INNOVATIVE LOW ENERGY ASPHALT TECHNIQUE FOR MINIMIZING IMPACTS FROM ASPHALT PLANTS TO ROAD WORKS

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ABSTRACT

Different proprietary low-energy asphalt (LEA) techniques at 90°C (194°F) have been recently developed by LEA-CO (low energy asphalt company) on standard asphalt plants as a real alternative to HMA (hot mix asphalt) which are usually produced at 150-190°C (302-374°F). LEA can be used as a relatively cheap way to minimize impacts during the manufacturing, transport, paving and compacting stages. In plant, this innovative eco-process enables a reduced binder ageing and a reduction of both energy consumption and greenhouse gases ranging from 30 to 50%. At the job site, fumes are overwhelmingly reduced and the release to traffic is immediate after compaction. This illustrative article proposes practical examples and case studies that deal with how building owners, prime contractors, asphalt producers and even equipment manufacturers can seek to realise sustainable environmental, economic and social policies and solutions for roads by turning to fostering and using LEA as a new asphalt generation for roadway construction and maintenance. Various examples of asphalt formulas validated both in laboratory and on road site, are presented in details. Both the preliminary laboratory studies and the follow-up of the on-site behavior since their startup are presented.

1. INTRODUCTION

HMA (hot mix asphalt) is traditionally produced by mixing binder with aggregate at very elevated temperatures (usually in excess of 150°C). The two most common hot mix facilities, drum mix plants and batch plants, heat aggregate in a rotating kiln to extremely high temperatures in order to drive off all water adsorbed to the aggregate, as well as all water absorbed within the surface pores of the aggregate. Total drying is required to ensure perfect aggregate coating and to minimize the moisture sensitivity of the final mix.

The ever-increasing price of oil and natural gas as well as more environmental reasons foster asphalt industry to promote new energy-saving coating techniques. The road industry first proposed cold-mix systems [1-2] the durability of which is difficult to predict and is often related to higher variability into the curing mechanisms compared with HMAs. That is why, the cold mix asphalts (CMAs) have not yet been able to gain ground in relation to HMAs. Insofar as the 2005 European annual production is concerned, the CMA tonnage was about 6 millions whereas that of HMAs was greater than 321 millions [3].

The so-called warm-mix asphalt processes have been recently proposed, resulting in a substantial reduction in production temperature (20 to 40°C) and exhibiting properties matching closely those of HMA. They use binders or combinations of binders and additives modifying the rheological properties of bitumen during mix manufacture and application. To meet field application conditions, the application temperature of these mixes remains actually higher than 100°C. Many recent European or North American articles have described and provided overviews of available techniques and their use [4-11].

It is within this context that different half-warm mix asphalt processes have also appeared, the binder being either an emulsion [12-15] or a foamed bitumen [16-20] or simply a bitumen [21-31]. The originality of these new techniques is characterized by a production temperature lower than 100°C, with application conditions amenable to an even lower temperature, varying according to climatic conditions at the time of construction. Experience shows that this temperature is generally between 70 and 90°C. The properties of the finished asphalt layers are not significantly differing from conventional layers.

2. BACKGROUD

2.1. Terminology

Figure 1 illustrates the different types of asphalt mixes in relation with their coating temperature, the corresponding consumed heating energy and the CO_2 emission [27, 32]:

- Cold mix asphalt (CMA), usually manufactured at ambient temperature from asphalt emulsions or foams,
- Half-warm mix asphalt (HWMA), produced at temperatures below 100°C,
- Warm mix asphalt (WMA), manufactured above water vaporization at temperatures ranging from 120 and 140°C,
- Hot mix asphalt (HMA), produced at 150-180°C in relation with the used binders.

2.2. Key figures

The basic calculation of the amount of heat energy required on a plant mainly relies on fundamental characteristics of specific heat of the aggregate $c_{aggregate}$=850J/kg/°C, of water c_{water}=4.2kJ/kg/°C, latent heat of evaporation of water $L_{vaporization}$=2250kJ/kg, specific heat of steam c_{steam}=1.85kJ/kg/°C. Therefore, energy consumed for heating mixes directly depends on the production temperature and the aggregate humidity. In brief, it is worth keeping in mind the two following statements:

- Energy required for the heating of dry aggregate is almost 5 times lower than that used to raise to the same temperature an equivalent mass of water,
- Latent heat of evaporation of water represents 5 times the energy required to raise the same mass of water from 0 to 100°C. Exceeding the 100°C threshold greatly increases the energy expenditures.

2.3. Energetic and environmental stakes

Both HWMA and WMA make it possible to save fossil energy (fuel or natural gas) in plants but in different proportions: WMA at 140°C enables temperature gains of 20°C generally with an excess cost of production due to the use of additives or to a more complex manufacture and/or a somewhat lower rhythm. Energy savings are of the order of 15%.

HWMAs –produced below 100°C– lead to as much as 50% reduction in energy consumption (depending on the used process, plant and materials). In the case of HWMAs employing either an emulsion-type binder or a foam-type one, the global reduction in energy consumption is slight. Indeed, the emulsion and the foam respectively contain about 35% and 5% of water, which implies a higher heating temperature of the aggregate. That's why anhydric bitumen was first adopted in the LEA process for simplicity and economic reasons. The energy balance, calculated according to the theoretical principles, is confirmed after asphalt production by means of the fuel or gas meter reading.

Lower coating temperatures also mean that greenhouse gas emissions (GGEs) will also be reduced. As the mean reduction in CO_2 emission is about 9 $kgCO_2$/ton through the LEA process, in Europe for instance, the CO_2 emissions could decrease by almost 3 million tons/year, in the US the CO_2 emissions could also decrease by about 5 million tons/year. Regarding emission of volatile organic compounds (VOCs), they come from bitumen fumes. Among these, polycyclic aromatic hydrocarbons (PAHs) present in small quantities have an essential impact on health. A reduction of 13°C in mix manufacturing temperature generates a reduction of the PAH emissions by a factor of 2. Reducing by more than 50% the application temperature reduces in considerable proportions the health risks involved.

