THE BALTIC JOURNAL
OF ROAD AND BRIDGE ENGINEERING

2011
6(4): 249–257

SUSTAINABLE ASPHALT MIXES: USE OF ADDITIVES AND RECYCLED MATERIALS

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Abstract. To respect and conserve the environment, many companies are trying to improve their plants and production processes to reduce contaminant generation. In this regard, asphalt mix industries are also making their contribution to reducing greenhouse gas (GHG) emissions, polycyclic aromatic hydrocarbons (PAHs) and benzene during the manufacturing and laying processes of bituminous mixes, as well as reducing waste generation when eliminating aged pavements or manufacturing surplus. In order to achieve this objective, mixes that can be produced and compacted at lower temperatures are becoming increasingly popular to bring about a reduction in gas emissions and obtain improvements in working conditions for employees in contact with them, without losing the mechanical characteristics of the conventional asphalt mixes (manufactured and compacted at 160 °C and 130 °C, respectively). This article summarizes the main techniques currently existing in the manufacture and placement of bituminous mixtures at lower temperatures, as well as the techniques applicable in the reuse of aged pavement, and introduces the use of some methods to assess the choice between different types of mixes, such as analysis of the life cycle and its economic variants.

Keywords: warm mix asphalt (WMA), additives, low temperature, green house emissions, recycled, life cycle.

1. Introduction

The reduction of greenhouse gas (GHG) emissions is related to the energy consumption required in the manufacturing and placement process of asphalt mixes. It has been found that a reduction of manufacturing temperature represents an energy saving of 20–75%, obtaining a decrease in the gas emission of 30–98% depending on the working conditions (Kristjansdottir *et al.* 2007), reducing the fuel consumption by at least 2 litres per ton of material (Silva *et al.* 2010).

The expenditure of energy includes the energy required for the extraction of renewable and non-renewable materials, transport and manufacturing of binder and aggregates and the final process of laying (Dorchies 2008). Dorchies (2008) showed how, depending on the type of mix to be manufactured, the required total energy varied, demonstrating its influence on the emissions of pollutants. For example, hot mix asphalt (HMA) consumes and emits five times more gas than in-situ cold mix recycling. In turn, he showed that, depending on the type of mixture, there are phases, such as the extraction of raw materials or manufacture, that have more influence in energy consumption and emissions.

De Groot *et al.* (2001) carried out a study comparing the emissions in plants producing HMA and warm mix asphalts (WMA), in particular mixes based on foamed bitumen. The gas measurements were performed in three locations: close to the mixer, near the silo and the last measurement carried out 50 m away. The emissions analyzed were Benzene Soluble Matter (BSM) and Polycyclic Aromatic Hydrocarbons (PAHs). The emissions observed during the manufacture of both types of mix showed that the BSM emissions of a WMA-type mix are less than 50 μg/m^3 at all points analyzed, while the values were between 200 and 500 μg/m^3 in the case of the HMA. Concerning the emissions of PAHs, they oscillated between 0.002 and 0.005 μg/m^3 in the case of the WMA, while in HMA near silos the value was 0.12 μg/m^3, decreasing near the mixer to 0.04 μg/m^3, and ten times less 50 m away. With these results, it was demonstrated that WMA, carried out in the same climatic conditions as HMA, produces less emissions during their manufacture (de Groot *et al.* 2001), although emissions met the threshold limit value (TLV) set by the American Congress of Governmental Industrial Hygienists (ACGIH) for asphalt fumes. Until the year 2000, the TLV was 5000 μg/m^3 measured as total aerosols (mineral

ISSN 1822-427X print / ISSN 1822-4288 online
doi: 10.3846/bjrbe.2011.32
http://www.bjrbe.vgtu.lt

and organic), from then reducing to 500 μg/m^3, measuring only the benzene-soluble aerosol of the inhalable fraction (Franzen, Trumbore 2000).

Due to the relationship between gas emissions and energy consumption, the asphalt industry is working on the development of asphalt mixes which can be made at lower temperatures, while maintaining the mechanical properties of HMA. Another advantage of the reduction of both temperatures is an improvement of working conditions, another important point to take into account, as during the manufacture of bituminous mixes, emissions of certain components that can be potentially carcinogenic (such as PAHs (Lee *et al.* 2004)) may be produced.

Another interesting idea is to obtain mixes that successfully use a greater amount of reclaimed asphalt pavement (RAP) to decrease as much as possible the formation of waste, and reduce spending on natural resources, thus achieving an environmental and economic improvement.

