Laboratory assessment of mechanical performance and fume emissions of LEA® HWMA (90°C) vs. traditional HMA (160°C)

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LABORATORY ASSESSMENT OF MECHANICAL PERFORMANCE AND FUME EMISSIONS OF LEA® HALF-WARM MIX ASPHALT VERSUS TRADITIONAL HOT MIX ASPHALT

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ABSTRACT

With the current trend in favour of reducing pollutant emissions and energy consumption, the road industry and bitumen manufacturers have also been pursuing a path of sustainable development. A series of new medium temperature coating and mixing technologies, under the label "warm and half-warm asphalt mixes" have come to the fore.
A study, carried out in the laboratory within the framework of a partnership established between EIFFAGE Travaux Publics and IFSTTAR, aimed at correlating potential fume emissions with mixing parameters for asphalt mixes, in relation to the mix mechanical properties and to bitumen ageing.
This study demonstrates that a decrease in manufacturing temperature leads to a global emissions reduction as well as slower bitumen ageing. Results obtained highlight the influence of mix parameters and processes, especially regarding fume emissions for both half-warm and hot mix asphalts (hma). As for the mechanical performance and durability of LEA® mixes, their complex modulus and fatigue resistance characteristics are similar to those of traditional hma.

INTRODUCTION

The topic of sustainable development is of prime importance to European road research, which has come to be based on a multidisciplinary approach to scientific problems, involving the environment, physics, chemistry, biology, the social sciences and societal issues.

Road construction companies, such as EIFFAGE Travaux Publics or its subsidiary LEA-CO, have adopted an approach that seeks to accelerate convergence between environmental demands and the development of energy-saving materials, called "warm and half-warm mix asphalts" (wmas and h-wmas) *(1)(2)(3)(4)*.

Within the framework of a scientific collaboration organised between EIFFAGE Travaux Publics and the French Institute of Science and Technology for Transport, Development and Networks (IFSTTAR, formerly LCPC) on half-warm mix asphalts (< 100°C) since 2005, research efforts have been devoted to the mechanical and environmental assessment of LEA®, as compared to its hot mix counterpart. This article is intended to present the main results obtained during this half-warm mix asphalt study.

BACKGROUND

The bibliographic references currently available regarding fume emissions during asphalt mixture manufacturing process are rather limited. Previous studies *(5)(6)(7)* have been conducted solely on fumes produced by bitumen with a focus on Polycyclic Aromatic Hydrocarbons. More recently, Paranhos *(8)* and Gaudefroy *(9)* have carried out at IFSTTAR a laboratory characterisation of Hot Mix Asphalt (hma) fumes during mixing in association with mechanical performance. The purpose of this research was to identify the effect of bituminous material design on bitumen emissions depending on various manufacturing factors, such as aggregate temperature and bitumen film thickness. As part of this laboratory-based study, a characterisation methodology combined with an assessment of mechanical and environmental performance was developed by IFSTTAR in order to differentiate the various mix formulae in the laboratory. Study results highlighted the strong influence of hma volumetric composition on emissions generated during manufacturing. The method derived consists of sampling the gas emissions generated during asphalt mixing. It should be pointed out that this process, which is comparable to a channelled source, makes it possible to analyse the pollutant emissions of bituminous mixes due to individual components alone, especially bitumen.

Much more bibliographic data are currently available on laboratory assessments devoted to the mechanical behaviour of warm and half-warm mix asphalts *(2)(7).*

The originality of the present study lies in the fact that it is intended to correlate potential fume emissions with mixing parameters for mix asphalts, in focusing on both the mix mechanical properties and bitumen ageing.

STUDY OBJECTIVES

This study, jointly performed by IFSTTAR and EIFFAGE Travaux Publics teams, has been aimed at determining the influence of manufacturing temperature and additives on the mechanical and environmental properties of LEA® asphalts, assessed in the laboratory by drawing comparisons with traditional hma, which is used herein as a reference material.

EXPERIMENTAL METHODOLOGY

Manufacturing processes

In this study, two processes have been employed: a traditional hma, used as the reference; and three variants of h-wma LEA®. The originality of this h-wma process stems from the ability of hot bitumen to foam or emulsify when placed in contact with residual aggregate moisture at right around the water vaporization point of 100°C, which therefore allows for coating at lower temperatures *(2)(3)* (see Fig. 1). As a result of water dispersed inside the bitumen, the spontaneous volume expansion of bitumen leads to a thicker binder film around aggregates (from the mixing and coating stage inside the plant to the paving and compaction stage at the jobsite), which in turn enhances mix workability. Some specific additives have been introduced in this study to improve the foaming and coating capability of the binder.