A laboratory estimation of the fumes emission potential during HMA or LEA productions was very recently carried out by the crew of Chantal De la Roche at the French LCPC (Laboratoire Central des Ponts et Chaussées) in Nantes: a lab mixer was equipped with a stack for gas emission sampling in normalized conditions and a continuous total organic compounds (TOCs) analyzer was used for characterizing fumes (for more details on this new experimental protocol of lab characterization of asphalt fumes during mixing, the reader can refer to the following reference [31]). Figure 2 displays the reduction in TOCs obtained in the case of a given dense asphalt typically used as wearing course in France.

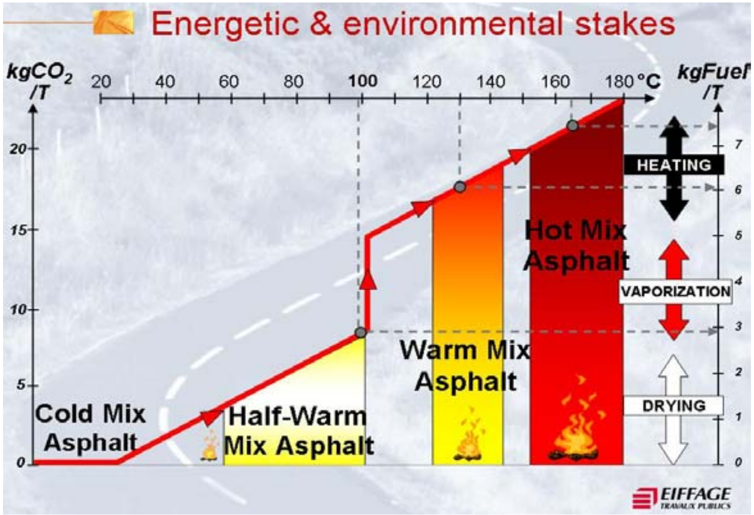

Figure 1. Fuel consumption and CO_2 emission for the heating of 1 ton of wet aggregates.

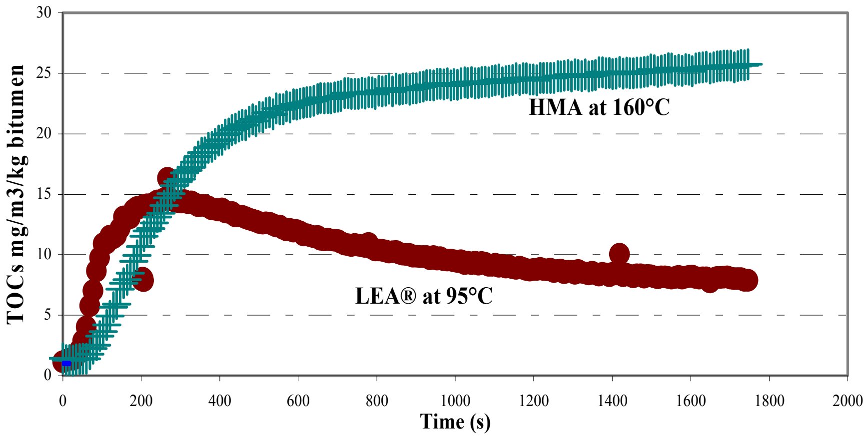

Figure 2. Reduction in the Total Organic Compounds (TOCs) emissions during the mixing of a French BBSG-type dense asphalt with the LEA process (LCPC lab in Nantes).

2.4. Review of the existing warm and half-warm mix asphalts technologies

These innovative low-temperature and low-energy coating technologies are based on at least one of the four following possible principles:

- Modification of the asphalt mixing process (without changing the mix components)
- Addition of substances which decrease the viscosity of bitumen
- Introduction of water causing in-situ foaming of the bitumen
- Use of low-viscosity vegetable binder

2.4.1. *Modification of Process Technology*

Modifications of the existing mixing plant technology allow a reduction of the mixing temperature without changing the components of the asphalt:

- KGO or “addition sequence” process: only the hot coarse aggregates are first blended with the bitumen until a homogeneous mix is obtained. The increased bitumen-aggregates ratio allows the mixing with cooler, *i.e.* higher viscous bitumen. The hot fine aggregates are then added and can be very well dispersed into the pre-coated coarse mix.
- Two-phase mixing process: in the first phase the aggregates are mixed with a very soft bitumen grade (Penetrability in the range of 160 to 400). The low viscosity allows reducing the process temperature. In the second phase a harder bitumen grade (Penetrability in the range of 35 to 100) is added and can be homogenized with the pre-coated aggregates at reduced temperature.

The feasibility has been demonstrated for both technologies and homogenous mixes with fully coated aggregates have been obtained. However, plant modifications are necessary and the available time for transportation and paving is reduced since the rolling has to be completed at similar temperatures as with conventional asphalt.

2.4.2. *Viscosity Reducing Organic Additives*

Such additives are solids at ambient temperature which melt, depending on the type of additive, between 70 and 140°C. The melts are low-viscosity liquids being homogeneously soluble in hot bitumen and can therefore quickly and easily be blended with pure or polymer-modified bitumen, e.g. by stirring. Significant viscosity reductions are obtained by adding 2-4 % into the binder. Owing to the solubility of the additives, the viscosity reduced binders are hot storage stable and the viscosity effect is permanent, even at asphalt recycling at the end of the service life of the layer. During the cooling time of the paved asphalt the molten additives solidify to microscopically small, uniformly distributed particles. The additives are either added as solids into the mixer, or as pre-blended, low viscosity binder. The latter is recommended to assure homogeneous distribution without lengthening the mixing time (no impact on the production rate).

Three classes of waxes are currently used:

- Montan wax (lignite wax) consisting mainly of fossil fatty acid esters. The pure wax melts around 70°C, bringing about some rutting problems at service temperatures. Thus, it is frequently blended with higher melting materials, such as amide waxes.
- Amide waxes, synthetic fatty acid amides with melting points around 140°C.
- Fischer-Tropsch wax which is a blend of long-chain alkanes produced from synthesis gas with the so-called Fischer-Tropsch process. The pure wax melts around 115°C, but when blended with bitumen, solvency effects shift the congealing temperature of the additive to 100°C. Therefore, the asphalt has to be paved and compacted above 100°C, that is to say soon after the production. Several million tons of hot mix have been modified by Fischer-Tropsch wax over the last decade.