This article cites the different techniques in the manufacture of sustainable mixes, using additives and recycled materials that currently exist. At the same time, it will provide an introduction to the life-cycle assessment (LCA) tool (Huang *et al.* 2009) and its economic alternatives such as the Economic Input-Output Life Cycle Assessment (EIO-LCA) (Norman *et al.* 2007) and Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) (Horvath 2003).

2. Manufacturing processes

Taking into account the manufacture and placing temperature to classify the bituminous mixes, there are four different types which in turn can be differentiated by the binder used: without additives, with additives, in the form of emulsion or foaming.

Ordinary mixes, due to their manufacturing process, are known as HMA, which use a choice of bitumen penetration depending on the climatology and layer of the pavement. The manufacturing temperature is around 160–180 °C, and compaction between 130 °C and 150 °C. Subsequently, attempting to improve working conditions of employees and save energy cold mix asphalts (CMA) were introduced, which use bitumen in emulsion. For these mixes, the manufacture and compaction are carried out at ambient temperature, so production is environmentally sustainable due to its lower energy consumption and rate of emission of pollutants. However, their use is very limited because they do not achieve the mechanical properties of HMA (Button *et al.* 2007).

An intermediate material between the two types of mixes has been sought, which is energetically and environmentally sustainable like cold mixes, while retaining the mechanical properties of HMA. Hence, WMA and half-warm mix asphalts (HWMA) appeared. The differences between these two kinds of mixes derive from working temperatures and in the type of binder. WMA uses additives in the binder to decrease the manufacturing temperature, which is around 120–140 °C while placement temperature is between 100 °C and 120 °C. In the case of HWMA, bitumen is foamed or in emulsion, achieving manufacture at temperatures between 40 °C and 100 °C and laying at ambient temperature (Vaitkus *et al.* 2009).

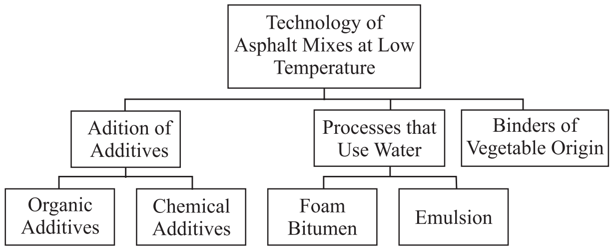

Fig. 1. Diagram of technologies in asphalt mixes at low temperature

The advantages of the use of sustainable asphalt mixtures are energy savings, decrease of GHG emissions, less fumes and odors, less oxidation of binder, hauling the mixture from greater distances, ease of compaction in some cases (Su *et al.* 2009).

Among energetically and environmentally sustainable bituminous mixtures there are different manufacturing processes, some based on the use of water in the mix design or in the binder, and others focused on the use of additives. In the case of the additives, these compounds can be divided into those that change the properties of the binder (organic additives), and those that do not change them (chemical additives) (Fig. 1).

2.1. Use of additives

The process of addition, either in mix or binder, can be of two types: modifying or not the characteristics of the bitumen, which also differs in terms of the composition and quantity of additive. There are both organic and chemicals additives.

a) *Organic additives* are waxes of different origins that through chemical reactions modify the viscosity-temperature curve of the binder. The amount to add is around 2–4% in weight of binder (w/b), and it can be added directly to the mixer or to the tank of bitumen. The following types exist:

1. Sasobit®, created by Sasol Wax, is a type of paraffin obtained through the process of Fischer-Tropsch synthesis. Due to its ability to reduce the binder viscosity, it improves the compactness and increases the resistance to deformation of the surface. It helps to reduce the working temperature of mix in a range of 18 °C to 54 °C. Below its melting point, around 102 °C, this wax forms a crystal structure in the binder, adding stability to the mix. The amount of product added to the binder is 3% in w/b, before entry in the mixer (Silva *et al.* 2010).

2. Asphaltan B®, created by Romonta GmbH, is a mix of substances based on the constituents of Montana wax and high molecular weight hydrocarbons. Its implementation reduces the binder viscosity, allowing the manufacture and placement of the asphalt mix at lower temperature than HMA. It is added in a ratio of a 2–4% in w/b direct-

ly into the mixer or previously into the binder, modified or not with polymers. This resin improves the binder flow at low temperatures, increasing the compactness and resistance to both rutting and damage by moisture (Button *et al.* 2007).