Materials

The formula selected is a dense, bituminous 0/14 mixture for base courses (according to the French designation "*Grave Bitume*", denoted "GB") with diorite aggregates, originating from France's La Noubleau Quarry (see Table 1). The filler is limestone from the Airvault Quarry (France).

TABLE 1: Design of the mix used in this study

Formula	Mineral composition (%)					Bitumen (%)
	Filler	Sand (0/2)	Aggregate (2/6)	Aggregate (6/10)	Aggregate (10/14)	
GB 0/14	0.8	33.6	14.4	13.4	33.6	4.2

In this study, hma and h-wma were prepared in the laboratory using bitumen heated to 160°C. This bitumen (class 35/50, according to the NF EN 12591 Standard) is paraffinic and displays the following characteristics: a pen grade of 42 (1/10 mm) (NF EN 1426), a ring and ball softening point of 52.6°C (NF EN 1427). Two proprietary additives of vegetal origin (O and G) have also been incorporated into the bitumen just before conducting the experiment (with an additive content of 0.5% by weight of bitumen). For this study, an initial water content of 1.5%/dry aggregate weight was adopted for the LEA® fabrication.

Presentation of this study's mixing principle

The hma was prepared with bitumen and aggregates heated to 160°C. In this specific study, the three LEA® variants (Fig. 1) have been adapted to the laboratory constraints for manufacturing asphalt mixtures (i.e. a mixing time of approx. 120 s) at a final temperature in the range of 95°-100°C with bitumen heated to 160°C and aggregates heated at different drying temperatures:

- the drying stage at 160°C only affects an initial fraction of the aggregates (75% of the entire aggregate skeleton), then coated by all of the hot bitumen. The remaining cold and wet portion (25% of the entire aggregate skeleton), which has retained its initial moisture, is then added (the second fraction typically corresponds to either the cold and moist sandy fraction or the cold and moist RAP aggregates). All mix components are then mixed (LEA1);
- the drying stage at 160°C affects just an initial fraction of the aggregates (75% of all aggregates), which are then mixed, prior to the coating stage, with the remaining cold and wet portion (25% of all aggregates) that has retained its initial moisture level (LEA2),
- the drying stage at 150°C applies to all aggregates and is carried out in a way that allows retaining a fraction of the initial moisture (whereby a controlled amount of water is simply added). This stage is followed by coating (LEA3).

In the laboratory, hma and h-hmas were manufactured at low temperature in a classical mixer with a stirring speed of 20 rpm. During coating, the fumes generated inside the mixer were channelled towards a stainless steel stack developed by IFSTTAR *(9)*. Experiments were performed in accordance with laboratory manufacturing conditions, as specified in the in-plant manufacturing protocol: hmas and h-wmas (approx. 80 kg) are mixed for just 2 minutes at 20 rpm, and then the materials are held in the batch mixer (at a temperature of 160°C for hma and 105°C for h-wma) for another 28 min, a period that corresponds to the time of transport (storage or resting position) from plant to jobsite.

