

A review of warm mix asphalt technology: Technical, economical and environmental aspects

Mezclas asfálticas tibias: revisión desde el punto de vista técnico, económico y ambiental

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ABSTRACT

In general terms, warm mix asphalt (WMA) technology has great potential for successful use in road works construction projects. However, concerns remain regarding the durability and behavior of WMA mixtures in the long term, which need to be addressed. This review focuses on the technical, economic and environmental advantages and disadvantages. The review concludes that the main advantage of this technology, at the moment, concerns the environment. At the end of this work, the authors include certain recommendations for future works in order to continue strengthening the development of WMA technology.

Keywords: Warm mix asphalt, WMA, manufacturing, design, additives.

RESUMEN

En términos generales, la tecnología de mezcla asfáltica tibias (WMA por sus siglas en inglés) presenta un gran potencial para ser usada con éxito en proyectos de obras de construcción de obras viales. Sin embargo, aún existe preocupación en temas concernientes a la durabilidad y al comportamiento a largo de plazo de esta tecnología. Con base en una revisión bibliográfica, el artículo presenta los aspectos más importantes concernientes a la tecnología WMA. Se reportan las ventajas y desventajas técnicas, económicas y ambientales de utilizar esta tecnología reciente. Al final del documento los autores exponen algunas recomendaciones como apoyo para continuar fortaleciendo el desarrollo de la tecnología WMA.

Palabras clave: Mezcla asfáltica tibia, WMA, producción, diseño, aditivos.

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Introduction

Based on the temperature used to manufacture hot mix asphalt in specialized asphalt plants, the mixtures are given the following four denominations: cold mix asphalt (CMA) (temperature lower than 60 °C), half warm mix asphalt (HWMA) (temperature between 60 °C and 100 °C), warm mix asphalt (WMA) (temperature between 100 °C and 140 °C) and hot mix asphalt (HMA) (temperature between 140 °C and 190 °C).

WMA is the mixture that, through the use of different techniques, can reduce the mixing and compaction temperatures of an HMA without significantly altering its mechanical properties. According to Bonaquist (2011), Epps et al. (2011) and Sterling (2012), the minimum decrease in the mixture manufacturing temperature, with respect to HMA in an asphalt plant must be 28 °C for a mixture to be designated a WMA mixture. The reduction of the mixing and

compaction temperatures is accompanied by a decrease in the energy required for the production of the mixture and a decrease in the emissions into the atmosphere (Romier et al. 2006; Kristjansdottir et al. 2007; Wasiuddin et al. 2007; Chowdhury and Button 2008; Biro et al. 2009; Tao et al. 2009; Bonaquist, 2011). According to Gandhi and Amirkhanian (2008) and Hearon and Diefenderfer (2008), the mixing and compaction temperatures of WMA are between 90 °C and 130 °C and between 100 °C and 135 °C, respectively. Researchers such as Goh and You (2008), Yan et al. (2010), and Mogawer et al. (2013) note that the manufacturing temperature of WMA mixtures ranges from 17 °C to 56 °C and from 30 °C to 50 °C, which make these lower than the temperature required to manufacture HMA mixtures. A similar observation is reported by Silva et al. (2010), who note that this decrease reaches 40 °C.

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According to the Asphalt Pavement Association of Oregon (APAO) (2003), Chowdhury and Button (2008), and You and Goh (2008), WMA mixtures generate less polluting emissions during their manufacturing and construction process in comparison to HMA mixtures, and the energy savings are approximately 30%. Blankendaal et al. (2014), using a life-cycle assessment (LCA) model, report that using WMA instead of HMA mixtures decreases the negative environmental impact of HMA mixtures by 33%.

By means of a scientific literature review on this subject, the present article summarizes the main aspects of WMA technology that the pavement engineer must know. For this purpose, the article begins by presenting the advantages and disadvantages reported in the WMA scientific literature review and, subsequently, the general manufacturing methodologies are presented. At the end, the conclusions reported by the authors are presented based on the performed review.

Advantages and disadvantages

Environmental

The main advantage reported in the different consulted documents and studies concerns the environment. As noted above, the fuel consumption and emissions in a plant are reduced when using WMA technology (Goh and You 2008; You and Goh 2008). This allows the mixture production plants to be located closer to cities. According to Robjent and Dosh (2009), the reduction in fuel is between 20% and 35%, but in some occasions, this reduction could be higher than 50%. Estakhri et al. (2009) note that the reductions of CO₂, SO₂, volatile organic compounds, CO, NO_x, and ashes are 30%-40%, 35%, 50%, 10%-30%, 60%-70%, and 20%-25%, respectively, in comparison to HMA mixtures.

In addition, they report a fuel cost saving of more than 40%; the more expensive the fuel is in the country where this technology is developed, the more this saving increases. This reduction in manufacturing temperatures and in energy consumption depends on the method used for the manufacturing of the WMA mixture. Using the Building for Environmental and Economic Sustainability model (BEES 4.0), Hassan (2010) reported that, in comparison to HMA mixtures, WMA mixtures generate reductions of 24%, 18%, and 15% in air contamination, fossil fuel consumption, and total negative environmental impacts, respectively. However, although there are extensive reports on the decrease in environmental impact when using this technology, few studies have measured the possible impacts generated by the manufacturing and use of organic, chemical, and synthetic additives during the production of WMA mixtures. During constructive processes of WMA mixtures, worker exposure to respirable fumes is significantly reduced, thus helping the environment and worker health and safety (McCarthy et al. 2012; Prowell et al. 2014; West et al. 2014).

