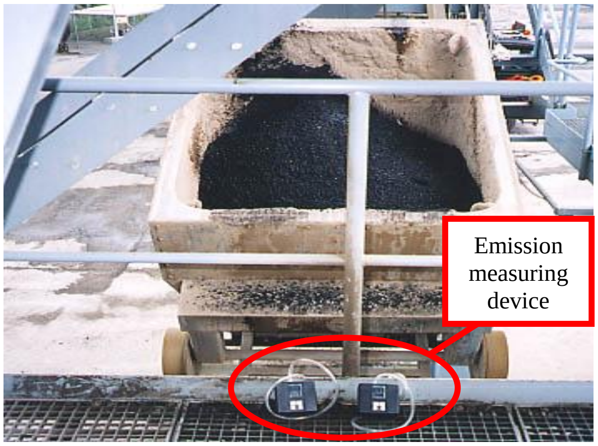


Figure 2 The emission measurement [19]

3.1.2 Economical Benefits

In terms of economical benefits, the advantages of WMA are according to the type of energy used during production process, maintenance cost of asphalt plant and also the types of gaseous pollution. Furthermore, there are road agencies of certain countries that have allocate some fund or tax reduction for any construction that can produce lesser CO_2 emission. Besides that, the energy consumption is quite high thus any reduction of energy will give a major value impact to all asphalt producers. Based on the previous study, the reduction of fuel consumption will directly depending on the amount of temperature reduction. The energy consumption of WMA is said to be around 60 to 80% of the HMA energy consumption [11-12].

3.1.3 Construction Benefits

After the modification of virgin asphalt binder with WMA additives, the viscosity of modified binder has changed and it creates better workability of the mixtures at lower temperature. In addition, previous study [20] showed that these technologies work as compaction aids and also in reducing the requirement of compaction effort.

There is yet another benefit which is the possibility of its construction during the cold weather. In that weather condition, the cooling period for asphalt mixture is less dramatic since it is closer to the ambient temperature. Therefore, it is possible to extend the paving season further into the year since there is more time for paving and compacting. Based on this reason also, it is feasible to haul longer distances between pavement construction sites and the existing of asphalt plant [11, 21]. Moreover, the reduction of temperature difference contributes to the reduce of road construction and opening time and it is also a really pleasant situation of certain road construction such as the airport, tunnel, rehabilitation area and high traffic city road [7, 14, 22].

3.1.4 Recycling Benefits

Reclaimed Asphalt Pavement (RAP) is a milling waste material produced from the milling processed of pavement surface when it reaches the end of its design life and can be used as aggregates for laying roads. RAP is a 100% recyclable material and has become a popular waste material in pavement construction and rehabilitation. In the United States, there are almost 100 million tons of RAP are produced annually, with about 60% is being used for new construction of asphalt pavements, while the remaining 40% is used for road base layer [14, 23-24]. Meanwhile, the National Asphalt Pavement Association concluded that high RAP mixtures containing 30 to 40% RAP are possible to be produced from the conventional HMA pavement surface [25]. However, studies have recorded that the RAP percentages over 50% can be used for the pavement construction using the WMA technology. The increased percentage of RAP usage could be due to less aging of the binder during the production of WMA mixture [11, 16, 21-22].

■4.0 CATEGORY OF WMA PROCESS

There are huge numbers of publications regarding the WMA technologies found in the literature and it can be classified into three major categories: (1) Foaming asphalt technology where foaming is caused by water or by natural or synthetic zeolite injection into asphalt mixture during mixing process; (2) Organic additives for the reduction of asphalt binder viscosity where additives are injected into asphalt mixer together with mineral materials and; (3) Chemical additives for the reduction of asphalt binder viscosity where additives are blended with asphalt binder before the modified binder is placed in asphalt mixer [11-12]. The explanations on each category are as follows:

4.1 Foaming Processes

Some authors subcategorised the foaming processes technology into two groups which are water containing and water based [12, 26-28]. As for the modification of asphalt mixtures using foaming process caused by water containing, natural or synthetic zeolite was injected into asphalt mixture during the mixing process. On the other hand, foaming processes technology for water based was conducted by spraying water into hot asphalt binder or by mixing the wet sand into asphalt mixture [11-12].

4.1.1 Water-Containing Technologies

In water-containing technologies, the synthetic zeolite is used to produce the foaming process. The aluminosilicates of alkali metal contained in the product has been hydrothermally crystallised. As the temperature rises, the crystallisation process which was released from the zeolite structure occurred with approximately 20% of water, thus causes a microfoaming effect in the asphalt mix. The microfoaming effect usually lasts about 6 to 7 hours.

Zeolite has a very unique structure composed of large air fractions that can be hosted by cations and even molecules or cation groups. Zeolite is formed in silicates framework and has large empty spaces in their structures and therefore it can allow the presence of large cations (sodium and calcium). The main characteristics of this special silicate framework make it able to lose and absorb water at the same time without damaging the crystalline structure. There are several products of synthetic zeolite available in the market such as Aspha-min® (product of Eurovia and MHI) and Advera® (product of PQ Corporation) [16, 29]

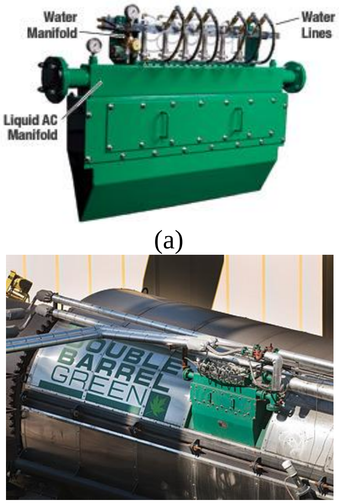
4.1.2 Water-Based Technologie

Basically, the foaming processes include the addition of small amount of water by injecting it into the hot binder or directly into the mixing chamber. The high temperature from the process of mixing hot asphalt binder with water will cause it to evaporate and trap the steam. A large volume of foam generated temporarily increases the volume of the binder while at the same time reduces mix viscosity. This effect remarkably improves the coating and workability of the mix, but its duration is limited. This means that the mix must be spread and compacted soon after production [29-30].