2.4.3. *Water-based Technologies*

Some WMA and HWMA technologies are based on the introduction of water into the mixing process. The common principle is the generation of water steam which increases the volume of the binder and decreases its apparent viscosity.

Two main classes of water-based warm technologies (>100°C) are currently used:

- The WAM (Warm Asphalt Mix)-Foam process uses a two-component binder system which needs a modification of the plant [4]. In the first step the aggregates are coated with a soft binder (Penetrability of about 160 to 400) and subsequently foamed, harder bitumen (Penetrability from 35 to 100) is added. The dry aggregates are coated with bitumen before the water is introduced; this is supposed to be advantageous with respect to adhesion of the binder on the aggregates. Trials and applications are mainly located in Norway where the process has been developed.
- Zeolites substitute a part of the filler and are added into the plant which has to be equipped with an additional storage silo and a feeding system. The structure of this synthetic sodium aluminium silicate mineral contains 21 wt. % water in small pores which is released upon heating within 2-3 hours. The evolving water steam causes an in-situ foaming of the bitumen. Zeolite is in use in Europe and in the USA [9].

Three main classes of water-based half-warm technologies (<100°C) are currently used:

- Emulsion technology: in-situ bitumen foaming can also be obtained by mixing bitumen emulsion with hot aggregate. This technology applies a special emulsion with 30% water content which is delivered and fed into the mixer at a temperature of around 90°C. The 30% water content in the emulsion is partially liberated in the form of steam when it is mixed with hot aggregates. This vaporization makes the mix temperature swiftly decrease below 100°C, which is the main advantage of the process. However, the heating and drying of aggregates above 100°C overwhelmingly limit the in-plant energy savings. First trials are mainly located in North America where the process has been developed [12].
- Foam technology: in-situ bitumen foaming obtained by mixing foamed bitumen with half-warm or warm aggregates. Despite very good energy savings (30-50%), the quality of this kind of mixtures appeared in the literature as lower than that of traditional HMAs [19].
- LEA (Low Energy Asphalt) process: the originality of this recent half-warm mix process lies in the ability of hot anhydric binder to transform into foam or to emulsify when in contact with the residual water of warm aggregates just below the water vaporization point at 100°C (in normalized pressure conditions at 1bar), thus allowing aggregate coating at lower temperatures. The spontaneous volume expansion of bitumen leads to a thicker binder film around aggregate, which fosters good mixture workability even at the processing temperatures of about 70 to 95°C. This paper aims at fully describing this innovative eco-process which is, until now, the simplest way to minimize impacts during the manufacturing (the partial drying of the aggregate enables a reduction of both energy consumption and greenhouse gases ranging from 30 to 50% [21-29]), transport, paving and compacting stages (fumes and odours are overwhelmingly reduced and the release to traffic is immediate after compaction). More details are given hereafter.

2.4.4. *Low-viscosity vegetable binder*

Two main French road contractors have already developed such low-viscosity vegetable binders which allow mixing, paving and compacting temperatures at approximately 130°C. Very few field trials have been realised until now.

3. LEA: A NEW GENERATION OF ASPHALTS

As illustrated in Figure 3, the LEA process lies in the ability of hot bitumen to transform into foam or to emulsify directly at the wet surface of warm aggregates just below the water vaporization point at 100°C, thus allowing aggregate coating at lower temperatures. The spontaneous volume expansion of hot bitumen leads to a thicker binder film around aggregate and a smaller mix viscosity, and thus fosters good workability. According to the results obtained during the lab study, some specific additives may be used to improve the foamability and coating ability of the binder if need be. Figure 4 displays the main possible proprietary LEA techniques (with or without pre-coating) that are currently used depending of the mix formula and the given asphalt plant. In order to manufacture LEA at around 95°C, different possible sequences can be used in relation to the plant configuration:

- The drying stage may only affect a first part of the aggregates, then coated by the whole bitumen. The remaining cold part which has retained its initial humidity is then added. All the constitutive elements of the mixture are then mixed, or
- The drying stage may only affect a first part of the aggregates, which is then mixed, before the coating stage, to the wet and cold remaining part, or
- The drying stage may also apply to the entirety of the aggregates and is carried out in conditions which allow a fraction of the initial humidity to remain. This stage is then followed by the coating one.

Possible addition of extra water allows for any required correction of aggregate moisture before and/or after introducing bitumen into the mixer. Such possible water addition and, if need be, some specific multifunctional additives, enable:

- Optimization of the spontaneous volume expansion of the binder (Figure 3), and
- Correction of the mixture workability. Indeed, the condensation of excess water, dispersed in part in the bitumen mass, creates the final workability of the mix at a temperature lower than 100°C.

Both the volume expansion of bitumen (bitumen foaming) and the residual water (<0.5%) after coating and mixing allow good workability, even at a temperature lower than 100°C.