Resistance and durability

From the perspective of aging, a lower level of oxidation in the short term of the asphalt binders is generally reported due to the lower temperatures used during the manufacturing, extension, and compaction processes of the WMA mixture, which can result in an increase in the resistance to fatigue and low-temperature top-down cracking (TDC) and oxidation ((Anderson et al. 2008; Gandhi and Amirhanian 2008; Hearon and Diefenderfer 2008; Estakhri et al. 2009; Robjent and Dosh 2009; Gandhi et al. 2009, 2009a. 2010; Ran et al. 2010; Zhao et al. 2012; Goh et al. 2013; Hossain and Zaman 2013; Vidal et al. 2013). The lower aging rate of the asphalt used to manufacture WMA mixtures is presented as an advantage, since an aged asphalt produces a decrease in the adhesion between the stone aggregate and the binder (increasing the increment probability of the "stripping" phenomenon) and a change in the behavior of the binder and the asphalt mixture from ductile to brittle (due to an excessive increase in stiffness and viscosity). The excessive hardening of asphalt cement is undesirable because it often leads to problems associated with the brittleness and cracking of the asphalt layer in the pavement, especially at low service temperatures. In general, studies report a lower stiffening of WMA asphalt and greater values of m (variation of stiffness with time) in creep tests. Certain researchers have reported that this lower stiffening during the manufacturing process of WMA mixtures can result in a decrease in the rutting resistance ((Anderson et al. 2008; Su et al. 2009; Kavussi and Hashemian 2012; Zhao et al. 2012). According to Safaei et al. (2014), the long-term implications of reduced production temperatures and, hence, reduced short-term ageing on long-term performance remain largely unknown.

The paved roads and highways that have been built (mainly in Europe and the United States of America) are relatively recent, making it difficult to observe and evaluate the long-term mechanical properties of the pavements that use WMA (Vaitkus et al. 2009; Rubio et al. 2012). There are different studies, in situ and in the laboratory, that show that WMA mixtures can exhibit properties comparable and even superior to those of HMA (Barthel et al. 2004; Prowell et al. 2007; Su et al. 2009; Kvasnak et al. (2009); Su et al. 2009; Wielinski et al. 2009; Yan et al. 2010; Kvasnak et al. 2010; Kim et al. 2012; ; McCarthy et al. 2012; Tan et al. 2012; Zhao et al. 2012; Behl et al. 2013; Topal et al. 2014). Prowell et al. (2007) report the results of a test at real scale in which approximately 515,333 equivalent single axle loads (ESALs) were applied for 43 days on a track built with an asphalt layer of HMA and WMA mixtures. In this study, both mixtures exhibit good resistance to permanent deformation. In a different study performed on a rural road, rehabilitated and divided into four segments (one with an HMA mixture and the other three with WMA), with an average circulation traffic of 2150 vehicles per day, Kvasnak et al. (2010) report that the properties of WMA mixtures depend on the type of additive used or on the manufacturing method. A similar conclusion is reported by Arega et al. (2011), Nazzal et al. (2011), and Sargand et al. (2012). In

addition, Nazzal et al. (2011) and Sargand et al. (2012) report that although WMA mixtures were compacted at a lower temperature, they reached a higher density in the field than HMA mixtures and a lower level of aging. Anderson et al. (2008) conclude that field WMA densities appear to be similar to HMA, with slighter ease of compaction noted for WMA mixtures. Behl et al. (2013) describe the results of measurements performed on two road projects in India constructed with HMA and WMA mixtures. Based on deflection measurements with Benkelman beams and tests of Marshall Stability, static creep, and resilient modulus on cores extracted in situ, they conclude that the road segments constructed with WMA mixtures exhibit a similar and even superior behavior to those constructed with HMA mixtures. This is mainly attributed by the researchers to the greater compacting densities reached in situ by the WMA mixtures and to the lower level of aging of the binder due to the lower manufacturing and compaction temperatures. Other studies performed in situ are described in Kvasnak et al. (2009) and Shen et al. (2011). Based on studies performed with X-ray computed tomography in order to characterize the air void distribution of a field core taken from WMA and HMA mix sections, Estakhri et al. (2009) reported that the distribution of air voids versus depth in the asphalt layer is similar. However, the air void distribution with depth is more uniform in warm mix compared to hot mix core samples. West et al. (2014) reported the analysis of engineering properties of WMA compared to HMA field performance test sections built across the United States; six WMA projects were built prior to the beginning of the study (from September 2006 to June of 2008) and eight more WMA projects were constructed and monitored during the course of the study (from April 2010 to December 2011). Different chemical additives and foam techniques were used to make WMA mixtures as Evotherm ET, Sasobit, Aspha-min, Advera, Evotherm DAT, Astec DBG, Aquablack, Evotherm 3G, Gencor foam, Heritage wax, Terex foaming system, Cecabase RT, SonneWarmix, BituTech PER. Some conclusions of this study are: i) WMA and HMA mixtures developed similar rutting resistance, ii) none of the field projects with WMA and HMA had any evidence of moisture damage, iii) The use of WMA did not appear to effect density changes under traffic compared to HMA, iv) Very little cracking of any type was observed in the field test sections monitored and WMA and HMA sections generally had similar amounts v) All of the test sections had similar amounts of surface texture and texture change after two or more years of traffic, and none of the test sections had significant amounts of raveling, vi) Testing of recovered binders from mixes obtained during construction generally showed that the WMA binders had aged slightly less than the corresponding HMA binders, vii) 11 of the 13 WMA mixtures developed in average 12% less dynamic modulus than HMA mixtures, ranged from about 5% more stiffer (only two WMA mixtures) to 40% less stiff, viii) Flow Number test results for plant-produced WMA mixes were statistically lower than corresponding HMA mixes in more than 2/3 of the comparisons. Kvasnak et al. (2009), based on the four point beam fatigue test reported that WMA