Since the water-based technologies use water in a direct way, special precautions on the nozzle setting must be taken when adding water in order to control the amount of water that should be just enough to produce the foaming effect. During the process, it creates a large volume of foam as water rapidly evaporates which causes a reduction of viscosity. As mentioned earlier, the decrease in viscosity can allow a lower temperature for aggregate coating and mixture compaction. The process of adding the water is basically looks like the same for most of these product and technologies, but the way of adding the water differs either through the water-containing technologies or water-based technologies. The excessive addition of water will cause a stripping problem. This category can be subdivided into the types of product used to produce the WMA mixtures [7, 11-12, 26]:

i. Double Barrel Green:
The Double Barrel dryer/drum mixer (Figure 3) combines the functions of a dryer and a continuous process mixer in one compact and efficient system. The basic principle for injecting the water is same but it uses several cold water to microscopically foam the binder. During the process, drying of the virgin aggregate need to be dried first and it takes place inside the inner drum. Then, aggregate and other ingredients are mixed and it happens in the outer chamber of the stationary shell. Each drying and mixing process are conducted in this drum [31].

ii. WAM Foam:
It is known as a two-phase method where there is two-component binder system that feeds a soft binder and a hard foam binder at different times into the mixing cycle during production. The foaming process begins with the mixing of soft asphalt with aggregate to precoat it. Next, the mixture is added with hard asphalt which previously foamed by the injection of cold water (quantity ranging from 2 to 5% of the hard binder) [11, 16, 32].



(a)

(b)

Figure 3 Double Barrel Green System: (a) before installation and (b) after installation [7, 29]

4.2 Organic Additives

The organic additives are also commonly used among pavement industries as warm asphalt additive. The implementation of organic additives is conducted by modifying the virgin asphalt binder with organic wax or by blending the additives with asphalt mixtures in order to reduce the viscosity of the binder. During the modification, mixing and compaction processes, the temperature of binder is high and the effect of the modifiers only take place when the modified binder is cooled. When the asphalt binder is cooled, the additive crystallises and forming a lattice structure with microscopic particles which could increase the binder stiffness and therefore could improve the rutting resistance [12].

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In simple words, the organic additive generally formed by a long chain of hydrocarbon atoms and it can reduce the viscosity of asphalt binder when heated above their melting point. The organic additives have carbon chains greater than C45 (carbon atom that has the length of 45 carbon backbone chain). The longer the carbon chain, the higher the melting point [7, 12]. Currently, there are several types of organic additives used in WMA technology such as Fischer-Tropsch wax, fatty acid amide, Montan wax and recycled pyrolytic polyethylene wax (RPPW).

4.3.1 Fischer-Tropsch Wax

Sasobit is a fine crystalline, long-chain aliphatic polymethylene hydrocarbon produced from natural gas using the Fisher–Tropsch (FT) process. The product is also known as FT hard wax and obtained through synthesis method of hydrocarbons and other aliphatic compounds from synthesis gas (CO/H_2) [7, 12]. During the synthesis process, coal or natural gas (methane) is partially oxidised to carbon monoxide which is subsequently reacted with hydrogen (H_2) under catalytic conditions producing a mixture of hydrocarbons having molecular chain length of carbon ranging (C_5) to C_{100} plus carbon atoms [33-34]. At the early stage of synthesis process, the gas is reacted with either an iron or cobalt catalyst to form products such as synthetic naphtha, kerosene, gasoil and waxes. Then, the liquid products are separated and the FT waxes are recovered into transportation fuels or chemical feed stocks. The Sasobit recovered is in the carbon chain length range of C_{45} to C_{100} plus. As for a comparison, macrocrystalline asphalt mixtures containing paraffin waxes have carbon chain lengths ranging from C_{25} to C_{50}. Studies have shown that the longer carbon chains in the FT wax lead to a higher melting point when modified with virgin binder. Studies also indicate that smaller crystalline structure of the FT wax can reduce brittleness at low temperatures as compared to binder containing paraffin waxes [7, 33-34]. The small pellets of Sasobit used in asphalt binder modification are shown in Figure 4.

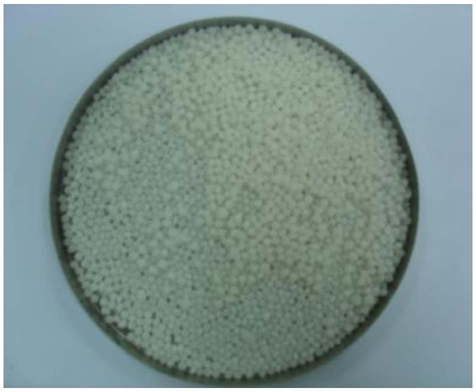

Figure 4 Small pellets of Sasobit [13]

4.3.2 Fatty Acid Amide

The product of Licomont BS 100 is developed by Clariant as an additive for WMA process. This additive is a product of fatty acid amide which is produced by reacting amines with fatty acids. Researchers stated that the melting point is ranging between 141 and 146°C, whereas solidification takes place at 135 to 145°C. After modification with virgin asphalt, it will form crystallites after the fatty acid amides cooled, thus increasing the asphalt stability and deformation resistance. For several years, similar products have been used as viscosity modifiers in asphalt, and have been used in roofing asphalt from the late 1970s to the early 1980s [11, 16].