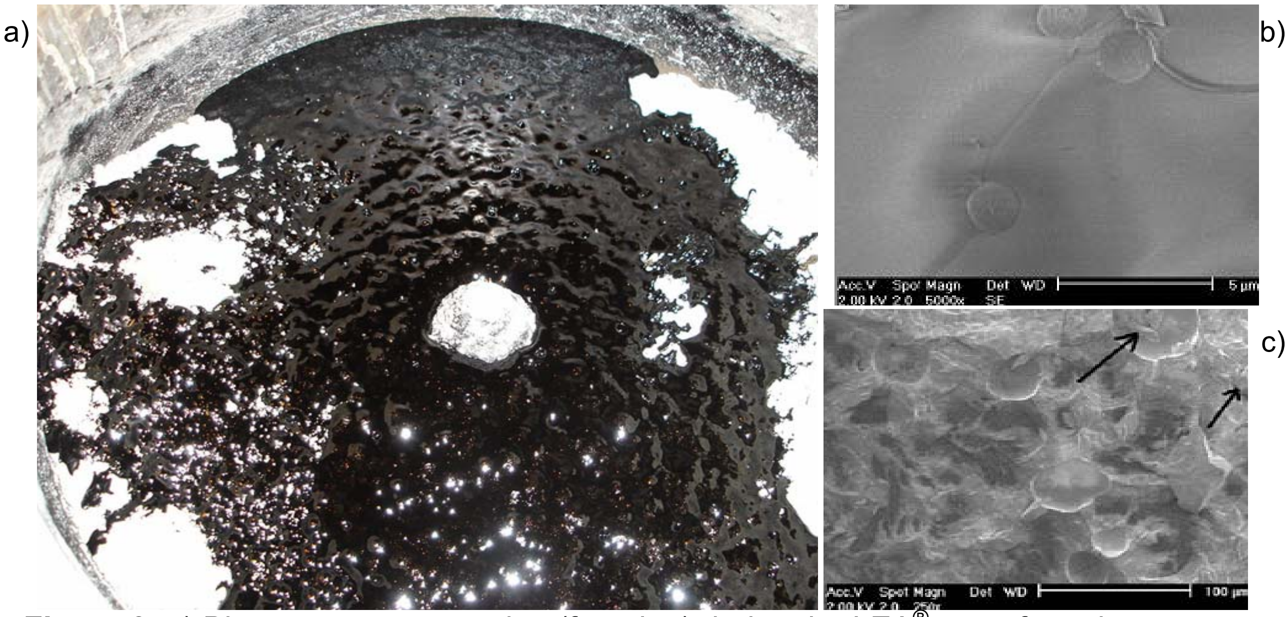

Figure 3. a) Bitumen auto-expansion (foaming) during the LEA® manufacturing process at the Eiffage Travaux Publics central laboratory, b) & c) Microscopic evidence about the dispersion state of water (liquid or steam) inside bitumen [26]. Craters correspond to water already evaporated or to fine droplets, the diameter of which being between 2 and 50μm.

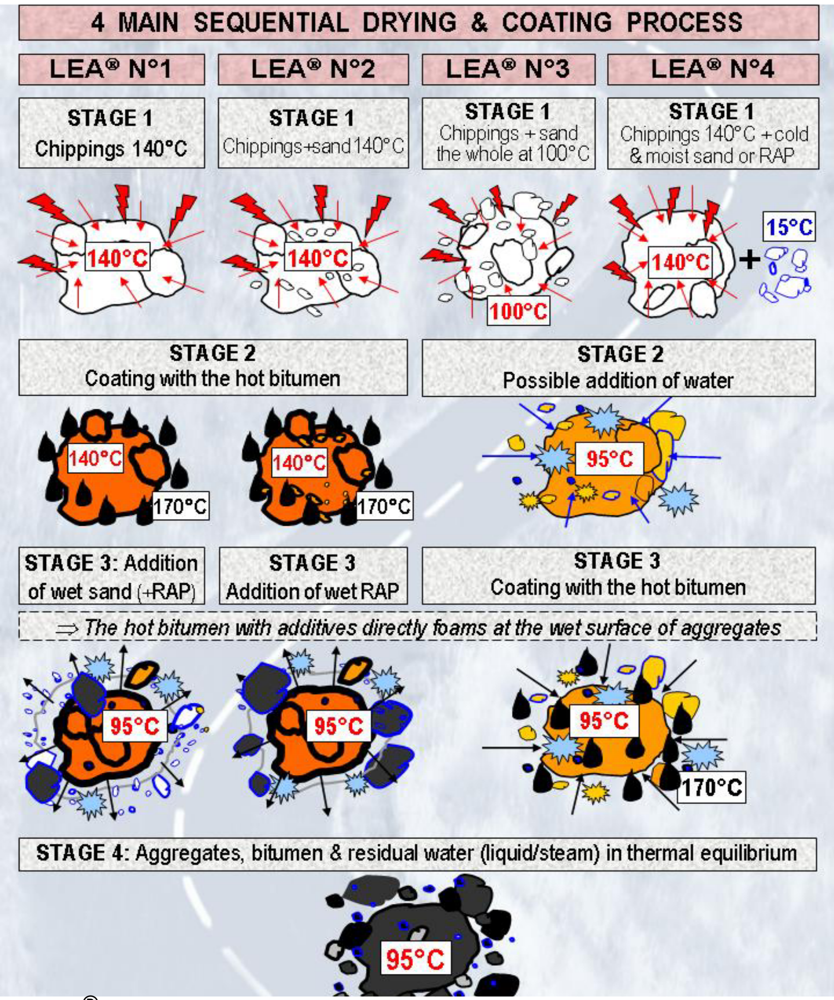

Figure 4. Main LEA® sequences matching the industrial facilities: drum or batch plants.

4. REDUCED ENVIRONMENTAL IMPACTS ON ASPHALT PLANTS

4.1. Principles of LEA production in drum or batch plants

Any drum or batch plant, either mobile or stationary can easily produce LEA mixtures. Some modifications in mixing and coating sequences are nonetheless required, plants are equipped with in-line water and additive dosage systems and automation system is modified, which necessitates training of the plant crew for this new know-how. Until now, 25 plants were fitted in Europe. Storage in plants is of course possible during a few hours. No fume emissions during the discharge of mixture in trucks.

Figure 5. No fume emissions during the discharge in a truck at a batch plant.

For simplicity reasons, just two practical examples are hereafter given: LEA n°1 & LEA n°4 productions on respectively batch plant and drum plant (with counterflow drying).