3. Rheofalt®LT70, designed by *Ventraco*, is a mixture of paraffin waxes, synthetic resins of hydrocarbons, thermoplastic polymers and oxidation inhibitors, especially designed to enlarge the range of working temperature. This additive is designed to modify the bitumen properties and obtain a plasticizer effect to favor reduction of its viscosity, achieving manufacture temperatures between 20 °C and 30 °C lower than in HMA, and laying temperatures around 70 °C, while maintaining the mechanical properties of HMA. This additive can be directly incorporated into the mixer or into the bitumen tank, requiring in this case a slight recirculation to achieve optimal dispersion. The amount to be added depends on the benefits required, although 2–4% in w/b is recommended.

4. Licomont®BS100, created by Clariant, is a diamide derived from a fatty acid with a low molecular weight and a melting point of 140 °C. It is white and is used in granulated form or powdered. With the modification of the binder viscosity, it optimizes the workability of bitumen, leading to a greater compactness and lower content of voids. Due to its polarity, this additive also has a positive influence on the adhesion between the binder and aggregates of quartzite or granite type. Adding 3% in w/b, it achieves a production temperature in plant between 20 °C and 30 °C lower than HMA. In Germany, a binder amended with this additive known as Sübit is used to improve the hardness of the pavement at high temperatures (D'Angelo *et al.* 2008).

5. Processes 3E®. COLAS has created three procedures called 3E® (Enrobés Environnementaux Economes en Energie), able to reduce manufacturing and laying temperatures by up to 40 °C, in all kinds of plants without modification or with little adjustments. The research led to a range of three products whose common characteristics are compatible with the specifications, and enable placing temperatures between 80 °C and 110 °C (Brosseaud 2006):

– procedure 3E «DB»: the coating is sequentially carried out to adjust the bitumen viscosity. Aggregates are dried and heated to 125 °C and subsequently coated. The final binder grade is chosen on the basis of the use;
– process 3E «DM»: coating is sequentially carried out. The aggregate is dried and heated to 125 °C and first surrounded with hot bitumen and then with foam bitumen. The binder grade is adapted to the final product desired;
– procedure 3E «LT»: The coating is performed in the traditional way, with the exception of the temperature, always at 125 °C. The binder 'LT' is sprayed onto the aggregates.

6. SEAM® (Sulphur-Extended Asphalt Modifier) is an additive in granular form developed and patented by Shell Bitumen that changes the binder's properties, reducing its viscosity and increasing its ductility. This product is added to the mixture achieving a mixing temperature under 140 °C. The mix design is changed depending on the nature of the combination between SEAM® and the binder, allowing the replacement of a part of the bitumen, approximately 25% in weight. Depending on the type of mixture, the amount of product to add varies, although to get an asphalt mix with the best structural properties, the proportion binder-SEAM® should be 60–40% in weight, respectively. The bituminous mixtures modified with SEAM® need several days to develop their end resistance, because of the progressive crystallization of sulfur in the mix (Cooper III *et al.* 2011).

b) In the case of *chemical additives*, in most amino compounds with tensoactive character, they improve the adhesion between different components of the mix, achieving 30 °C lower temperatures for the manufacture and placement without changing the physical and chemical properties of bitumen. They do not alter the mix design or manufacturing process. The following types exist:

1. Rediset™WMX is an additive created by the R&D&i team at Stenungsund (Sweden). This granular compound incorporates an adhesion promoter that improves the behavior under indirect traction (ITSR) and therefore the passive adhesion in the mix, making possible the use of different types of aggregates with optimum working conditions. This additive can be added to the mixer or directly to the bitumen prior to the process of mixing specifying in that case a small agitation so the additive dissolves correctly in the bitumen. The dosage is 1–3% in w/b (Chowdhury, Button 2008).

2. Iterlow-T, created by the Italian company *Iterchimica SRL*, is a surfactant formed by different amino substances. This additive is added to the bitumen in a ratio of 0.3–1% in w/b according to the type of bitumen, amount of RAP incorporated and the final working temperature. The addition can be performed directly in the tank of bitumen, needing only a slight recirculation to obtain the best dispersion. This compound interacts with the binder structure, its chemical action being reflected in the physical characteristics of the mixture, helping obtain mixing temperatures of 120 °C and the laying in values between 90–100 °C. This reduction of temperature does not affect the mechanical properties of the mixes, obtaining the same quality as HMA.