4.3.3 Montan Wax

Asphaltan-B supplied by Romonta is a refined Montan wax blended with fatty acid amide is implemented as warm asphalt additives in Germany. Montan wax is a combination of nonglyceride long-chain carboxylic acid esters, free long-chain organic acids, long-chain alcohols, ketones, hydrocarbons, and resins. Montan wax is obtained by solvent extraction of certain types of lignite or brown coal. Besides that, it is also known as lignite wax or OP wax which is traditionally used to build cars, shoe polishes, paints and as a lubricant for moulding papers and plastics. About a third of its production worldwide is used in car polishes. Unrefined Montan wax contains asphalt and resins, which can be removed by refining. Since the melting point of this wax in its pure state is ranging between 82 to 95°C, it is often blended with materials with a higher melting temperature such as amide waxes. During the asphalt mixture production, Montan waxes can be fed directly into the mixer or into the mobile stirrer for mastic asphalt and this process required additional mixing time [11, 16, 22].

4.3.4 Rh-WMA Modifier

RH-WMA which is shown in Figure 5 is a polyethylene wax based asphalt binder additive produced from cross-linked polyethylene developed by Research Institute of China Highway Ministry of Transport [35]. It is designed to reduce the viscosity of asphalt binder at high temperature while strengthening the asphalt crystalline structure at low temperature. RH-WMA contains most of the benefits stated earlier when implementing the WMA technology including reduction in production temperature without compromising the performance of pavement [36].

Figure 5 Grains of RH-WMA additive

4.3.5 Recycled Pyrolytic Polyethylene Wax (RPPW)

In China, researchers [37] have studied the application of recycled pyrolytic polyethylene wax (RPPW) made from recycled cross-linked polyethylene (XLPE) as WMA additive (Figure 6). The XLPE has an excellent insulating characteristic and has been widely used as an insulating material for electric wires and cables in higher temperature conditions. XLPE waste was burned as fuel or buried due to the difficulty of recycling because of its low fluidity and poor moldability. Based on their finding, the viscosity of virgin asphalt binder modified with RPPW was decreased and the rutting resistance was improved which could promise remarkable construction performance at lower temperature for warm mix asphalt [37].

Figure 6 The recycle cross-lick polyethylene, RPPW used as warm asphalt additive [37]

4.4 Chemical Additives

The WMA mixtures using chemical additives are frequently used in the USA and the European countries such as Netherlands, France and Norway. Currently, there are many manufactures starting to develop their own WMA technologies especially on the chemical additive process since many countries are now trying to implement the WMA technology for their pavement construction and maintenance activity. In general, the processes of chemical additive products do not depend on foaming or viscosity reduction for lowering the mixing and compaction temperatures. It is basically an innovation through a combination of emulsification agents, surfactants, polymers, and additives in order to improve coating, mixture workability, and compaction, as well as adhesion promoters (anti-stripping agents). The chemical additives are mixed with virgin asphalt binder before batching the binder into the asphalt mixer. The examples of WMA technologies using chemical package include Cecabase® RT [38] , RedisetTM WMX [39] and Evotherm [40].

Cecabase (Figure 7) is a product of Arkema Group in France, is an organic additive which is liquid at 25°C and used as an additive in the production of the WMA. The Cecabase RT® additive acts at the interface between mineral aggregate and asphalt, in a similar way that a surfactant acts at an interface between water and asphalt that does not significantly change the rheological properties of asphalt. Cecabase RT 945 enables to reduce the asphalt mix production and lay down temperature by 20 to 40°C and keeps the same mechanical properties as a standard HMA [38, 41].

Figure 7 Cecabase additive

Meanwhile, Rediset WMX (Figure 8) was introduced in 2007 to mitigate the perceived deficiencies of then current warm mix technologies. In particular the system was designed to solve potential problems with the effects of water on warm mixes; the reduced stiffness in warm mixes compared to hot mix; and with the uncertain low temperature properties. Rediset WMX falls in the chemical group of asphalt modifiers which does not involve the addition of water to the system. Rediset WMX comprises of a dry chemical additive in solid pastillated form which is added to the asphalt before or during the mixing process [39]

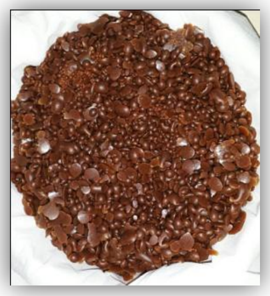

Figure 8 Rediset WMX additive

Besides that, the earlier product of Evotherm™ (Figure 9) is a typical case where it is in a package of additives which is used in a form of emulsion. However, there is an improvement for the third generation process of Evotherm (Evotherm 3G) where it is a water-free WMA technique. In this new innovation, the Evotherm 3G additive is incorporated into asphalt binder before it is delivered to asphalt plants. Therefore, there is no equipment changes required either at the plant or job site when using the Evotherm additive. This product also can significantly reduce the production temperatures of asphalt mixtures without compromising its quality. The workability and compaction at reduced temperatures are easier than HMA, especially for coarse mixes and polymer modified asphalts. Currently, the Evotherm binder performance matches or surpasses the qualities found in new hot-mix asphalt and allows higher percentages of RAP to be used [12, 40, 42].