produced in laboratory often exhibited a lesser fatigue life than HMA, while the plant produced WMA often resulted in a greater fatigue life.

In some cases, the physical and mechanical properties of WMA mixtures are lower in comparison to those of HMA mixtures (Vaitkus et al. 2009), mainly in rutting resistance and moisture damage (Diefenderfer et al. 2007; Kvasnak et al. 2009; West, 2009; Arega et al. 2011; Punith et al. 2011; Kavussi and Hashemian 2012; Ali et al. 2013; Doyle and Howard 2013; Kim et al. 2014). The rutting phenomenon is one of the main damage mechanisms of asphalt layers in flexible and semi-rigid pavement structures. It can be defined as the permanent vertical deformation that accumulates in the pavement due to the repetitive passing of vehicles, which generates the formation of thin longitudinal depressions along the trajectory of the wheels. Information regarding the rutting and fatigue phenomena on hot mix asphalt can be found in Rondón et al. (2012) and Rondón and Reyes (2015).

According to Tarefder et al. (2003), water generates a loss of resistance in the interface between the asphalt binder and the stone aggregate, increasing the accumulation rate of permanent deformation due to the loss of cohesion of the mixture by moisture. This phenomenon was identified in the 1930s (Caro et al. 2008), and the reference literature calls it "stripping" (Caro et al. 2008; Kringos et al. 2008, 2008a; Kassem et al. 2009). The causes that generate this phenomenon are complex because they involve physical, chemical, mechanical, and thermodynamic aspects. An updated state of knowledge on the subject can be found in Mehrara and Khodaii (2013). The lower manufacturing temperatures can make the drying of the stone aggregate in asphalt plants insufficient, producing the loss of adhesion between the stone aggregate and the asphalt binder in the mixture (Vaitkus et al. 2009; Xiao et al. 2010; Mallick et al. 2011; Mogawer et al. 2011a; Kanitpong et al. 2012; Ali et al. 2014; Sengöz et al. 2013; Xiao et al. 2011, 2013, 2013a) and generating mixtures that are susceptible to moisture damage. In the laboratory design of mixtures, this phenomenon is not apparent because, in general, the stone aggregate is dried in ovens before being mixed with the binder. To increase the resistance to moisture damage, some researchers have opted to add hydrated lime (conventional and in nanoparticles) to the stone aggregate or anti-stripping additives, such as amines, diamines, liquid polymers, Portland cement, fly ash, and combustion powder (e.g., Buddhala et al. 2011; Kavussi and Hashemian 2011, 2012; Cheng et al. 2011; Arabani et al. 2012; Hossain et al. 2012; Shivaprasad et al. 2011a, 2012; Xiao et al. 2010, 2012; Diab et al. 2013; Xiao et al. 2013; Kavussi et al. 2014). Certain researchers, such as Kanitpong et al. (2012) and Sangsefidi et al. (2014), report that the deficiencies found in WMA can be addressed by the use of good stone aggregates and an optimum grading curve, which generates high adhesion properties with the asphalt and cohesion. These properties are based on the fact that the stone aggregate in an HMA, in general, constitutes between 80% and 90% of the total volume, and the response of the