3. Cecabase®RT945 is an additive patented by CECA, a subsidiary of the Arkema group. It is composed of a mixture of surfactants whose composition has at least 50% of renewable raw materials, one of them being a biodegradable compound. Adding this compound to the bitumen, the manufacturing temperature can be reduced to 120 °C, while maintaining the mechanical properties of a traditional wrapped material. The amount to add to this product ranges between 0.2–0.4% in w/b without changing the asphalt properties. It can also be used with modified bitumen, with fibers, with RAP, etc. (Silva *et al.* 2010).

4. Revix^TM^WMA, additive developed by Mathy Technology and Engineering Services and Paragon Technical Services, Inc. and marketed by MeadWestvaco under the name of Evotherm^TM^3G, helps decrease the manufacture and laying temperature of the bituminous mix between 15–25 °C, because it reduces internal friction that occurs between the binder and aggregates. This process is not related to the principles of foam or reduction of the asphalt viscosity. Revix^TM^ is a mix of surfactants, waxes, polymers, etc., resulting in an additive that added in the binder reduces the resistance to the wrapped material even at low temperatures. This compound does not require making any change in the design of the mixes. Usually, it is added to the binder at the end of the process, so the plant does not require any modification (Chowdhury, Button 2008).

2.2. Use of water

There is a variety of processes that use water to obtain foamed bitumen or emulsion. Some are based on the use of additives within the mix to achieve a foam or emulsion of bitumen. Others are based on the use of a system of nozzles or wet aggregates during the production process to achieve foaming binder.

1. Ecomac® is a technology patented by Screg. It is an emulsion of asphalt concrete, obtained by heating up to 50 °C a mix previously made in cold. This process patented uses specific equipment of HWMA. It optimizes the properties of homogeneity and workability of a wrapped material in cold, its use being recommended for thin layers of surface (Mahé de la Villeglé *et al.* 2005).

2. Evotherm® is a technology developed in the United States by MeadWestvaco Asphalt Innovations, based on a chemical process that includes: adhesion promoters, cationic emulsification agents and additives to improve the covering of the aggregates and the workability of the bituminous mix. The product is presented in form of emulsion with a high level of residue asphalt (70%) and the amount to add is 0.5% in weight (Hurley *et al.* 2006). The water in the emulsion is released in the form of steam when it comes into contact with the hot aggregate, the resulting WMA obtaining the same appearance as the HMA in terms of coating and color. The thin film of water that exists between the aggregate and the binder emulsified drops improves the workability of the mix even at temperatures below 90 °C. This film of water promotes a quick coalescence of the drops, inducing a fast healing later. The cationic emulsifiers are fixed by adsorption on the surface of aggregate with the functional groups positively charged and exposing the hydrocarbon tails outwards, promoting a strong adherence to the binder improving the resistance to the moisture. This product can be used with modified bitumen (Button *et al.* 2007). This process does not require making any change in the plant, taking the precaution to keep the temperature of the conduit of this additive above 90 °C to prevent breaking emulsion in the lines (Hurley *et al.* 2006).

3. Zeolites. There are two synthetic zeolites, Aspha-Min®, patented by Eurovia Services GmbH and used in Europe and Advera®WMA, related to PQ Industries and used in the US. These two differ in the water content in their structure, 21% of its mass in the first case and between 18% and 22% in the second (Chowdhury, Button 2008). When heating the mix to a temperature between 85 °C and 180 °C, the water contained in the structure of zeolite is released, causing a volumetric expansion of bitumen that result in the emergence of foam bitumen. This will improve the manageability of the mixture and the laying process, as well as the cover of aggregates by the binder at lower temperatures than HMA (Button *et al.* 2007). This method consists in incorporating the binder and zeolite in powder form at the same time in the mixer, in a ratio of 0.3% in weight of the total mixture. The zeolite can be added directly to the pugmill of a batch plant, or pneumatically fed into a drum plant using a feeder (Hurley et al. 2006).

4. LT-Asphalt® (Low Temperature Asphalt) is a technology developed by NYNAS Bitumen, which uses 0.5–1% of hygroscopic filler, which helps to maintain and control the moisture of the foam, providing a good placement of the mix. Aggregates are heated to 90 °C and a binder is foamed with special nozzles and mixed with the aggregates, including the filler, producing bituminous mixtures at 95 °C (Brosseaud 2006).