Figure 9 Evotherm additive

■5.0 WMA MIX DESIGN METHOD

Currently, most researchers and industries have implemented either the Marshall or Superpave mix design method for their works which depends on the local standard specifications. In Europe and Asia, the Marshall mix design method has been widely implemented while the Superpave design has been implemented in most of the states in the USA. Therefore, researchers can select their own interest of mix design methods in order to evaluate the performance of WMA technologies with different asphalt mixture gradations [11-13].

5.1 Aggregate Gradation

The aggregate gradation depends on the selection of asphalt mixture gradations and all of the tests following HMA guidelines. The test process is the same for all cases. The result of comparing both control HMA mixes and WMA mixes with the same gradation showed that no obvious differences were noted in the aggregate gradation of WMA [11].

In practice, it can be said that WMA has been used in producing all types of asphalt mixture gradations. Studies conducted among researchers have shown that WMA has been used in producing all types of asphalt mixture gradations such as dense-graded asphalt mixture, porous, polymer-modified asphalt (PMA), stone mastic asphalt (SMA), crumb rubber modified (CRM) asphalt mixture, asphalt mixture incorporating RAP. As a result, the mechanical properties of WMA can vary in a large range depending on the specific WMA technique applied as well as the selected type of asphalt mixture gradation [11-12].

5.2 Asphalt Binder Content

In laboratory practices among researchers, the optimum binder content (OBC) for WMA mixtures can be determined based on the OBC of control HMA mixtures (without the addition of warm asphalt additives) according to the standard HMA design procedures. This method was practiced among researchers in their previous works when dealing with WMA modifications [27, 32, 40]. Therefore, the preparation of WMA specimens for the performance test will be based on the same OBC as the beginning of the mix design determination.

5.3 Additives

The percentages of WMA additives are vary depending on the recommended amount by manufacturers and it may slightly differ when modified with different sources of virgin asphalt binders. In addition, Goh [7] and Rubio [11] had shown the recommended usage for certain additives according to their manufacturers which is presented in Table 2.

5.4 Production And Compaction Temperature

For the production of WMA mixture, most researchers prepared the specimens at temperatures in the range of 16 to 55°C lower than the typical HMA [11, 43]. Since there is no standard specification available for WMA mixing and compaction temperature, specimens of WMA were prepared at three different production temperatures within that range. In addition, the compaction temperature was approximately 10°C below the mixing temperature [34, 43-46].

Table 2 Examples of existing and potential warm mix technologies [7, 11]

WMA Additives	WMA Technology	Company	Recommended Additive/ Usage
Foaming Additive	Aspha-min®	Eurovia and MHI	0.3% by total weight of mixture
	Advera® WMA	PQ Corporation	0.25% by total weight of mixture
	WAM-Foam®	Kolo Veidekke Shell Bitument	No additive. It is a two component binder system that introduces a soft and hard foamed binder at different stages during plant production.
	LEA®	LEA-CO	3% water with fine sand mix with hot coarse aggregate
	LEAB®	Royal Bam Group	0.1% by weight of binder
	Double Barrel Green	Astec	2% by weight of binder
Organic Additives	Sasobit®	Sasol	0.8-4.0% by weight of binder
	Asphaltan-B®	Romonta	2.5% by weight of binder
	Licomont BS 100®	Clariant	3% by weight of binder
	RH-WMA	Research Institute of China Highway Ministry of Transport	3% by weight of binder
Chemical Additives	Cecabase RT®	Arkema Group	0.2-0.4% by weight of mixture
	Evotherm®	Meadwestvaco Asphalt Innovations	0.5% of mass of binder emulsion where the emulsion contains 70% of binder. Generally pumped directly off a tanker truck to the asphalt line using a single pair of heated valves and check valves to allows for recirculation
	Rediset WMX®	Akzo Nobel	2% by weight of binder

■6.0 PERFORMANCE OF WARM MIX ASPHALT

As discussed earlier, WMA has been implemented worldwide because of the increasing concern among the road agencies on saving energy and reducing emissions throughout the production process. The WMA additives work in many ways to either reduce the viscosity of the binder or to allow better workability of the mix in order to construct the mixtures at lower temperatures. The onsite pavement construction using the WMA technology did not begin until the middle of 1990's. Therefore, there were limited reports that had been published on the long term effect of WMA performance [11-12, 47]. Nevertheless, because of this reason, discussions on the performance of WMA mixtures on various applications will be mostly based on the results obtained from laboratory tests which had been conducted by researchers. In this section, the discussion is based on the performance of WMA technology according to the asphalt mixture gradations such as dense-graded asphalt mixture, porous, PMA, SMA, CRM asphalt mixtures and asphalt mixture incorporating RAP.