mix in service is strongly dependent on the type of stone aggregate, the grading curve used, the maximum particle size, the content of fines, and the manner in which the granular skeleton is distributed and compacted. Another strategy to minimize moisture damage in WMA mixtures is the good construction practices (good compaction to high density, ensure complete drying of aggregates, place good drainage and waterproofing the pavement surface) (Epps et al. 2011). Conversely, there are studies that report that the resistance of WMA mixtures to moisture damage is superior to that exhibited by HMA mixtures. Some studies have even concluded that WMA appears to be more susceptible to stripping and coating issues in laboratory tests; however, such moisture damage has not been evident in the field (Epps et al. 2011). Based on measurements made with an atomic force microscope and using the surface free energy (SFE) concept, Al-Rawashdeh and Sargand (2013) reported that the adhesion and cohesion of two binders used in the manufacturing of WMA mixtures is similar and, in some cases, superior to those used for the manufacturing of an HMA mixture. Other studies that report successful results of WMA mixtures regarding moisture damage can be found in Wasiuddin et al. (2011) and Ghabchi et al. (2013). On this subject, diverse researchers note that on some occasions the conclusions reported on the high degree of potential moisture damage with WMA mixtures are based on measurements obtained by the TSR (Tensile Strength Ratio) test, which is not representative enough to evaluate this damage mechanism. Based on the results reported by these authors, a method that provides a better mechanistic comprehension of the moisture damage of HMA in service is the SFE method (Cheng et al. 2002; Bhasin and Little 2007; Arabani et al. 2012; Ghabchi et al. 2013, 2013a). Using this method, the mechanisms of adhesion and cohesion in HMA subjected to moisture damage are better described.

An adverse determination of the mixing temperature can result in a bad coating of the aggregate, making it more vulnerable to moisture damage. Similarly, an adverse determination of the compaction temperature of WMA mixtures has an effect on its density and therefore on its behavior during its service time. This temperature depends on the type of stone aggregate and additive, additive percentage, type of asphalt binder, and compaction equipment, among others. When performing the characterization of WMA mixtures in the laboratory, it is important to take into account the effect developed by the type of compaction on these types of mixtures (Sanchez et al. 2012) and the compaction temperature (Lee et al. 2012).

In addition, one of the main limitations reported regarding WMA technology is that there is no standardized mixture design procedure (Bonaquist, 2011; Hamzah et al. 2013). Currently, two of the most recent technical documents on the design of WMA mixtures are Nos. 691 and 714 of the National Cooperative Highway Research Program (NCHRP), reported by Bonaquist (2011) and Sterling (2012), respectively. In these reports, the conclusions obtained from the NCHRP 09-43 project,

whose goal was to develop design and analysis criteria for WMA mixtures, are summarized. According to Bonaquist (2011), one of the critical issues confronting WMA mixtures is the lack of a formal design procedure. In most of the WMA projects built in the United States, these mixtures have been designed under the same criteria as the HMAs, without any modifications in the working process.

Constructive

In the constructive area, it is constantly noted that the viscosity of the asphalt binder used to manufacture WMA mixtures is lower than that of the binder used for HMA mixtures (Goh and You 2008; You and Goh 2008), which results in an earlier opening of the paved road and an improvement to workability (Goh and You 2008; You and Goh 2008; Estakhri et al. 2009; Robjent and Dosh 2009; Vasconcelos et al. 2010; Yan et al. 2010; Capitão et al. 2012; Morea et al. 2012; Wang et al. 2013). Some researchers report that instead of reducing the viscosity, some additives improve the workability of the mixture due to a better lubrication between the asphalt binder and the stone aggregate at a microscopic level. This improvement reduces the internal friction generated in the mixtures due to the high shear stress values to which they are subjected during the manufacturing and compaction processes (Anderson et al. 2008; Baumgardner 2008; Hanz et al. 2011; Goh et al. 2013). The reduction of the mixing and compaction temperatures enhances the use of these mixtures for the manufacturing of thin asphalt layers (Tao et al. 2009; Yan et al. 2010). In addition, the additives allow a greater transport distance of the mixture prior to extension and compaction (Robjent and Dosh 2009) and allow extension and compaction in colder environments (Goh and You 2008; You and Goh 2008; Hearon and Diefenderfer 2008; McCarthy et al. 2012; Tao et al. 2009; Ran et al. 2010), leading to the use of this technology in the manufacturing of emergency roads in regions that are subject to natural disasters (Howard et al. 2014). West et al. (2014) reported, based in the study of 14 highway sections built across the United States with WMA and HMA technologists, that no difference was observed between the opening times to traffic of WMA and HMA mixtures after rolling. According to Kvasnak et al. (2009), the production and placement equipment for WMA is the same as those used for HMA.

Economic

From the economic perspective, diverse studies report that WMA technology reduces the wear of the asphalt plants where WMAs are produced due to the lower manufacturing temperatures, resulting in a decrease in the maintenance costs and extension of their service life (Hurley and Prowell 2006 a,b; Biro et al. 2009; Gandhi and Amirhanian 2008). In addition, in countries where the energetic cost is high, WMA mixtures can offer economic advantages in the short term (Rubio et al. 2012; Mokhtari and Nejad 2013). Similarly, in countries where the environmental laws are more demanding, the economic benefits would be more

representative because the cost could decrease when using WMA on a large scale. However, in some cases, the savings of fuel and energy do not compensate for the extra cost generated by the production of the binder and additives required to manufacture the WMA mixture (Anderson et al. 2008; Gandhi and Amirkhanian 2008; Biro et al. 2009; Vaitkus et al. 2009; Capitão et al. 2012). In some WMA mixture manufacturing processes, in particular foamed additives and asphalts, it is necessary to make changes to the asphalt plants, increasing the initial cost of this mixture. In general terms, the initial cost of producing WMA mixtures is higher than that of HMA mixtures (Rubio et al. 2012), and it varies depending on the type of technology and the additives used. In the consulted documents, very few studies have been conducted to correlate and evaluate the costs of the short and long-term use of WMA mixtures. Furthermore, few studies have been conducted to evaluate the cost-benefit relationship from the technical, economic, social, and environmental perspectives.