5. Double-Barrel®Green is a technology developed by Astec Inc. where a device nozzle has been designed to work with its plants Double Barrel®. Each nozzle is designed to provide sufficient foam in order to mix 50 tonnes per hour of WMA, and a computerized system setting the number of usable nozzles on the basis of production rate. A pump controls the water injection, whose speed is regulated with regard to the pump speed of asphalt. The water is injected into the mix in a proportion of 2% in w/b together with the asphalt. The injection of water causes a foaming and consequent expansion in the bitumen, which helps the binder to wrap the aggregates at lower temperature. The tests carried out by Astec indicate that the production of VOCs can be significantly reduced if the temperatures remain below 140 °C (D'Angelo *et al.* 2008).

6. WAM Foam® is a production process patented by Shell Bitumen and Kolo Veidekke, is characterized by the replacement of the conventional binder for the use of two bitumens separated in the stage of mixture. First, soft bitumen is added at a temperature of 100–120 °C to mix with the aggregates. Next, hard bitumen is incorporated in the form of foam or emulsion. This process of obtaining a binder helps to reduce its viscosity and therefore works at lower temperatures. The process of obtaining these mixes is perfectly defined and described in the publication by Koenders *et al.* (2000). It has the disadvantage of needing a modification of the production plants of HMA for the production of the WAM Foam®, because it is necessary to introduce a foaming device and a system of air extraction to offset the increased pressure caused by the expansion of bitumen. If it is used with an emulsion, a colloidal mill will be needed.

7. LEA® (Low Energy Asphalt) is a technology patented by LEACO, Fairco and EiffageTP. This process only dries the coarse aggregate, reaching a temperature about 150 °C. Later, it is mixed with hot bitumen treated with additives of Fairco. When mix has been completed, the fine aggregate and sand are added at room temperature without drying them, in order to take advantage of their residual water the mixing process. This will achieve a reduction in energy consumption and form less dust in the dryer drum. According to Fairco, the moisture contained in the fine aggregate initiates a reaction, causing the foaming of the bitumen, encapsulating the particles of the fine aggregate with the foamed binder. This reaction is improved through additives that generates a growth in the specific area of binder and decreases its apparent viscosity. In this case, the plants need to be modified because to heat only the coarse aggregates, the traditional dryer and the dust filters are oversized. Another change to be made is the introduction of a condenser to treat the cold vapors produced by the introduction of water in the process (Romier *et al.* 2006).

2.3. Use of binders of vegetable origin

It is possible to replace the binder obtained from the cracking of petroleum by a series of compounds of vegetal nature which are translucent, helping a better integration with the environment, reducing the visual impact that the bituminous mixtures generate. In turn, this new generation of binders can be used in mixes at low temperatures. These compounds are:

1. Végécol® is a Colas product. It comes from renewable raw materials of vegetable origin and it may be used in roads or in civil engineering in general. The mixes manufactured with this compound have similar characteristics or even better than their bituminous counterpart. As the compound is translucent, it can be easily colored by different pigments. Besides, it presents a good workability at lower temperatures. Due to their particular rheology, a decrease of 40 °C in the manufacturing temperature is enabled. The stiffness modulus can be adapted depending on the use it is aimed at, presenting in turn a strong resistance to fatigue. It can be used in plants with a specific line to dispense the compound (Poirier, Martin 2007).

2. Biophalt®, created by Eiffage, is a product of vegetable origin, derived from by-products of the paper industry. It shows a translucent aspect, which highlights the natural color of the aggregates for a better integration with the environment, and may be colored if necessary. It can produce mixtures for surface layer of thickness between 2–5 cm and a particle size between 0/4 and 0/10, at a manufacturing temperature of 130 °C and placement at 115 °C (Guillamot *et al.* 2007).

3. Floraphalte®, designed by *Shell Bitumen*, can be colored with different pigments according to the use that you want to give it (bike lane, parks, sports stadiums, etc.) The range of mixing temperature is between 130–150 °C, and shows an excellent performance against aging and favoring adhesion and resistance to water (Nadjar 2008).

Table 1 shows a brief summary of the sustainable asphalt mixes.

3. Reutilization of materials

Another way to contribute to the environment is the use of recycled materials. In the case of road construction, it consists of the replacement of raw aggregates by another type of products. This will safeguard natural resources and avoid impact due to extraction of these materials (Horvath 2003). The use of industrial by-products is estimated to save around 600 000 tons in CO_2 emissions (Eckelman, Chertow 2009).

At present, among the recycled materials that can be used in the construction of a pavement are industrial by-products, such as steel slag; demolition by-products, such as tiles, bricks, etc. and road by-products (Horvath 2003).