6.1 Dense Graded

At the present, most of the studies on WMA technology are focusing on the dense-graded asphalt mixture but using different methods and/or different WMA additives. Ali et al. [18] had carried out a laboratory study in order to evaluate the effect of temperature reduction, foaming water content, and aggregate moisture content on the performance of foamed WMA. The mixtures were produced based on the standard Superpave mix design method. The foamed WMA mixtures were produced using three production temperatures (16.7, 27.8 and 38.9°C) lower than the conventional HMA using three foaming water contents (1.8, 2.2 and 2.6%) which were added by weight of the asphalt binder and included three different aggregate moisture contents (0, 1.5 and 3%). However, the results of this research focussed on the performance comparison HMA and the foamed WMA which was prepared using 16.7°C temperature reduction, 1.8% foaming water content, and fully dried aggregates. The test results showed that the reduction temperature during production of the foamed WMA may increase susceptibility to permanent deformation (or rutting) and moisture-induced damage, while increasing the foaming water content (up to 2.6% of the weight of the asphalt binder) may not have a negative impact on the foamed WMA performance. The results also indicated that the using of moist aggregates may cause inadequate aggregate coating which can lead to moisture-induced damage and long-term durability problems.

Besides that, Zhao et al. [43] investigated the rutting characteristics of WMA mixtures with various warm additives which were identified as additives A, B, C and D. The additives A and B were wax based products while additives C and D were chemical products. During the modification with virgin asphalt binder, additives A and B were added at a rate of 1.5% by the weight of asphalt binder while additives C and D were added at a rate of 0.3 and 0.5% by the weight of asphalt binder, respectively. Then the typical aggregate gradation and mix design of all mixtures were following the South Carolina Department of Transportation (SCDOT) technical specification for Hot-Mix Asphalt material properties. In their study, the nominal maximum aggregate size (NMAS) was 12.5 mm and the optimum binder content was 5.35%. As for the production of WMA, three level of mixing temperatures (150, 135 and 120°C) and compaction temperatures (135, 120 and 105°C) were selected. From the test, they found that there were similarity of rutting characteristic between chemical additive modified mixture and the control mixture which indicates that the chemical additives do not soften the binder, nor do they stiffen the binder. In addition, they also suggested using the virgin binder with higher G*/sin δ values in order to increase the rutting resistance of WMA mixtures incorporating chemical additives.

Petit et al. [48] had performed an experimental study to evaluate mechanical properties, in terms of shear fatigue and stiffness of WMA using Sasobit type Fisher–Tropsch process (FT). In their study, the 150°C of hot virgin asphalt binder grade PEN 70/100 was modified by adding the additive at a rate of 3% by mass of binder and it was blended using a portable mixer for 30 minutes. Then, the modified binder was used for WMA samples which were mixed at 120°C and compacted at 110°C while the HMA samples were mixed at 160°C and compacted at 150°C using the virgin binder. Both HMA and WMA samples preparation were based on a typical dense gradation curve for binder course HMA concrete which was classified as AC 16 binder grade 70/100, in accordance with the UNI EN 13108-1 Standard. The experimental results and related modelling work from their study had demonstrated that the adding of WMA additive into the WMA mixtures composition does not hinder either the destructive or non-destructive performance as compared with HMA. This finding was supported by the measurement of fatigue life and stiffness.

In the study conducted by Caro [49], the evaluations were based on WMA mixtures incorporating Aspha-Min, Evotherm and Sasobit which represent the three groups of WMA technologies. The results obtained from the study indicated that Aspha-Min-WMA fine mixtures (a water-based WMA technology) is the most prone to moisture damage. In contrast, fine mixtures modified with Evotherm showed satisfactory results. If compared to the control-HMA, Sasobit-WMA fine mixture showed to be more prone to moisture damage but not as critical as Aspha-Min WMA fine mixtures. Overall, actual moisture damage susceptibility of WMA fine mixtures was influenced by the type of WMA technology used. In addition, the researcher also observed that the actual fatigue life values for his this material in both dry and wet conditions were considerable smaller than those obtained for all WMA fine mixtures although the fatigue resistance of the control HMA fine mixture was not significantly affected by moisture.

In USA, Kim et al. [46] had presented a laboratory evaluation integrated with field performance in order to examine the performance of WMA using foaming and emulsion technology. The trial pavement sections of the WMA and HMA mixtures were implemented in Antelope County, Nebraska. In their study, the field-mixed loose mixtures were collected at the time of paving and were transported to the laboratories for further evaluation based on various experiments. As for the production of WMA mixtures in the lab, they were using synthetic zeolites (0.25% by total weight of mixture) and chemical emulsion (5.0% by weight of asphalt binder) as WMA additives. All mixtures were prepared based on conventional Superpave method of mixture design. The HMA mixtures were produced at 165°C and compacted at 135°C while the mixing and compaction temperature for WMA mixtures were 135°C and 124°C. According to the laboratory test results, it was found that the

WMA mixtures showed greater susceptibility to moisture conditioning than the HMA mixtures, and this trend was identical from multiple moisture damage parameters including the strength ratio and the critical fracture energy ratio. In addition, they also reported that satisfactory rutting-cracking performance were obtained for both WMA and HMA sections according to the early-stage of field performance data which were collected for three years after placement on site.

In Japan, Su et al. [50] had conducted a study on the application of WMA for airport maintenance using a chemical additive (small solid pellets of synthetic wax) which is made by a Japanese company. During the mixing process, the additive at a rate of 3.5% by mass of the binder was directly added into the aggregate mix together with asphalt. Then the additive was melted and blended together with asphalt binder to coat the aggregates homogeneously. The aggregate gradation used in this study was a dense graded asphalt mixture and its design was based on the general Marshall procedure (ASTM D1599) with 75 blows per side using the standard Marshall hammer. In their study, they found that the WMA produced at temperature 30°C lower than the normal indicated a practical application due to its performance which was similar or slightly lower than the control HMA mixture except for moisture sensitivity characteristic. They also suggested that the WMA mixed at 143°C is applicable for use in the pavement maintenance and rehabilitation in airport areas where it can contribute to early open to traffic.