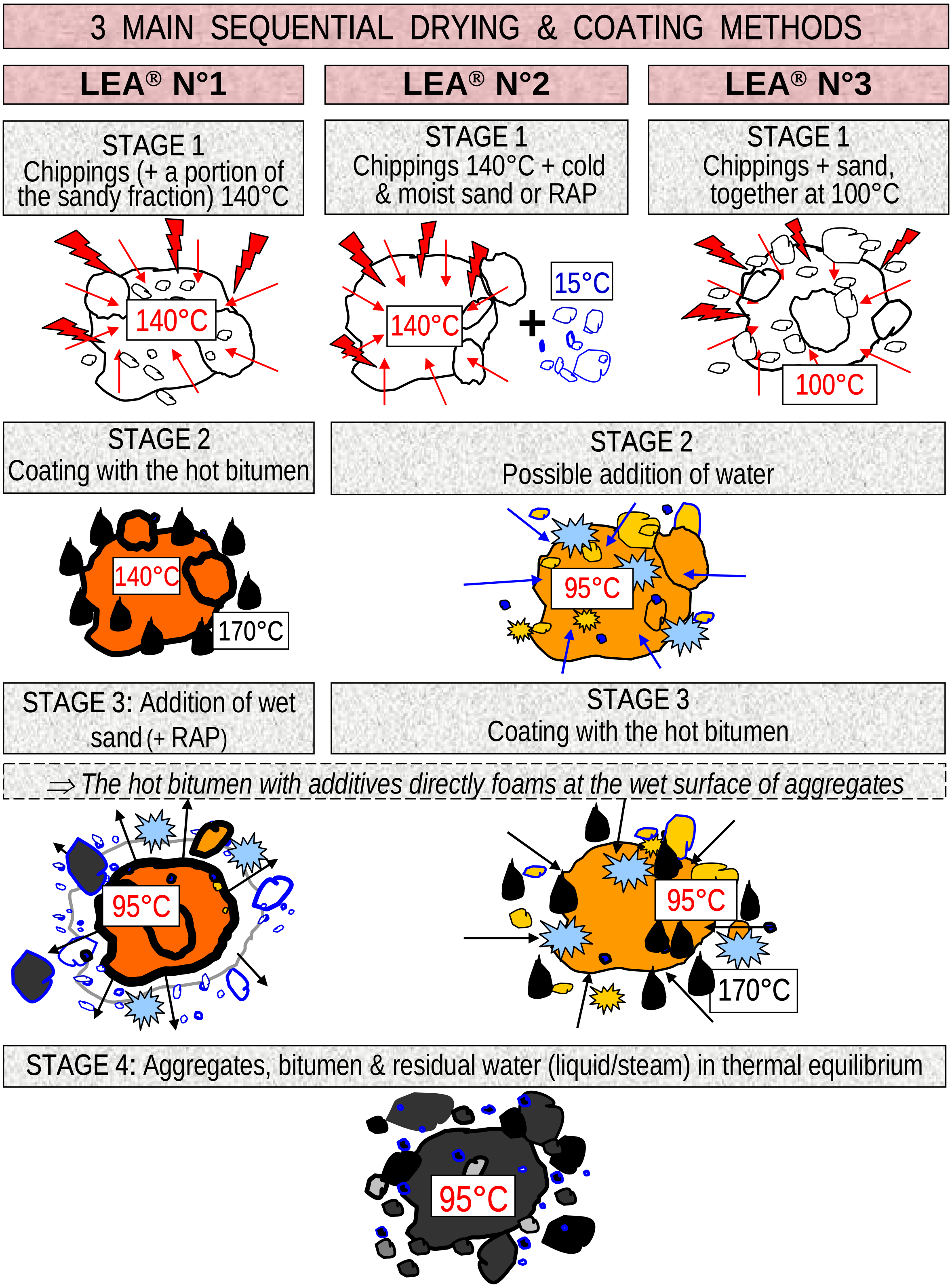

FIGURE 1: LEA® process diagrams with or without pre-coating

Experimental techniques applied

Device and tests used for mix formulation and mechanical behaviour

Gyratory Shear Compactor Tests

The French laboratory methodology for hot mix asphalt is devoted, in part, to a compactability assessment, whereby samples are characterised by tests by using the onsite Gyratory Compactor *(10)(11)*. In this test, loose material is simultaneously subjected to compressive and shear stresses, which in turn serve to reorganise the internal aggregate skeleton. This test allows proceeding with the void content measurement, which is conducted as a function of the number of gyrations. For all testing procedures, a gyratory shear compactor test, compliant with the EN 12697-31 Standard (i.e. three specimens, 200 rotations, 1° angle, heating device set at the mixing temperature), was performed.

Workability test

The workability test consists of measuring the maximum force required to shear a volume of loose cold mix contained within a mould. The lower the force necessary to remove the mix from the mould, then the greater the onsite workability. In accordance with EIFFAGE's internal methodology, tests were conducted on two samples (with the same volume) cured 2 hours at 110°C for hma and at 75°C for h-wma.

Direct compressive strength test and stripping resistance

Optimised mix formulations were subjected to the modified "Duriez" test (NF P 98 251-4). Twelve cylindrical specimens were compacted. An initial set was stored for 8 days in water at a temperature of 18°C, while the second set was stored in an oven at 18°C and 50% moisture. Next, the compressive strength of the two specimens sets (r: compressive strength of specimens stored in water; R: compressive strength of specimens stored in air) was measured, with the r/R ratio characterising the material's stripping resistance.