Within this strategy, milled aged pavements, termed RAP, are used as partial substitutes for natural aggregates. They can be used in situ without the need of transport, which implies a cost saving and an environmental improvement, because it achieves a reduction in the consumption of non-renewable and raw materials and the amount of waste created (Pereira, Picado-Santos 2006).

RAP can be used in hot, cold and warm mixes but it has a great influence in the characteristics of the final product (Soto Sánchez 2006). All of these materials recovered from bituminous mixtures can be recycled, except those which have suffered deformations. These materials are mixed in suitable proportions with virgin aggregates, new bitumen and/or an anti-aging material, to produce new mixes that comply with the specifications of quality, strength and durability required for each type of layer.

The Washington State Department of Transportation (WSDOT) issued recommendations for the use of this type of materials; the highlights include the use of up to 20% of RAP in the manufacture of new mixes without the need for a specific design and the use of 80% of RAP in the manufacture of new mixes provided that the specific design complies with the same criteria used for HMA (Swearingen *et al.* 1992).

In the case of the cold recycling of pavements, known as In-Situ Recycling Cold with emulsion, it is carried out at ambient temperature and on the surface to be treated. Compared to other possibilities, it provides economic savings and minimizes environmental impact, reducing the energy consumption by eliminating the need to heat the material and avoiding part of the transport. In addition, it obtains a drastic drop in the need for virgin aggregates and binders (Pereira, Picado-Santos 2006). This type of recycling has the advantage of flexibility and adaptability for a wide variety of thicknesses, from a few centimeters (5/6 cm) up to a recycled in depth of 10/15 cm. However, the recycling with emulsion presents some limitations. Any operation of cold recycling requires a thorough study of the sections and materials, and it does not allow some types of problems in the pavement to be solved, in particular those associated with poor quality of the subgrades or deep layers (Pereira, Picado-Santos 2006).

Currently, studies on the use of nanoemulsions are being carried out to make cold recycling mixtures. These nanoemulsions are made with High Internal Phase Ratio (HIPR), between 75–95% in weight, obtaining a viscosity above 1 Pa×s, getting control of the drop size in the emulsion. The use of these emulsions causes an increase in the specific surface, improving the quality of the wrapped material. This can be seen in the strength results that Lesueur *et al.* (2008) obtained in their studies, in which an improvement in both the dry and submerged strength can be observed, in addition to the retained strength. Furthermore, they deduced that with 2% of nanoemulsion, the results

Table 1. Comparison of different technologies existing in sustainable asphalt mixes

Classification	Technologies (manufacturer)	% Additive, (w/b or w/m*)	Properties
Use of chemical additives	Rediset™WMX (Azko Nobel)	1–3% in w/b	Improve the behavior under indirect traction
	Iterlow-T (Iterchimica SRL)	0.3–1% in w/b	Maintain the mechanical properties of HMA
	Cecabase® RT945 (CECA)	0.2–0.4% in w/b	Maintain the mechanical properties of HMA
	Revix™WMA or Evotherm™3G (MeadWestvaco Asphalt Innovations)	–	Reduce internal friction between binder and aggregates
Use of organic additives	Sasobit® (Sasol Wax)	3% in w/b	Improve the compactness and the resistance to deformation of the surface
	Asphaltan B® (Romonta GmbH)	2–4% in w/b	Increase the compactness and resistance to rutting
	Rheofalt® LT70 (Ventraco)	2–4% in w/b	Have greater range and mix workability
	Licomont® BS100 (Clariant)	3% in w/b	Optimize the bitumen workability, greater compactness and lower content of voids
	Processes 3E® (COLAS)	–	Does not change standard characteristics
	SEAM® (Shell Bitumen)	binder-SEAM® 60–40% in weight	Need several days to develop their end resistance. More advantage in semi-rigid pavements than in the flexible ones
Use of water: emulsion	Ecomac® (Screg)	–	Optimize the properties of homogeneity and workability. Recommended for thin layers of surface
	Evotherm® (MeadWestvaco Asphalt Innovations)	0.5% in weight of bitumen emulsion	Improve the covering of the aggregates and the bituminous mix workability
Use of water: foam bitumen	Zeolites [Aspha-Min® (Eurovia Services GmbH), Advera® WMA (PQ Industries)]	0.3% in w/m	Improve the manageability of the mix and the laying process, as well as the cover of aggregates
	LT-Asphalt® (NYNAS Bitumen)	0.5–1% of hygroscopic filler	Maintain and control the moisture of the foam, providing a good placement of the mix
	Double-Barrel® Green (Astec Inc.)	2% of water in w/b	Help to wrap aggregates at a lower temperature
	WAM Foam® (Shell Bitumen and Kolo Veidekke)	2–5% water by mass of hard binder	Special process of obtaining a binder helps to reduce its viscosity and therefore works at lower temperatures. Disadvantage: modification of the production plants
	LEA® (LEA-CO)	3% water introduced with fine sand	The moisture contained in fine aggregate causes the bitumen foam, decreasing its apparent viscosity. Disadvantage: modification of the production plants
Binders of vegetal origin	Végécol® (Colas product)	Replacement the bitumen obtained from the cracking of petroleum	Good workability. Stiffness modulus can be adapted
	Biophalt® (Eiffage)		Produce mixtures for surface layer
	Floraphalte® (Shell Bitumen)		Excellent performance against aging and favoring adhesion and resistance to water