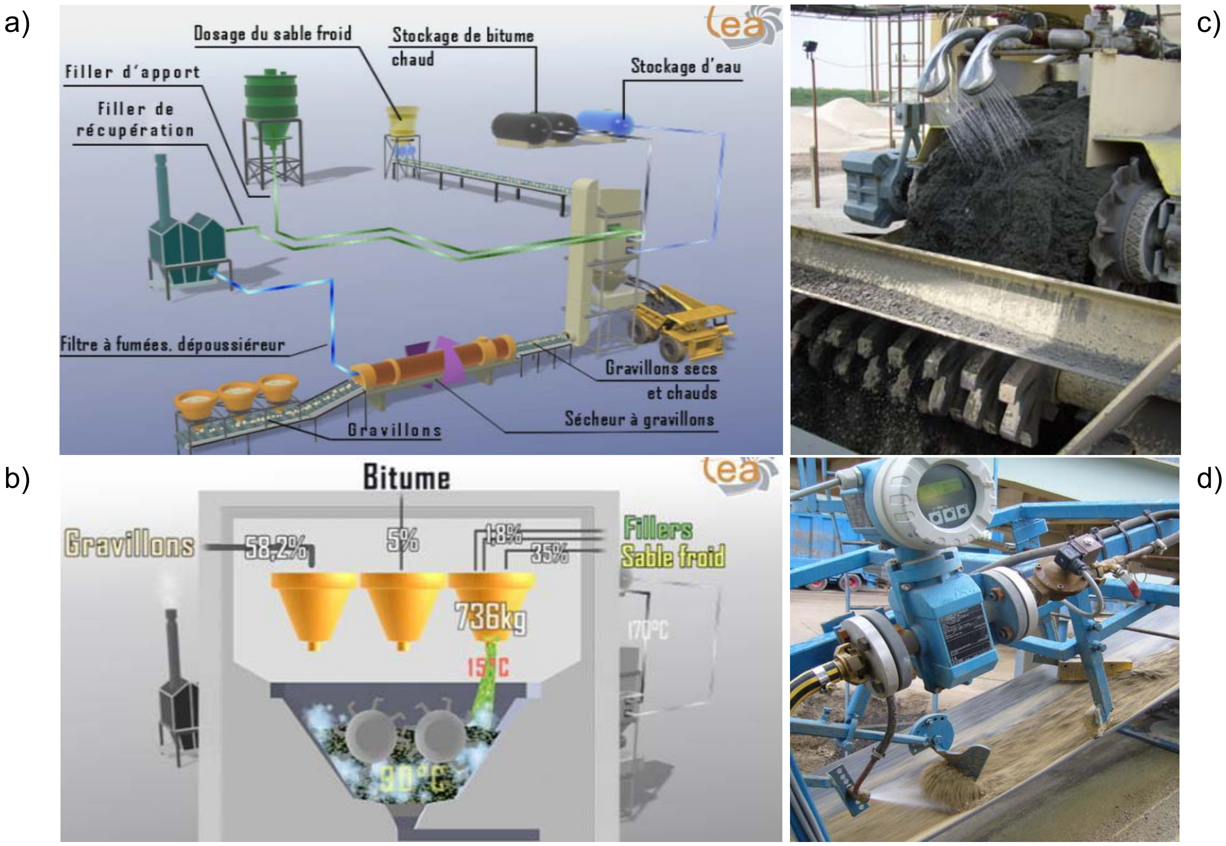

Figure 6. a) Overall view of the LEA® n°1 process on a batch plant with cold introduction of the sandy fraction directly into the mixer, b) Typical mixer in batch/discontinuous mode, c) & d) Extra water addition systems to control the initial moisture of cold aggregates.

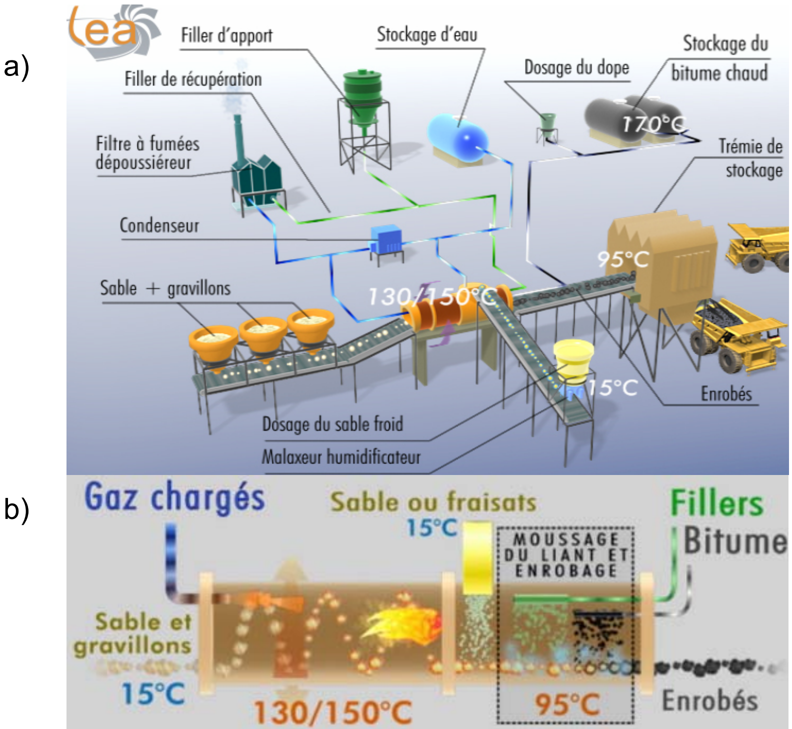

Figure 7. a) Overall view of the LEA® n°4 process on a drum plant with introduction of cold and wet sand or RAP into the conventional recycling ring, b) Counterflow dryer mixer.

4.2. Example of comparative heat balance of hot-mix and half-warm-mix asphalt

On account of the partial drying and the corresponding residual aggregate moisture, the in-plant energy consumption can be halved (see Figure 1). This section aims at evaluating and demonstrating the possible energy savings. Only the energy required to heat the components is taken into account in what follows.

Let's consider for instance an application of LEA n°1 or n°4 process to a mix formula with 35% of 0/2 sandy fraction. As illustrated in Figure 6a, in the case of LEA n°1 process on a discontinuous/batch plant, the cold and wet sand is introduced directly into the mixer. As shown in Figure 7a, in the case of LEA n°4 process on a continuous/drum plant, the cold and wet sand is introduced into the recycling ring. It is noteworthy that the LEA production can be eventually optimized by varying the sand content that is introduced cold and wet.

4.2.1. *Assumptions*

- Gradation of aggregate skeleton comprising 65% of 2/D (coarse aggregates, "D" is the maximum aggregate size) and 35% of 0/2 (fine aggregates/sandy fraction)
- Mean water content (field moisture before mixing) of aggregates: 4%
- Heating of the entirety of the aggregates to 170°C in the case of HMA and heating of only the coarse aggregates to 140°C in the case of LEA production
- Ambient temperature: 10°C
- Specific heat of the aggregate $c_{aggregate}$=850 J/kg/°C, of water c_{water}=4 200 J/kg/°C
- Latent heat of evaporation of water $L_{vaporization}$=2 250 000 J/kg
- Specific heat of steam c_{steam}=1 850 J/kg/°C

4.2.2. *Theoretical HMA heat balance (manufacturing temperature=170°C)*

Calculation of calorific energy for 1000kg of dry aggregates heated from 10°C up to 170°C:

- Aggregate heating energy = $c_{aggregate}$ x 1000kg x (170°C – 10°C) = 136 000 kJ
- Water heating energy = c_{water} x (1000/960-1)1000 x (100 – 10) = 15 750 kJ
- Vaporization (conversion of water into steam requires the latent heat of steam to be overcome) = $L_{vaporization}$ x (1000/960-1)1000 = 93 750 kJ
- Water vapor heating energy = c_{steam} x (1000/960-1)1000 x (170 – 100) = 5 396 kJ

Total of calorific energy ≈ 251 MJ per ton of HMA.