Complex modulus and fatigue resistance

Bituminous materials are both viscoelastic and heat-dependent. Their behaviour varies according to loading frequency and temperature; moreover, their complex stiffness modulus has been evaluated at 15°C and 10 Hz, as per the French pavement design method *(12)*. Complex modulus measurements have been carried out on trapezoidal samples, in compliance with the European Standard NF EN 12697-26.

Fatigue resistance measurements were recorded at 10°C and 25 Hz (NF EN 12697-24 Standard) by means of a strain-controlled test on trapezoidal specimens. The classical fatigue criterion, referenced as Nf50, was used as part of this protocol. According to this criterion, fatigue life corresponds to the number of cycles during which the stiffness modulus decreases to 50% of its initial value. The strain amplitude value leading to failure at 1 million cycles, hereafter denoted ε_6, is used in the French design method *(12).*

Device and protocol implemented for environmental behaviour

In order to collect fumes emitted from the mixture, a stainless steel stack has been connected to the mixer *(9)(13)*. The purpose of this stack is to direct asphalt fumes to the sampling devices, on which two openings allow positioning the sampling probes. The sampling device for TOC(e) has its own suction system (with an integrated pump). Continuous sampling and analysis of TOC are carried out using a portable and automated device for measuring total hydrocarbons (see Figure 2). This continuous measurement reading allows plotting a curve showing the mass concentration of the emitted total organic compounds (TOC(e), expressed in terms of $mgEqC/Nm^3$.kg of bitumen) vs. time.

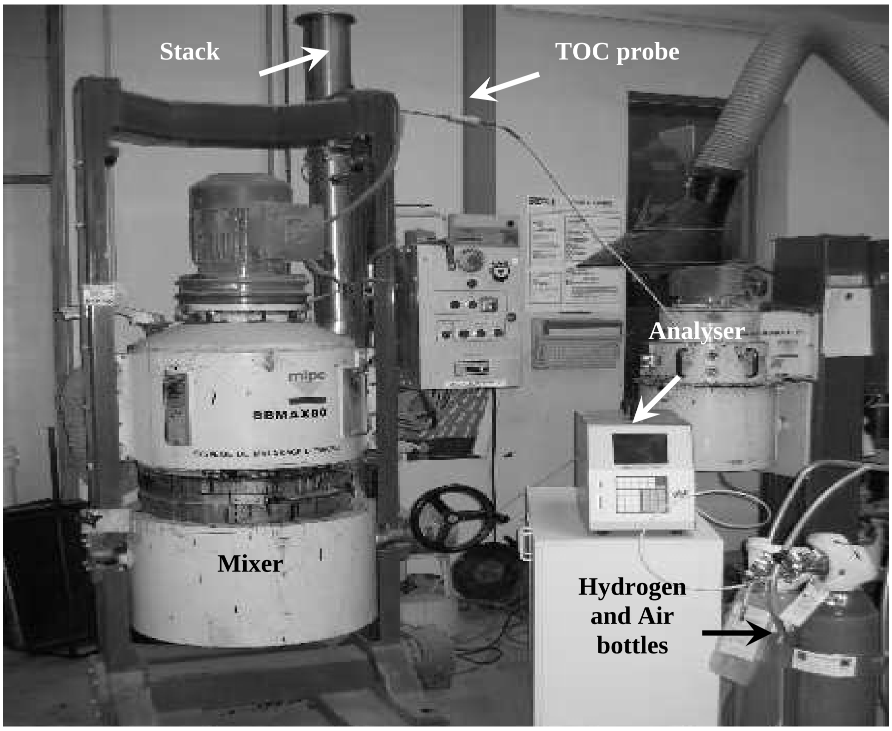

Figure 2: Views of mixer and stack for asphalt mixes

By definition, $TOC(e)_{max}$ corresponds to the maximum concentration measured by the analyser during the test and this parameter is expressed in mgEqC/Nm^3/kg of bitumen. An Emissions Potential (denoted "EP"), expressed in mgEqC.s/Nm^3.kg of bitumen and defined for analytical purposes, describes the capacity of the bitumen to generate Total Organic Compounds over a defined period. This EP is calculated by integrating the area under the TOC(e) curve, with a mixing time of 2 min followed by a rest period of 28 min for each test.