The contracting entity must choose the most adequate manufacturing process of WMA mixtures and technology based on the following criteria: a) the available performance data, b) the cost of additives, c) the expected temperatures of production and compaction, d) the expected production rates, e) the mixture production capacity of the plant, and f) the required modifications to successfully use the WMA process with the available laboratory and field equipment.

Opportunity of use

Another widely noted advantage of WMA technology is the opportunity for manufacturing HMA modified with recycled rubber from tires or other polymers, for which there is the need to decrease the manufacturing and compaction temperatures (Akisetty et al. 2008, 2009, 2010; Kim et al. 2011; Shivaprasad et al. 2011; Liu et al. 2010; Morea et al. 2012; Wu and Zeng 2012; Fakhri et al. 2013; Rossi et al. 2013; Hajj et al. 2014; Yu et al. 2014). The use of this technology in mixtures modified with recycled rubber from tires decreases the compaction temperature by between 20 °C and 30 °C without significantly affecting the engineering properties (Hurley and Prowell 2005; Wang 2011; Yu et al. 2013, 2014). Despite the above, studies must be performed in order to deeply evaluate: i) how could the physical (viscosity, specific gravity, stiffness, among others) and rheological properties of the modified asphalt and the resistance and durability at short and long time be affected, as a result of the reaction between the type and amount of additive and asphalt with the rubber grain; and the effect of that reaction over the design of the modified asphalt (asphalt, additive and rubber) and the WMA final mixture; ii) the development of a standardized process to establish the production temperature of the WMA using asphalt modified with rubber; iii) the corresponding relationship cost/benefit using technical and environmental considerations; iv) the influence on adherence and cohesion from catchment oils from asphalt from rubber. In mixtures modified with rubber and RAPs, the aim of using WMA technology is to improve workability during their manufacturing and compaction

processes, rejuvenate and soften the aged asphalt binder of the RAP, and create new construction methods with high environmental and economic benefits (Zhao et al. 2013). Nonetheless, most researchers report that high contents of RAP produce mixtures that are so stiff that structural failure can occur in the field, mainly fatigue cracking (Bonaquist 2005; McDaniel et al. 2007; Behnia et al. 2011; Doyle and Howard 2013; Mogawer et al. 2013). This is mainly due to the increase in stiffness that is a product of the asphalt aging in the RAP. However, other researchers, such as Hill et al. (2013), dispute this claim, reporting that WMA mixtures manufactured with four different additives exhibit a greater cracking resistance at low service temperatures. The reference literature reports successful cases of HMA designed with WMA asphalts, recycled tire rubber granules, and a maximum of 25 % RAP (Mogawer et al. 2011, 2013). Doyle and Howard (2013) report that a high content of RAP (25 % and 50 %) + WMA generates resistance to permanent deformation and moisture damage, similar to the traditional HMA manufactured with low RAP content (less than 25 %). Based on Marshall, dynamic creep, and indirect tensile strength tests, Nejad et al. (2014) report an optimum RAP content of 50 % in a WMA asphalt mixture using an organic additive. Few studies have been performed on WMA mixtures with high RAP contents (above 50 %) compared with those performed on WMA mixtures with RAP contents between 20 % and 50 % (Howard et al. 2013). Certain researchers, such as Ameri et al. (2013), note the opportunity to use this technology to manufacture WMA mixtures with properties comparable or even superior to those of HMA mixtures when the natural stone aggregate is replaced with blast furnace steel slags.

Manufacturing of WMA mixtures

There are three general manufacturing methodologies for WMA mixtures: modifying the asphalt with organic additives, modifying the asphalt with chemical additives, and foaming the asphalt (West et al. 2014).

Modification of the asphalt or asphalt mixture with additives

The modification can be performed by a wet process (incorporating the additive into the asphalt) or a dry one (incorporating the additive into the stone aggregate). In general, the most commonly used modification method is the wet process. Organic additives include Sasobit[®], Thiopave[®], TLA-X[®], REVIXTM, and Asphaltan-B. Chemical additives include Cecabase[®], RTEvotherm[®], HyperTherm[®], Rediset WMX[®], QualiTherm[®], and SonneWarmix[®].