4.2.3. *Theoretical LEA heat balance (manufacturing temperature=90°C according to LEA n°1 or n°4 process)*

The sandy fraction (35% of aggregates) is neither dried nor heated up, whereas the coarse fraction (65% of aggregates) is dried and heated up to only 140°C.

Energetic consumption for 1000 kg of dry aggregates heated from 10°C up to 140°C:

- Aggregate heating energy = $c_{aggregate}$ x 1000kg x (140°C – 10°C) = 110 500 kJ
- Water heating energy = c_{water} x (1000/960-1)1000 x (100 – 10) = 15 750 kJ
- Vaporization (conversion of water into steam requires the latent heat of steam to be overcome) = $L_{vaporization}$ x (1000/960-1)1000 = 93 750 kJ
- Water vapor heating energy = c_{steam} x (1000/960-1)1000 x (140 – 100) = 3 083 kJ

Sub-Total of calorific energy ≈ 223 MJ.

Total = 65% x 223 ≈ 145 MJ per ton of LEA®, which corresponds to 42% of theoretical energy savings in plant. The follow-up of the in-plant consumption confirms the order of magnitude of 30 to 50% of energy savings thanks to the proposed low-temperature coating process. The resulting drop of CO_2 emission is of the same order as the energy saving.

5. REDUCED ENVIRONMENTAL IMPACTS ON ROAD WORKS AND IMPROVED WORKING CONDITIONS

Like coating and mixing temperatures, lay down and compaction temperatures are almost halved. This brings about less embarrassment for the paving crew and the residents as well: comfort of placement, large decrease of emissions and odor on the worksite (Fig. 8). Worth noting, an unexpected cool rain on the half-warm asphalt may cause far less water evaporation and a strong reduction in thick fog, which can then be a notable safety factor. Besides, the residual moisture of about 0.2 to 0.5% in the final mix is not only favorable for compacting –without affecting performances (cf. evaluation of mechanical performances in section 7)–, but also for cleaning of equipment. Indeed, less soiling is observed due to the presence of fine water droplets condensed on equipment surfaces (drying/mixing drum, paver-finisher, truck) thus facilitating cleaning and reducing the use of solvents.

6. REFERENCES ROAD WORKS OF THE YEARS 2005-07

To prepare the first LEA road works in 2005, almost 20 prior full scale suitability tests were carried out on several plants of the EIFFAGE Travaux Publics Group mainly. These preliminary field trials made it possible to validate the technical choices, the manufacturing and control methods before applying LEA at the sites. To date, almost 60,000 tons of LEA mixes were thus manufactured on 21 French plants, 3 Spanish ones and also an American one in New-York State, which enabled to check the adequacy of LEA with the different kinds of plants (drum mix plants with parallel flow or counter flow drying as well as batch plants) and with very different aggregate types and gradations. The manufactured mixes were very often stored in the finished product storage hopper for a few hours.

Figure 8. 1400-ton roadwork whose operating temperatures range from 60 to 95 °C.

Figure 9. Example of a 3100-ton LEA® roadwork for an aerodrome near Béziers (France).

French-type granular dense formulas BBSG 0/10 and 0/14, BBME 0/10, GB 0/14 and EME 0/20, and thin/porous formulas BBM 0/10 and BBTM 0/6 have already been used with very different materials until now. Pure 20/30, 35/50 or 50/70 pen grade binders are often used. The process feasibility was also checked with pure 10/20 and 70/100 binders, and with SBS modified binders (Biprene® binders of the EIFFAGE Group) with or without cross-linking. In most cases, especially with hard bitumens and PMBs, some specific multifunctional additives were used to improve the foamability and the coating ability of the binder. The use of 10 or 20% of reclaimed asphalt pavement (RAP) aggregate is common.

The climatic conditions usually corresponded to normal seasonal values, sometimes with air temperature a few degrees above freezing in the morning. As the difference with the ambient temperature is smaller for LEA than for its high-temperature counterpart, the drop in temperature with time is lesser, which allows longer haul distances if need be. If the LEA mix in trucks is maintained at a temperature of the order of 70-95°C a time of 5 or 6 hours between production and laying/compaction has turned out not to be a problem at all.

LEA mixes were applied by the paver-finisher and compacted by double-roll vibrating compactors (Figures 8 & 9) and sometimes with pneumatic tyre rollers in accordance with usual application procedures. With the right additives used in the process and with compaction effort equivalent to that required for HMA, similar void contents were achieved in the LEA layer. LEA had a surface appearance comparable to that of HMA, including at joint locations. After the application on site, usual measurements of thickness, density and macrotexture were done. After several months (first trials in 2004 and 2005), these different sites were revisited to assess the condition of pavement and/or to take cores to assess density and complex or secant modulus of these field cores in IDT mode (see detailed description of the test in references [33-35]).

7. EVALUATION OF LABORATORY PERFORMANCES

7.1. Objective and description of the testing procedures

Many a laboratory study was conducted so as to determine the mechanical performances of LEA mixes, including:

- Workability, measured from the Nynas workability tester [36]. The units are in Newtons. A high value implies a stiffer mix difficult to pave.
- Compacting capability, measured from the French gyratory shear compacting press ("Presse à Cisaillement Giratoire" (PCG), see Figure 10), following the requirements of the standard NF P 98 252. This test, simulating the effect of job-site compactors, gives a good idea of the voids content values observed on the job site, according to course thickness. This is the test most widely used in France for optimizing the composition of HMAs. Conducted ahead of the other mechanical tests, the PCG test can at least be used to make a preliminary selection or screening of mixes.
- Water resistance, measured from the Duriez test (French standard NF P 98-251-1) which consists of unconfined direct compression test on two sets of cylindrical samples, one set after conditioning in water. If the ratio of the results after and before conditioning is above a certain value, the material is deemed to be acceptable. Note that this ratio is the French counterpart of the ITSR (Indirect Tensile Strength Ratio) value with Marshall samples.
- Resistance to rutting at 60°C, characterized with the French wheel tracking test in accordance with standard NF P 98-253-1. Rectangular mix specimens are subjected to repeated passes of a wheel fitted with a tyre, mounted on a carriage that moves back and forth at a sinusoidal rhythm, inducing permanent deformation.
- Stiffness modulus and fatigue resistance at 10°C-25Hz, following the requirements of the NF P 98-261-1 (controlled strain fatigue test on trapezoidal specimens).