The laboratory tests have all been carried out just once. Meanwhile, test repeatability was investigated for a formula manufactured at 152°C and featuring a 5.1% binder content. Six tests were conducted and all TOC(e) curves exhibit the same trend, which suggests test repeatability, except over the long term, under identical experimental conditions. The average EP value with the corresponding standard deviations equals 438 ± 40 mg.s/m^3/kg of bitumen with a coefficient of variation of 9.2%. This result underscores the limitations of this test, though the observed scatter still allows differentiating the various parameter effects.

LABORATORY TEST RESULTS

Workability and compactability

Figure 3 illustrates a slightly lower workability of LEA® mixes, in comparison with their hot mix counterparts. The additive G marginally raises the level of LEA® workability.

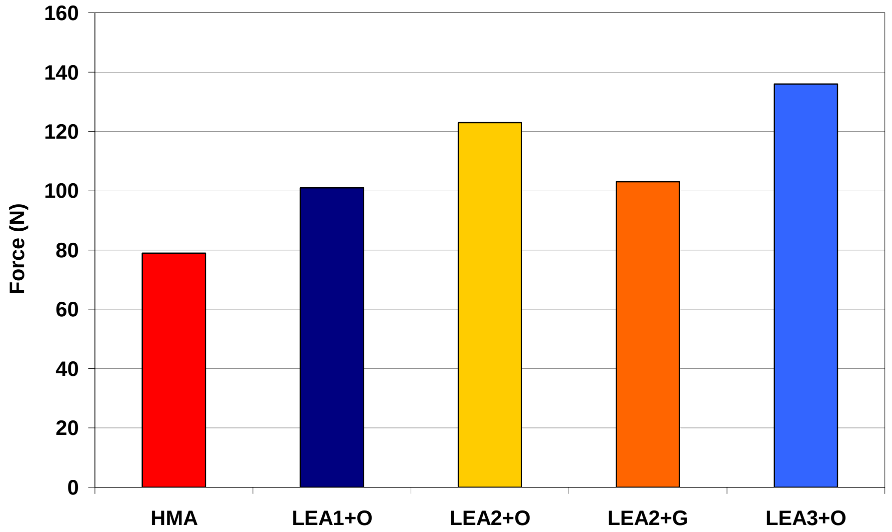

FIGURE 3: Process influence on both HMA and H-WMA workability

Figure 7, by focusing on the Gyratory Shear Compactor (GSC) results, confirms the previous observation: LEA® mixes appear to be less workable than hma.

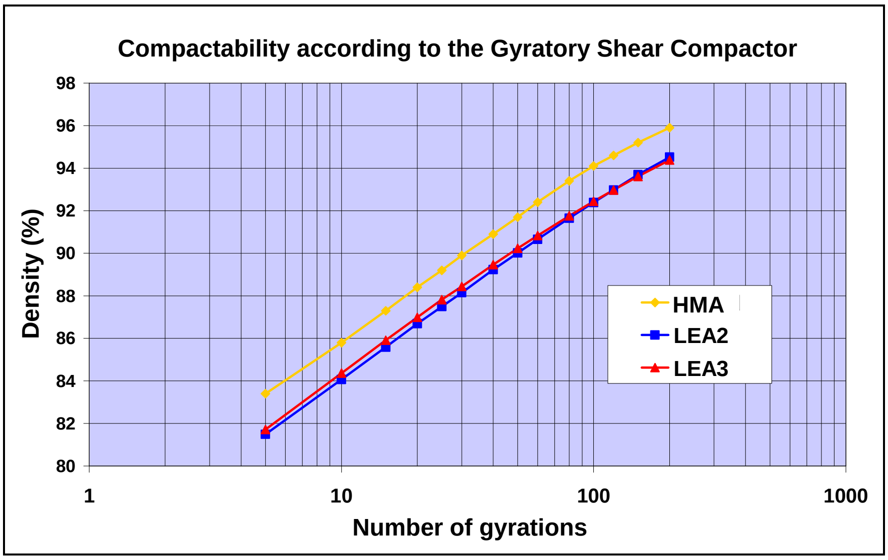

FIGURE 4: Gyratory Shear Compactor

Direct compressive strength and stripping resistance

The stripping resistance values of LEA® mixes were found to lie above the minimum specification limit (70% for such base course materials used in France). The resistance to humidity of LEA® however is slightly less than that of hma (roughly -10%, see Fig. 4). The additive G makes LEA® a bit more resistant to water.