6.2 Porous Asphalt Mixture

Porous asphalt (PA) which is also known as open graded asphalt mixture is used in the top layers and usually comprises of 20% air void after being laid and compacted based on the reduction of sand content together with higher proportion of coarse aggregates. The PA consists of interconnected micro voids which can allow water to flow into the asphalt mixes. Therefore, it can prevent aquaplaning on the pavement surface and improves visibility while driving during raining season. Besides that, the high porosity of PA was found to be significantly reduces traffic induced noise emissions. However, the average service life of PA mixture is limited between 10 to 12 years which is lower than the traditional dense asphalt mixtures with a service life of approximately 18 years [52-52].

In the past few years, several studies have been performed to evaluate the effect of the PA mixtures preparation using WMA technology. In USA, Goh et al. reported in their studies [7, 53] regarding the performance of PA mixtures containing 15% of RAP and 0.25% of Advera® as WMA additive. The PA mixtures with and without RAP were designed based on guideline published by National Asphalt Pavement Association (NAPA) with the nominal maximum aggregate size (NMAS) was designed to be 12.5 mm using a PG 58-34 asphalt binder. All WMA mixtures with 0.25% Advera® WMA were mixed and compacted at 135 and 110°C, respectively. The laboratory test results showed that the WMA made with 0.25% Advera® WMA had significantly lower dynamic modulus (|E*|) results than the control HMA mixture. In addition, it was observed that the |E*| was higher for porous asphalt mixture containing RAP than the control mixture. However, there was only a slight decrease in |E*| observed when Advera WMA® was added to the porous asphalt mixture containing RAP. Meanwhile, it was found that WMA had a lower indirect tensile strength test (ITS) value due to not well coated of coarse aggregate during the low temperature mixing process. Additionally, WMA with RAP was found to be significantly higher than HMA containing RAP. Therefore, the researchers claimed that higher RAP percentage could be used for designing warm PA mixtures where the WMA additive could improve the high temperature mixing for mixtures containing RAP.

In a more recent study, Aman [52] evaluated the effect of water sensitivity of warm porous asphalt incorporating Sasobit. In his research, hydrated lime and Pavement Modifier (PMD) were used as anti stripping additives and the warm PA mixtures were prepared based on Dutch PA gradation but follow the Malaysian quarry practices. From this research, results indicate that the warm PA specimen containing PMD increase stripping resistance as compared with warm PA mixes with hydrated lime regardless of compaction temperature. The findings also shown that the warm PA mixes containing hydrated lime and PMD can be compacted to temperatures as low as 125 and 135°C, respectively.

6.3 Polymer Modified Asphalt Mixture

In many years, polymer modified asphalt binder (PMA) has been used as modifiers for asphalt binder to reduce pavement failures such as permanent deformation at high temperatures and cracking at low temperatures. PMA binders are more viscous compared to conventional virgin asphalt binder and its characteristic can improve the binder coating by increasing the film thickness on aggregates which caused effective bonding. Due to higher viscosity properties, asphalt mixtures produced with PMA binders have to be produce and compact at a higher temperature [9]. In pavement industries, polymers that have been used to modify asphalt include styrene–butadiene–styrene (SBS), styrene–butadiene rubber (SBR), Elvaloy, rubber, ethylene vinyl acetate (EVA), polyethylene (PE), polypropylene (PP) and others [55].

Kim [9] reported the performance evaluation of SBS modified asphalt mixtures using WMA technologies. In his study, two types of addition processes of the WMA additives into SBS modified binders or mixtures were used. Process 1 involved the addition of Aspha-min at 5% by binder weight through manual blending at a temperature of 150°C. Meanwhile, process 2 involved the addition of Sasobit at 1.5% by binder weight into the SBS modified binders and it then blended using a mechanical mixer at 150°C for 5 minutes. For asphalt mixtures preparation, the researcher used the surface course type A for the Superpave mix design as following the SCDOT specifications which was considered for the higher traffic zone design. In this study, the HMA and WMA mixtures were produced at 163 and 143°C, respectively. The compaction temperatures of 96 and 118°C were selected to evaluate the effect of WMA additives at relatively lower temperatures. Based on the rheological results, researcher stated that the SBS modified binders containing WMA additives resulted in higher failure temperatures than control binders which suggested better rutting resistance at high temperatures. However, SBS modified binders containing WMA additives generally showed higher G*sin δ values (at 25°C) than the control binders which indicated as having less resistance to fatigue cracking. In addition, the SBS modified binders incorporating WMA additives were found to have significantly higher stiffness values (at -12°C) which relate to reduce the low temperature cracking resistance. In terms of asphalt mixture performance, the results indicated that there were no significant differences between HMA and WMA mixtures according to TSR, rutting and resilient modulus evaluation.

Meanwhile, Shang et al. [37] investigated the physical and rheological effects of adding recycled pyrolytic polyethylene wax (RPPW) to SBS modified asphalt. In this study, they used the RPPW as WMA additive and the RPPW was added at 1, 3, 5 and 7% by binder weight into 1500 g of base asphalt and SBS modified asphalt respectively. Then, the samples were blended at 400 rpm using tachometer for 30 minutes at 150°C. The findings from this study showed that the addition of RPPW reduce penetration, increase softening point and penetration index of both virgin and SBS modified asphalt. Furthermore, the addition of RPPW also increases the complex modulus and decrease the phase angle of virgin and SBS modified asphalt.