One of the most commonly used organic additives worldwide is Sasobit[®]. This product, developed by Sasol Wax, is a synthetic wax produced in the coal gasification process (Hurley and Prowell, 2006d; Chowdhury and Button 2008; Ghandi et al. 2010) and is generally added in a 3 % to 4 % proportion with respect to the total asphalt weight. This additive, when introduced to the asphalt, chemically changes

the temperature-viscosity curve, generating a reduction in the manufacturing temperature of approximately 18°C to 54°C, and a 20% reduction in the energy consumption of the asphalt plant (Kheradmand et al. 2014). According to Nazzal et al. (2011), when WMA mixtures are manufactured with Sasobit, the polluting emissions into the atmosphere decrease by at least 50% for volatile organic compounds, 60% for carbon monoxide, 20% for nitrogen oxides, and 83% for sulfur dioxide in comparison to HMA mixtures. When decreasing the temperature, the additive can crystallize inside the asphalt, increasing its stiffness. Therefore, some researchers have reported an increase in the resistance to permanent deformation of WMA mixtures manufactured with asphalt modified with Sasobit® (Biro et al. 2009; Goh and You 2009; Silva et al. 2010; Hossain et al. 2011; Liu et al. 2011; Capitão et al. 2012; Wu and Zeng 2012; Xiao et al. 2012a; Jamshidi et al. 2013, 2013a). For example, Hossain et al. (2011) report an increase in the maximum service temperature performance grading (PG) of 6°C (from PG 64°C to 70°C) when the base asphalt cement was modified with 2% Sasobit® by weight of asphalt. A similar conclusion is reported by Prowell and Hurley (2005) and Zelelew et al. (2013). This increase in the resistance to permanent deformation can produce a significant decrease in the cracking resistance at low service temperatures and fatigue (Hossain et al. 2011; Medeiros et al. 2012). The evaluation and modeling of the rheological properties of asphalt binders modified with Sasobit® can be found in Hamzah et al. (2012), Jamshidi et al. (2013, 2013a), and Qin et al. (2014), and the morphological and thermal characterization of this additive can be found in Qin et al. (2014). Information on the use of this additive for the manufacturing of WMA mixtures can be found in Jamshidi et al. (2013). Another recently developed organic wax is Licomont BS 100, which is added in amounts of 3% and 4% by weight of asphalt. At these percentages, a significant reduction of the asphalt binder is obtained, increasing its resistance to permanent deformations and hardness (Rodríguez et al. 2013). Other organic waxes, along with their descriptions, can be found in Rubio et al. (2012).

Similar to Sasobit®, chemical additives such as Rediset® and Cecabase® reduce binder viscosity, decreasing the manufacturing and compaction temperatures of the asphalt mixture when added at 1.5% and 3% by weight of asphalt, respectively. In the reference scientific literature, these chemical additives are noted as products that are formed by anti-stripping surfactant agents. By using these two additives, the manufacturing temperature of HMA is decreased by approximately 15°C to 30°C. A detailed description of these additives can be found in Kheradmand et al. (2014). Based on permanent deformation tests under cyclic load, Ouni et al. (2014) report that WMA mixtures manufactured with Cecabase® generated resistances comparable to dense-type and HMA. An issue of concern widely identified in the reference literature is that the manufacturers of these additives do not provide specific information, composition, and characteristics (Bonaquist 2011; Sterling 2012).

Another of the most commonly used additives is Evotherm ET, developed by MeadWestvaco Asphalt Innovations and used at 0.3% by weight of asphalt (Hurley and Prowell, 2006c). According to Chowdhury and Button (2008), the product reduces the mixing temperatures by approximately 38°C, generating energy savings of 55% in the asphalt plant and resulting in a 45% reduction in the levels of CO₂ and SO₂ emitted to the atmosphere. This type of additive is used in the form of an asphalt emulsion. In general, these emulsions are used for the manufacturing of HWMA mixtures (Rubio et al. 2012, 2013). The development of this additive and the manner in which the WMA mixtures are manufactured can be found in Bonaquist (2011). According to Hill et al. (2013), liquid chemical additives generally act as emulsifying agents and contain amine groups that can improve the cracking resistance at low service temperatures and the resistance to moisture damage.

According to Bonaquist (2011), the waxes are added to the asphalt to reduce viscosity and improve lubrication. According to Hanz et al. (2010), lubrication instead of viscosity reduction can be the main mechanism by which many WMA manufacturing processes improve workability and compactness at lower temperatures. In general, the waxes have melting points below the normal production temperatures of HMAs. At temperatures above the melting point, these materials reduce asphalt viscosity, and below the melting point, they tend to increase asphalt stiffness. It is important to highlight that even though some waxes stiffen the asphalt when crystallizing, certain natural waxes can affect the asphalt properties and reduce the rutting resistance of the WMA mixture; therefore, studies on the subject are being conducted to overcome this deficiency.

As noted, certain additives used for the manufacturing of WMA mixtures may increase asphalt stiffness and rutting resistance after crystallization occurs (Sanchez et al. 2011). In this sense, the additive must be selected so that when it stiffens, it does not lower fatigue cracking resistance at low or intermediate service temperatures.

Studying the behavior exhibited by the modified binder of the WMA mixture is complex, because it mainly depends on the crude type of the base asphalt, the initial chemical composition of that asphalt, which then changes due to oxidation during the manufacturing processes and during the service life of the asphalt mixture, and the type of modifying additive used. These aspects have led to the implementation of techniques such as spectroscopy in order to attempt to understand how the physical and rheological properties of the modified asphalts change when the chemical properties of the modified binder are varied (Hossain et al. 2013).