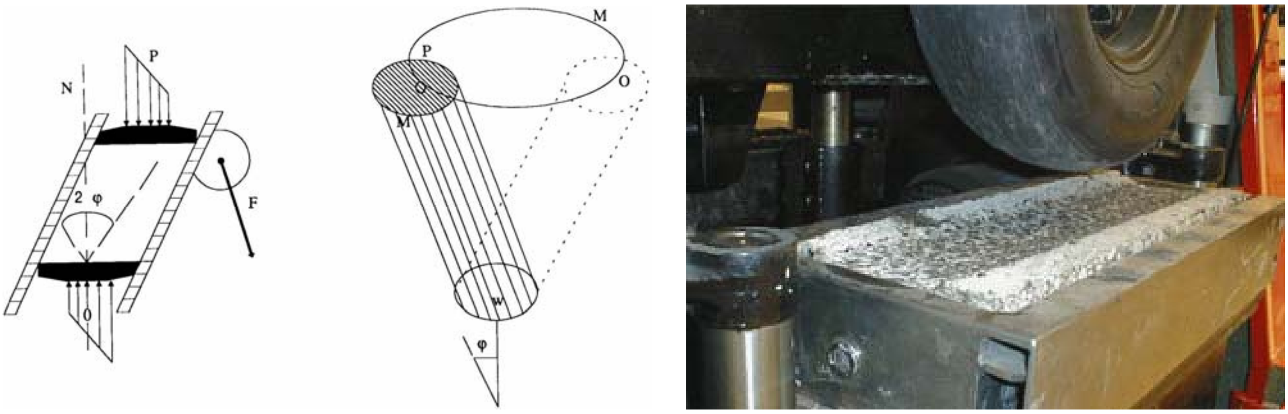

Figure 10. a) Principle of compacting with the gyratory shear compacting press, b) French pavement rutting tester wheel and slab at the end of the testing procedure.

7.2. Two examples of typical formulation study on dense graded LEA mixtures

Two lab studies were conducted on dense asphalt mixes using French-type GB 0/14 & BBSG 0/10 diorite grading with a 35/50 pen grade bitumen (typical commercially available binder in France), respectively used as sub-grade or base course and as wearing course. The results obtained on the control HMA and on the LEA material are of the same order and judged to be satisfactory (see Tables 1 & 2).

The water resistance of the GB 0/14 La Noubleau formula, measured with the (severe) Duriez test, appears nonetheless as slightly lower than the HMA, which is actually due to a slightly too low manufacturing temperature. 87°C appeared as a little bit too low temperature. A minimum temperature of 90°C is in particular recommended for production in plants (90°C < ideal range < 100°C). Even if the water content of the LEA mix is very low after compaction (<0,5%), one can imagine that the residual water trapped in the coated aggregate may cause moisture damage. Under those circumstances, many other lab studies have been from then on realised, all following the requirements of the current HMA standards. Especially for LEA mixtures with water-sensitive aggregate types, the Duriez test is simply run first to make a preliminary selection or screening of mixes instead of the PCG test (with the gyratory shear compacting press) generally run first for HMAs.

Let's emphasize that as far as the BBSG 0/10 (Table 2) is concerned, the divergence of their voids contents found on fatigue test samples explain the slight difference between the respective measured resistances. Indeed, the French LPC method, mentioned in the "LPC assistance manual for the formulation of HMAs" [37], was used here for estimating the levels of fatigue resistance at equi-density; the variation of the $\varepsilon 6$ value ($\Delta\varepsilon_6$) in accordance with a variation of density (ΔD) can be approached by the following formula, namely $\Delta\varepsilon_6 = 3.3*\Delta D$ (this LPC prediction formula was initially developed with the same mix formula). For this BBSG 0/10 asphalt at 5.4% voids, the reference HMA and the LEA have the same resistance to fatigue (97µm/m).

Table 1. Mix design of the LEA® diorite GB 0/14 compared with the control HMA.*

Material	GB 0/14 La Noubleau, binder 35/50		Standard values Class 2 NF P 98-138
	HMA (160 °C)	LEA® (87 °C) with additive	
Nynas Maniabilimeter (at the supposed paving temperature)	79N at 110°C	120N at 75°C	150N corresponds to the maximum acceptable value
PCG Test (100 gyrations)	5.9 %	7.6 %	≤ 11 %
Duriez Test (Direct Compression Test and water resistance)	R = 11.4 MPa r/R = 0.94	R = 9.5 MPa r/R = 0.70	R ≥ 6 MPa r/R ≥ 0.70
Wheel Tracking Test (60°C, 10000 cycles)	4.7 %	4 %	≤ 10 %
Fatigue Test 10°C-25Hz (2-point bending fatigue test, trapezoidal samples)	Voids content not measured E*(10°C-25Hz)=16700MPa ε_6=92µm/m	Samples at 7.9% voids E*(10°C-25Hz)=13400MPa ε_6=86µm/m	$\varepsilon_6 \geq$ 80µm/m

*Study realized at the LCPC (Laboratoire Central des Ponts et Chaussées) Nantes.