6.4 Stone Mastic Asphalt

Stone matrix asphalt (SMA) is typically produced using HMA method, consists of a coarse aggregate skeleton, high binder content typically 5.5 to 7% and high filler content. Basically, the use of regular asphalt binder together with fibrous material as a drainage inhibitor is sufficient for ordinary SMA. However, in the case of high temperatures and heavy loading, a harder asphalt grade is normally been used by substituting the fibrous material with polymer such as PE, PP or SBS. One of the main purposes of SMA is to provide a mixture that can provide good skid resistance because the texture depth range is between 0.7 to 1.0 mm. SMA has also shown high resistance to rutting under heavy axle loads, as well as good low temperature properties [56-59].

Al-Qadi et al. [60] reported the results of the early-age performance of warm-mix SMA with an Evotherm additive according to laboratory testing and on-site loaded wheel testing. The early-age performance of WMA was concern mainly because of its curing process. Usually the time-dependent hardening or curing may occur within a short period after construction. This condition was due to the asphalt binder regained its original viscosity or as a certain amount of entrapped moisture was evaporated from the WMA. The deterioration of WMA occurred at an early stage which may directly affect its long-term performance. Therefore, within the first 24 hours of placement, the early-age performance of WMA was investigated in order to certify that the roadway is not to be opened to traffic too soon. In their study, both HMA and WMA specimens' preparation were based on 12.5 mm SMA which is one of the typical SMAs that has been used by contractors in Chicago, Illinois. In their study, both mixtures used PG 64-22 asphalt binder with 12% ground tyre rubber and 8% fine fraction of fractionated recycled asphalt pavement. In terms of WMA mixtures preparation, the Evotherm 3G was added at a rate of 0.5% by weight of binder. The compaction temperatures of the control SMA and the Evotherm SMA (WMA) were 152 and 127°C, respectively. The test results indicated that the early-age performance of the Evotherm SMA was generally comparable to the conventional SMA at the same curing period which was between 3 hours and 7 days after compaction. They have also found that the curing process increased the dynamic modulus of both Evotherm SMA and conventional SMA but did not significantly affect other laboratory test results. At the same temperature, the Evotherm SMA on site modulus was found lesser than the conventional SMA. However, the lower compaction temperature will cause the pavement constructed with the Evotherm SMA could be opened to traffic earlier than the pavement constructed with the conventional SMA while providing the same modulus.

Meanwhile, Yero [61] presented findings regarding the binder characterisation and performance of warm stone mastic asphalt mixture (WSMA) . In his study, the WSMA 14 mixtures were selected and the samples preparation was based on Marshall mix design method and followed the Standard Specification for Road Works of Malaysia. The WSMA mixtures were produced by modifying the virgin grade PEN 80/100, PEN 60/70 and PG 76-22 with certain percentages of Sasobit at temperature 20 to 40°C lower than the control HMA. The results indicate that the addition of Sasobit caused higher failure temperatures than the control binders which indicate better resistance to rutting at high temperatures. In addition, the resilient modulus test results from the study showed that the WSMA shown better rutting resistance. Yero also claimed that the Sasobit is an effective WMA additive to enhance rut resistance.

6.5 Crumb Rubber Modified Asphalt Mixture

About 300 million scrap tyres are generated every year in the United States because of the serious problem disposing this material. One of the actions taken by asphalt industries was to introduce crumb rubber which is a product from the grinding of scrap tyres in the asphalt binder. Currently, the use of crumb rubber modified (CRM) asphalt mixtures have been increasing steadily which contributes an environmentally sustainable tyres disposing method [36, 62-64]. In general, CRM asphalt can be divided into two categories, the wet process and the dry process. The wet process is the most efficient to produce HMA [64].

As an example, Wang et al. [34] evaluated the effect of high temperature properties of CRM binders with WMA additives. The CRM binders were manufactured in the laboratory at 177°C for 30 min by an open blade mixer at a blending speed of 700 rpm. In their study, the crumb rubber was produced at ambient temperature with the maximum size of 0.425 mm. Then the crumb rubber with percentage of 10, 15, 20 and 25% by weight of the virgin asphalt binder was added to the container. Then the WMA additive (Sasobit, RH and Advera) was added into the binders followed by mixing with a shear mixer for 5 minutes to achieve consistent mixing at 2, 4, and 5% by weight of the mixture respectively. The results from this study had shown that there were different effects on high failure temperature properties of unaged and RTFO-aged CRM binders with different crumb rubber concentrations and test temperatures. In addition, the addition of WMA additives can improve the rutting resistance of the CRM binders.

In the terms of an intensive experimental works, Akisetty [64] evaluated the effect of warm asphalt additives on performance properties of CRM binder and mixtures. In order to produce the CRM binders, the crumb rubber that passed the mesh of 0.425 mm was added into the container at 10% by weight of the virgin binder. Then, the sample was blended at 177°C using a mechanical mixer at a speed of 700 rpm for 30 minutes. After that, Aspha-min (0.3% by weight of the mixture – a binder content of 6% was assumed) and Sasobit (1.5% by weight of the binder) was added into the binders followed by mixing with a shear mixer for 5 min to achieve consistent mixing. For the mixtures preparation, the combined aggregate gradations for 12.5 mm mixtures were selected in accordance with the specification published by the South Carolina Department of Transportation (SCDOT). In addition, the asphalt mixtures containing of 10% CRM and incorporating WMA additives were prepared at 20°C lower than the asphalt mixture containing 10% CRM. Based on the results obtained from the rheological test, the researcher summarised that the rubberised binders with WMA additives indicated higher failure temperature than the control rubberised binders which showed better rutting resistance at high temperature. Furthermore, the researcher stated that in most cases, moisture susceptibility, rutting resistance, and resilient modulus properties of CRM mixtures containing the warm mix additives were not significantly different than those of the control CRM mixtures. Thus, it is suggested that the use CRM mix incorporating WMA additive can be produced at lower temperatures and it does not have negative effect on the mixture properties.