* w/b – weight of bitumen; w/m – weight of the total mixture

Table 2. Comparison between different types of recycled mixes (Soto Sánchez 2006)

Rate	Type of recycled mix		
	Hot	Warm	Cold
RAP, %	< 50	100	100
Initial cohesion	Very good	Good	Poor
Maturing period	No need	No need	Several weeks
Contribution aggregates	Yes	No	No
Binder	Bitumen	Emulsion	Emulsion
Working temperature	High temperature	> 60 °C	Ambient temperature

obtained are similar that in the case of 3% of a conventional emulsion (Lesueur *et al.* 2008).

The warm recycled mix has emerged as a result of the limitations of the previously commented recycling techniques. Thus, while cold recycling requires several weeks for maturing, hot recycling has the great disadvantage of being inefficient: only between 20% to 30% of RAP may be used because the viscosity of modified bitumen could increase quickly, making the placement so difficult (Pereira, Picado-Santos 2006; Soto Sánchez, Blanco Morcillo 2003).

Warm recycling, based on the possibility of recycling 100% of milled asphaltic layers, does not require a later period for curing (Soto Sánchez 2006). The material is heated up to 90 °C with a conventional plant, to mix later with an emulsion (Soto Sánchez, Blanco Morcillo 2003). In Soto Sánchez and Blanco Morcillo's article (2003) tests are carried out in manufactured specimens with this technique, and the results presented positive conclusions, such as the improvement of retained strength with respect to cold recycling, higher densities and a dynamic modulus similar to HMA.

Table 2 gives a summary of the characteristics of the three types of recycling.

4. Tools available for choosing an asphalt mix

The different types of mix commented on in this article affect the environment in a positive way compared to HMA, either focusing on the decrease of temperature, which directly affects the gas emissions and in the fuel consumption, or in the reuse of materials such as substitutes for the natural aggregates.

For choosing between one mix or another, not only the reduction of total energy consumption (Eq (1)) should be taken into account, but also their mechanical properties, as the durability of the mixes has an impact on economic issues and that has to be considered by the companies. For example, if HMA lasts approximately between 20–30 years, and WMA or HWMA's duration is only 5–10 years, it would not be feasible, either environmentally or economically, because that road would have to be re-surfaced in more frequently, with the consequent economic investment and the formation of new wastes. To solve this problem, comparative studies are being carried out at laboratory level and on real scale, checking their mechanical characteristics and their behavior (Sanchez-Alonso *et al.* 2010; Su *et al.* 2009; Vaitkus *et al.* 2009). For this reason the companies must make an analysis taking into account three parameters: environmental improvement, the mechanical characteristics and their economic viability, optimizing each of them (Horvath 2003).

$$E_{total} = E_{binder} + E_{aggregates} + E_{mix} + E_{transport} + E_{laid} \quad (1)$$

At present, there is a tool called life cycle assessment (LCA), which enables the engineer to compare and evaluate the potential impact on the environment of a product or activity throughout its life cycle through the quantification of the use of resources and emissions associated with the system that is being evaluated (Huang *et al.* 2009). This tool can be useful to obtain a clearer idea about the benefits of the use of new technologies, such as mixes at lower temperature compared to conventional ones and/or the use of recycled materials against raw aggregates. The LCA model must be developed in accordance with *ISO 14044 Environmental Management – Life Cycle Assessment– Requirements and Guidelines*, and has been applied and tested in real projects. This model consists of five steps: process parameters, pavement parameters, unit inventory, project inventory and characterization results (Huang *et al.* 2009). The first two are specific to each project. The 'process parameters' worksheet includes data about transport distance, the fuel and energy consumption in production of material and construction of the pavement. The 'pavement parameters' worksheet includes data about dimensions and amount of materials to use. Later, in the 'unit inventory' worksheet an input and output about the inventory environmental of the project is realized, which includes the energy consumption and emissions predicted during the process. In the 'project inventory' worksheet, items of the unit inventory are added to the unit of pavement projects, based on the loads of work calculated under the process parameters and pavement parameters. Finally, the 'characterization results' is where the results are selected to define the impact categories, characterized by the models and submitted by categories of indicators (Huang *et al.* 2009).