Table 2. Mix design of the LEA® diorite BBSG 0/10 compared with the control HMA.**

Material	BBSG 0/10 La Noubleau, binder 35/50		Standard values Class 2 NF P 98-130
	HMA (160 °C)	LEA® (90 °C) (without additive)	
Nynas Maniabilimeter (at the supposed paving temperature)	55N at 110°C	60N at 75°C	150N corresponds to the maximum acceptable value
PCG Test (60 gyrations)	9.1 %	7.1 %	9 % ≥ ≥ 4 %
Duriez Test (Direct Compression Test and water resistance)	R = 11.7 MPa r/R = 0.98	R = 10.8 MPa r/R = 0.84	R ≥ 7 MPa r/R ≥ 0.75
Wheel Tracking Test (60°C, 30000 cycles)	6.4 %	6.5%	≤ 7.5 %
Fatigue Test 10°C-25Hz (2-point bending fatigue test, trapezoidal samples)	Samples at 3% voids E*(10°C-25Hz)=15700MPa ε_6=105µm/m & slope b=-0.19 LPC estimate at 5.4% voids $\Delta\varepsilon_6$=3.3*Δdensity = 3.3*2.4 $\Rightarrow \varepsilon_6$ = 97.08µm/m	Samples at 5.4% voids E*(10°C-25Hz)=14400MPa ε_6 = 97µm/m & slope b=-0.17	$\varepsilon_6 \geq$ 100µm/m (seldom required)

**Study realized at the Research Centre of EIFFAGE Travaux Publics in Lyon.

LEA feasibility has also been set in lab, using a large variety of pure or elastomeric binders and of dense or open-graded formulations. More than seventy LEA formulation studies of have been carried out to date, all demonstrating the equivalence between the mechanical performance of LEA and that of HMA, as shown in Tables 1 & 2.

7.3. Parametric study

The effects of the initial moisture content (before partial vaporization during foaming of bitumen) and of the RAP (reclaimed asphalt pavement) content were specifically investigated in order to mitigate the potential for moisture damage of a given poorly water resistant mix formula. The results of such a study (without any use of bitumen additives), illustrated in Figure 11, point out in particular the range for the initial humidity of aggregate (from about 0,9 to 1,4%) and even the RAP content (about 25% for this particular mix design) to be targeted in plant. Therefore, however interesting and innovative LEA mixtures may seem, the laboratory optimisation of their mix design is actually as much important as that of any hot mix asphalt mixture.

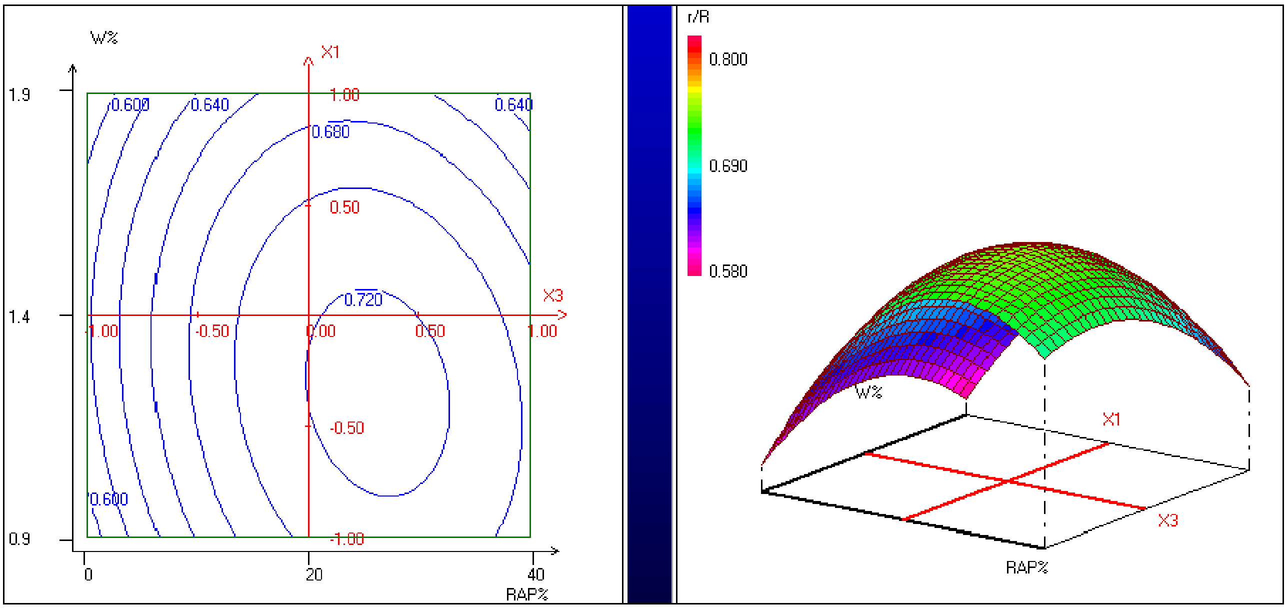

Figure 11. Example of optimisation of the resistance to moisture of a LEA formula according to its initial water content and to its RAP content.

CONCLUSION

Based on fundamental thermal principles and customary conditions of bitumen use, the LEA® process minimizes the amount of energy required for complete coating of the aggregate skeleton. It results in limited heating of part or of the entirety of the aggregate skeleton and is based on the combined action of temperature, water and mixing energy on the components. This innovative process optimizes the physical properties of the bitumen, in particular the “foaming” phenomenon to coat the aggregates and combination with residual water, to maintain mix workability at a temperature not exceeding 100°C.

Heads of plants, operation managers and working teams who participated in this first phase of development have all enthusiastically adopted this new technology of low-temperature and low-energy asphalt which, linked to the demand and satisfaction of the first customers, makes it possible to predict a certainty of future development. The success of this process comes from both its simplicity and its effectiveness. It is indeed a cheap way for minimizing impacts from asphalt plants to road works. However, like any new technique, it is initially necessary to learn and to master it, specifically through the use of a certain equipment and know-how adapted to the different HMA stations.

Unlike cold mix asphalts, LEA mixtures have a performance tantamount to that of hot mix asphalts, but owing to the 0,2 to 0,5% residual water in the LEA® mix under 100°C, a special attention is to be paid to the evaluation of potential for moisture damage in laboratory. This simple checking is in particular necessary for any of the water-based warm or half-warm technologies currently developed in the world.

Furthermore, additional efforts are still to be made in order to pursue and bring to a successful conclusion the reproducibility of the process, in particular while applying it to more and more discontinuous formulations (porous asphalt, open-graded wearing course), using the different methods of sequential bitumen coating of asphalts. Eventually, implementation in other countries still needs to be realized in order to check the validity of the LEA® process with other materials, other climates and other mix design methods.

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