Foamed asphalts

This technique has been used for more than 50 years to produce CMAs. Some methodologies use synthetic zeolites or chemical materials that are introduced to the stone aggregate in order to foam the asphalt, decrease its viscosity, and improve the coating of the stone aggregates and the workability of the mixture during the manufacturing

process (Rondón and Fernández, 2014). Some natural zeolites are stones (called “boiling stone” by some researchers) that, when heated, produce a considerable amount of water vapor. When in contact with the asphalt this water vapor release foams it. According to Bonaquist (2011), zeolites are minerals that have approximately 20% water in weight trapped in their porous structure. By heating them to approximately 85 °C, the water is released, and when this occurs in the presence of hot asphalt, the asphalt foams. Two commonly used zeolites worldwide are Aspha-Min® and Advera® (developed by Hubbard Group & PQ Corporation). According to Chowdhury and Button (2008) and Gandhi et al. (2010), Aspha-Min® is a zeolite manufactured from sodium aluminosilicate, which is generally added in a 0.3% proportion by weight of asphalt. According to the producers of Aspha-Min®, it can produce a reduction of the mixing temperature of more than 10 °C and produce energy consumption savings of 30% in the asphalt plant. Nazzal et al. (2011) and Sargand et al. (2012) report that the emissions of organic compounds, carbon monoxide, nitrogen oxides, and sulfur dioxide are reduced by at least 50%, 60%, 20%, and 83%, respectively, when WMA mixtures are manufactured with Aspha-Min® and Sasobit® in comparison to an HMA mixture. Advera® is a synthetic zeolite (thin powder of hydrated sodium aluminosilicate) that is hydrothermally crystallized. Water represents between 18% and 22% of its composition and is added to the asphalt in a 0.25% proportion by weight of WMA mixture (Hossain et al. 2012). According to Topal et al. (2014), the WMA mixtures manufactured with synthetic zeolites exhibit better properties under cyclic load (resistance to rutting and fatigue) in comparison to those manufactured with natural zeolites. Other additives used to foam asphalts are AccuShear, AQUAblack foam, AquaFoam, Double Barrel Green/Green Pac, ECOFOAM-II, Low Emission Asphalt (LEA), Meeker Warm Mix foam, Terex foam, Tri-Mix foam, Ultrafoam GX, WAM-Foam, and LT Asphalt. Middleton and Forfylow (2009) suggest that the foamed asphalts used to manufacture WMA generate reductions of 10% in CO, CO₂, and NO_x and a reduction of 24% in energy consumption, maintaining similar moisture damage in comparison to HMA mixtures.

Another technique used to foam asphalt consists of combining the hot asphalt binder with pressurized water jets (also called cellular asphalts). This technology is mainly used for the stabilization of non-treated granular materials or for the manufacturing of cold and recycled mixtures. It consists in adding cold water (1% to 2% by weight of asphalt) and pressurized air in an expansion chamber to an asphalt cement at high temperature (160 °C–180 °C) in order to foam it, rapidly increase its volume (approximately 15 times), reduce binder viscosity, and increase the adhesion between the asphalt and the stone aggregate. This method was developed in 1956 by Dr. Ladis H. Csanyi, a professor at the Iowa State University Engineering Experimental Station (USA). When foaming the asphalt, its viscosity considerably decreases and its adhesion and workability properties increase (Ali et al. 2014) in the short term as well, making it suitable to be mixed with

cold and wet aggregates. However, this technology has the main disadvantage that the foamed binder often exhibits a low resistance to moisture damage, and in this case, it is necessary to use adhesion and anti-stripping improvers.

Another asphalt foaming technique consists of introducing wet stone aggregates to the mixture. This technique is called Low-Energy Asphalt® (LEA) and was developed by Fairco De Zozay, in France (Romier et al. 2004, 2006). The process consists of mixing the asphalt cement (in general, modified) (between 135 °C and 180 °C) with coarse hot stone aggregates (145 °C) and then incorporating part of the fine wet stone aggregates at room temperature. The moisture in the fine aggregates (between 3% and 4%) in combination with the heat, foams the asphalt. In order to use this technique, it is necessary to make diverse modifications to conventional asphalt plants.

The WAM-Foam® technique, developed by Shell International Petroleum Company Ltd and Kolo-Veidekke (Chowdhury and Button 2008), consists of a two-component binding system, a soft asphalt cement with a stiff foamed cement. The soft asphalt is mixed with the aggregate in the first production stage of the mixture between 100 °C and 120 °C. In the second stage, a stiff asphalt cement is foamed at high temperature by the addition of cold water (between 1% and 5%), and this foam is added to the mixture obtained in the first stage. The compaction of the mixture is performed between 80 °C and 110 °C. The soft asphalt cement represents between 20% and 30% by weight of asphalt.