However, LCA will lack the economic variant, which is often the predominant factor in a choice. There are two tools that make an environmental and economic estimation about the use of different products, materials or services: the Economic Input-Output Life Cycle Assessment (EIO-LCA), and Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects (PaLATE), specifically for pavement construction (Horvath 2003).

The EIO-LCA model estimates the materials, the energy resources and the environmental emissions resulting from different industry sectors, quantifying their direct and indirect incidences in the economic system. This software considers the interaction of around 500 sectors across the economy. This method is based on the national economic input-output and publicly available resources and data of emissions of each country (Norman *et al.* 2007). The use of this program can help to indicate priority areas for reduction of environmental impacts, to examine the total direct and indirect economy-wide effects on emissions and energy consumption resulting from changes in production, for instance.

The program PaLATE performs environmental and economic estimations for the use of different materials in construction and maintenance of roads, although it does not give information about the mechanical behavior of them. PaLATE is based on the LCA model, supplemented with the use of a computer program that utilizes economic and environmental parameters. In the economic aspect, the program takes into account the infrastructure costs, its maintenance, etc. Therefore, the net present value of the new pavement is estimated with several alternatives of maintenance, and their annual cost to compare pavements with different times of life cycle. In the environmental case, the program relates emissions and materials during production, construction, transportation and maintenance of pavements, and may incorporate data on the use of raw or recycled material. This program can also make an estimate of the energy consumed and the emissions of CO_2, NO_x, PM10, SO_2 and CO (Horvath 2003).

5. Conclusions

Different manufacturing techniques for sustainable asphalt mixes have been presented. They can be divided in two main groups: production at lower temperature and/or reuse of materials. In the first group, there has been realized a classification of asphalt mixes according to the use of additives, water or vegetable binders in the manufacture process. In some processes, a modification of the plants will be required. In the second group, the raw aggregates are substituted in a certain percentage by industrial by-products, construction and demolition waste or milled pavements.

The choice of one or another depends both on the characteristics of the mixes as well as the investment that companies want to make in their plants. One difficulty to be found is the lack of information about the long-term behavior of these mixes in comparison with HMA, although comparative studies at laboratory level and on real scale demonstrate that their mechanical characteristics and their behavior are similar.

To assess the choice of possible mixes to be used, a LCA of the pavement can be performed; analyzing the energy consumption that the construction of the road requires is performed, from the extraction of the raw material until its placement, also exploring the emissions which occur throughout the process. If an economic assessment of the various possibilities is added to this analysis (EIO-LCA or PaLATE), it can provide a very real approximation to the economic costs which the construction and maintenance of pavements involve, and it may be used as a criterion for choice by contractors and public authorities.

Acknowledgment

This paper is based on the initial literature review for the Fenix Project. The development of the Fenix Project (www.proyectofenix.es) has been possible thanks to the financial contribution of the Center for Technological and Industrial Development (CDTI) within the framework of the Ingenio 2010 programme, through the CENIT Programme. The companies and research centers involved in the project wish to express their gratitude for the contribution.

The authors are grateful to all organizations and companies participating in the Fenix Project: Centro de Investigación Elpidio Sánchez Marcos (CIESM), Centro Zaragoza, Construcciones y Obras Llorente (Collosa), Ditecpesa, Asfaltos y Construcciones Elsan, Intrame, Pavasal, Repsol YPF, Sacyr, Serviá Cantó, Sorigué, CARTIF, CEDEX, CIDAUT, CSIC (IIQAB), GIASA, Intromac, Labein, Universidad de Alcalá de Henares, Universidad Carlos III de Madrid, Universidad de Castilla La Mancha, Universidad de Huelva, Universidad de Cantabria, Universidad Politécnica de Cataluña, Universidad Politécnica de Madrid, and our many partners whose work capacity and effectiveness have enabled the development of this project in an environment of cooperation.

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Received 19 February 2010; accepted 20 January 2011