6.6 Asphalt Mixture Incorporating Rap

RAP is a milling waste material produced from the milling processed of pavement surface when it reaches the end of its design life. When the emerging of RAP with WMA technology, it may be beneficial in two ways: 1) the viscosity reduction could assist the compaction efforts, and 2) the decrease aging of the binder due to the lower production temperatures where it may help to reimburse the aged RAP binder [16].

In Portugal, researchers [63] reported the results of using surfactant based additive to reduce the production temperatures of conventional and recycled asphalt mixtures with 50% RAP. In their study, the binder content of each type of HMA mixture either for conventional or recycled mixtures were determined using the Marshall Mix Design Methodology. Prior to the samples preparation, the binder was modified with Cecabase® RT 945 at amount of 0.3% (by mass of binder) in order to produce the RAP mixtures that incorporating WMA technology. The RAP was obtained from a National Road in Portugal and the material was milled off from a surface course after 15 years in service. The RAP has a binder content of 6.2% (which corresponds to 3.1% with a 50% recycling rate). Therefore, only 2.1% of new asphalt binder grade PEN 50/70 was added in order to obtain the target binder content of the recycled mixture. The reduction temperature for mixing and compaction of WMA mixtures were range from 10 to 35°C. The laboratory test results showed slightly improved performance of WMA mixtures in terms of rut resistance. The researchers also highlighted that the use of WMA additive associated with the reduction of temperature does not affect the stiffness and phase angle results of mixture. In addition, the fatigue resistance of the WMA recycled mixture showed better results than the HMA.

In USA, Shu et.al [66] evaluated the moisture susceptibility of plant-produced foamed WMA incorporating high percentages of RAP. The researchers used the coarse aggregate with NMAS of 19 mm, asphalt binder PG 64-22 and the optimum asphalt content was 4.2 %. A combination of 12.7 mm and 8 mm fractionated RAP was incorporated in the mixtures for all the samples preparation and the RAP content in the mixtures ranged from 0 to 50%. In order to produce the WMA mixture, the researchers had selected the foaming process method. The WMA samples were compacted on site using the Superpave gyratory compactor (SGC) to avoid re-heating and further moisture loss. HMA samples were compacted in the laboratory after re-heated. The test results of the plant-produced foamed WMA indicated approximately no different in terms of moisture susceptibility as compared with the HMA mixture. The researchers stated that the combined beneficial effect from RAP and foamed WMA were expected to have the same performance in terms of moisture damage as compared to the HMA mixture. In addition, they also suggested that the increase percentages of RAP were beneficial to increase the moisture resistance of both WMA and HMA mixtures.

■7.0 CONCLUSIONS

The concept of WMA technologies is to reduce the mixing and compaction temperatures that are typically 20 to 30°C lower than conventional HMA. The WMA mixtures can be produced using several technologies which can be classified as foaming, organic and chemical additives which allow full coating between the binders and the aggregates with appropriate workability conditions [67]. From the various WMA methods, the modification of virgin asphalt binder with an additive is one of the most commonly used by industries [49]. Studies also exhibit that the WMA technology can be implemented for all types of asphalt mixture gradations [9-10, 18, 23, 26, 35, 37, 53, 66, 68-74].

The implementation of WMA technology on asphalt pavement either for new construction or for maintenance of existing layer shall represent a new addition on additive or technology as compared to the conventional HMA which caused an additional cost as compared to HMA. Yet, the WMA applications usually come with the new specification and technical restriction by the local authorities. These are some issues that need wisdom actions by the road agencies and stakeholders in order to overcome the barriers including technical or non-technical aspects. Therefore, extra efforts such as research activity and free information services are very important to attract many participation from industries since the road agencies has already implement tax reduction, commercial opportunities, and enhance the profitability of green technology through motivation, legislation or financial incentives [75-79].

In addition, the life cycle cost analysis (LCCA) should also been carried out together with the performance tests in order to compare the long term benefits between the WMA and HMA. Capitao [12] had stated that the LCCA is usually been divided into four phases which are the production of raw material, construction, maintenance and repair and recycling or demolition. The LCCA study is very important because it allows the analysing and assessing of the long term effects of the technology used for WMA production from the selection of raw materials to the end-of life of pavement surface [12, 80-83]. Beside the actions and long term assessment that can be taken by the road agencies, there are also some roles that can be focused among researchers to further evaluate the effectiveness of WMA technology for local conditions (traffic and weather) using local sources as a raw materials.

In conclusion, this paper described current practical experienced among researchers and industrial practitioners while implementing WMA technology including constituent materials, mix design and mechanical performance issues. Within this, the dosage recommendation for most of WMA additives and its benefits were clearly explained as essential for a better understanding of the application of WMA technology in pavement constructions.

Acknowledgements

The authors would like to appreciate the funding support from Universiti Tun Hussein Onn Malaysia and Ministry of Education Malaysia under the Fundamental Research Grant Scheme (FRGS) Vot 1458.

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