The two main concerns of the foamed asphalts to be addressed are moisture damage (Ali et al. 2013) and the time they require for the moisture in the asphalt to dissipate. The dissipation rate of this moisture depends on the asphalt type that is foamed and on its performance grade. Kutay and Ozturk (2012) note that the moisture dissipation rate is lower in stiffer asphalts and in asphalts with a greater performance grade; therefore, they are more susceptible to moisture damage when foamed than softer binders. During the foam dissipation process, when the temperature decreases rapidly, the moisture can remain trapped in the mixture during the compaction process, generating failures during the service life manifested as loss of adhesion between the binder and the stone aggregate and stripping (Khodaii et al. 2012). Nonetheless, Huang et al. (2013) report that, based on Small-Angle Neutron Scattering (SANS) measurements of foamed asphalts, the amount of water trapped in the asphalt is very small (a film less than 0.1 mm thick). According to Yu et al. (2013a), very few studies have been conducted to evaluate the significant effect of the water content when foaming the asphalts. There is an optimum water content at which the foam is sufficient to improve the workability of the mixture without the water being retained in the asphalt, which would generate problems associated with moisture damage, a decrease in rutting resistance, and loss of adhesion between the binder and the stone aggregate. Another aspect that has been shown with foamed asphalt technology is that this asphalt adheres more to the fine fraction of the stone aggregate than to the coarse fraction (Van de Ven et al. 2007). This behavior makes it necessary

to add adhesion improver additives or coating promoting additives of aggregates to asphalt so that the coarse fraction does not remain uncovered by asphalt, which would lead to the development of problems associated with moisture damage and stripping in the mixture.

Ozturk and Kutay (2014) presented an image-based testing system called the asphalt foam collapse test (AFCT) to measure expansion ratio (ER), half-life (HL), and foam index (FI) of foamed warm mix asphalt (WMA) binders. According to them, a low water content and low pressure produced foams with smaller bubbles in comparison to foams made with high water content and high pressure, which affect the aggregate coating.

In order to optimize the foaming characteristics for any given asphalt binder without adversely affecting the performance of the resulting asphalt mixture, it is necessary to measure and model the foaming process and the factors that influence the ability of asphalt to foam (for example surface tension, temperature, viscosity, content and quality of water, presence of anti-foaming agents, size and dispersion of the water droplets or additives introduced in the asphalt binder) (Newcomb et al. 2012).

Conclusions

Based on the scientific literature review performed, it is concluded that the main advantage of using WMA mixtures concerns the environment. It is widely reported that reduction in the mixing and compaction temperatures when using this technique, in comparison to HMA mixtures, is accompanied by a decrease in the energy required for its production and in the release of polluting emissions into the atmosphere. However, few studies have been performed to measure the possible impact generated by the manufacturing and use of organic, chemical, and synthetic additives during the production of WMA mixtures. Even the studies in this area should focus on assessing the full cycle of the emissions and energy expended to produce WMA mixtures, and not separately. There is not a clear policy about a quantifiable method for measuring these aspects.

The different research studies reported, as main failure modes in the measurement of WMA's resistance, the moisture susceptibility and rutting. From the perspective of aspects such as the durability and resistance of WMA mixtures measured in the laboratory and in situ, the reference literature is ambiguous. For instance, it is generally reported that WMA mixtures experience a lower level of aging and oxidation in the short term of the asphalt binder, mainly due to the lower temperatures during the manufacturing, extension, and compaction processes. This lower level of aging in the short term can result in a mixture that is less fragile and more resistant to phenomena such as cracking by thermal fatigue and other types of TDC. However, this advantage of WMA mixtures can reduce their resistance to permanent deformation and to fatigue in thick

asphalt layers. In addition, in the consulted literature, very few studies have been conducted to measure and evaluate aging in the long term. In this sense, it is not clear whether the advantage reported in the lower level of aging of WMA mixtures in the short term is significant in comparison to the aging they could experience during the service life in the pavement. While some researchers report that WMA mixtures are potentially susceptible to experiencing greater moisture damage (especially in laboratory test results), others conclude the opposite.

The cost-benefit relationship of working with this technology from the technical, economic, and environmental perspectives does not remain completely clear. This uncertainty takes into account that many of the studies on the subject have been conducted by companies that produce this technology, which can lead to subjective conclusions.

WMA technology can be successfully used for the manufacturing of other types of mixtures that use recyclable and environmentally friendly materials, such as RAP mixtures and mixtures modified with waste materials. In addition, these mixtures provide a great opportunity to replace part of their granulometric composition with stone aggregates, such as steel slags, fly ashes, and rubble, among others.

Although aggregates are the high component on mixture, few studies had been made to evaluate the effect of the type and mineralogy of these material in the mechanical performance and durability of the WMA.

Recommendations for future works

As future needs to develop this technology and enhance its use increase, the following actions become necessary: a) standardizing the formal processes of the manufacturing and design of WMA mixtures in the laboratory for each production technique; b) conducting studies (economic, technical, and environmental) that involve the total life cycle of the mixture, considering all of its stages: plant production, extension, and compaction in work, service life, maintenance, rehabilitation, and reconstruction (in summary, evaluating its behavior in the short and long term); c) establishing the potential use of different technologies depending on the weather and load conditions to which the materials will be subjected; d) better evaluating of the effects of the stone aggregates (grading curve, aggregate type, shape, and maximum particle size, surface texture and hardness, among others) on the durability of WMA mixtures; e) establishing a formal procedure to determine the laboratory manufacturing and compaction temperatures; f) a more clear understanding of the influence of the additive or the production processes on the physico-chemical properties of WMA mixtures; g) development of a WMA technology evaluation program.

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