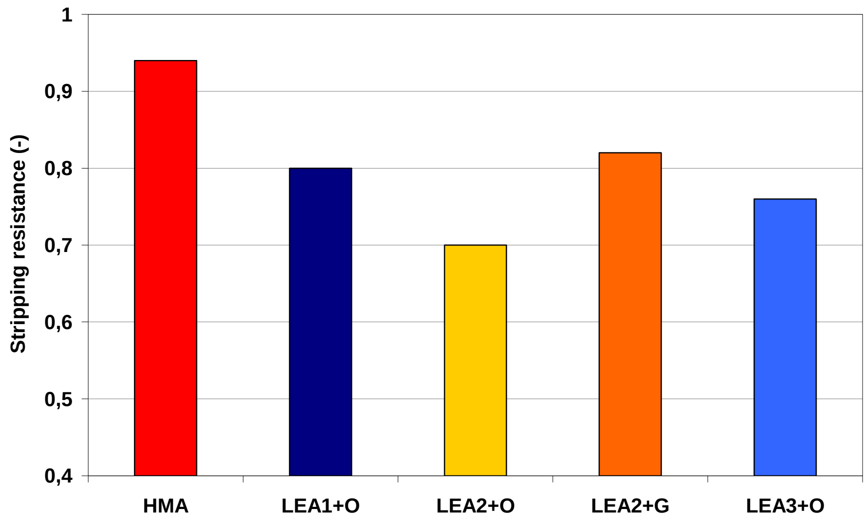

FIGURE 5: Change in stripping resistance (r/R ratio) vs. mix process

Complex modulus and fatigue resistance

Table 2 presents the influence of aggregate temperature on the complex modulus measured at 15°C and 10 Hz. It is not apparent that the increase in mixing temperature favours a higher complex modulus value. This phenomenon may be explained by the void content value of test samples. As shown in Table 2, the complex modulus results of h-wma mixes are in agreement with void content values, regardless of the LEA® mix variant. Moreover, both workability and compactability of the mix increases with temperature.

TABLE 2: Primary characteristics of half-warm mixes and the reference hot mix

Process		HMA	LEA1 (H-WMA)		LEA2 (H-WMA)			LEA3 (H-WMA)		Standard NF EN 13108
Additive		-	O		O	G		O		
Manufacturing temperature (°C)		160	95	95	95	95	95	95	95	
Direct compressive strength test and stripping resistance	Voids (%)	9,6	6,0		10	6,4		8,7		-
	R "dry resistance" (MPa)	11,4	10,9		9,5	11,5		9,7		-
	r/R ratio (-)	0,94	0,80		0,70	0,82		0,76		min 0.70
Complex modulus (15°C-10Hz)	Voids (%)	5,1	4,9	4,9	7,9	5	4,6	10,1	3,5	7 to 10%
	E* (MPa)	12 804	11 921	11 217	9 987	11 630	11 765	8 405	12 956	min 9 000
Fatigue resistance (10°C; 25Hz)	Voids (%)	5,3	5,2		7,8	4,7	4,2	10,3	3,5	7 to 10%
	Strain applied (-)	80.10^{-6}	86.10^{-6}		80.10^{-6}	86.10^{-6}	85.10^{-6}	79.10^{-6}	87.10^{-6}	-
	Average life duration (-)	2 690 000	799 500		1 479 000	917 625	676 500	597 000	1 668 000	-
	ε_6 (Slope at -5)	92.10^{-6}	83.10^{-6}		86.10^{-6}	85.10^{-6}	79.10^{-6}	71.10^{-6}	96.10^{-6}	min 90.10^{-6}
Workability (Nynas test)	HMA studied at 110°C (N) H-WMA® studied at 75°C (N)	79	136		123	103		101		-
Extracted binder	Penetration (1/10 mm)	27	33		36	31		34		-
	R&B temperature (°C)	58,5	56,4		54,6	56,4		55		-

According to the methodology developed by Moutier *(14)* and Francken *(15)*, the theoretical complex modulus has been back-calculated using binder properties for both hma and h-wma. Figure 6 shows that the theoretical complex modulus values determined are less than the experimental values regardless of the process used.

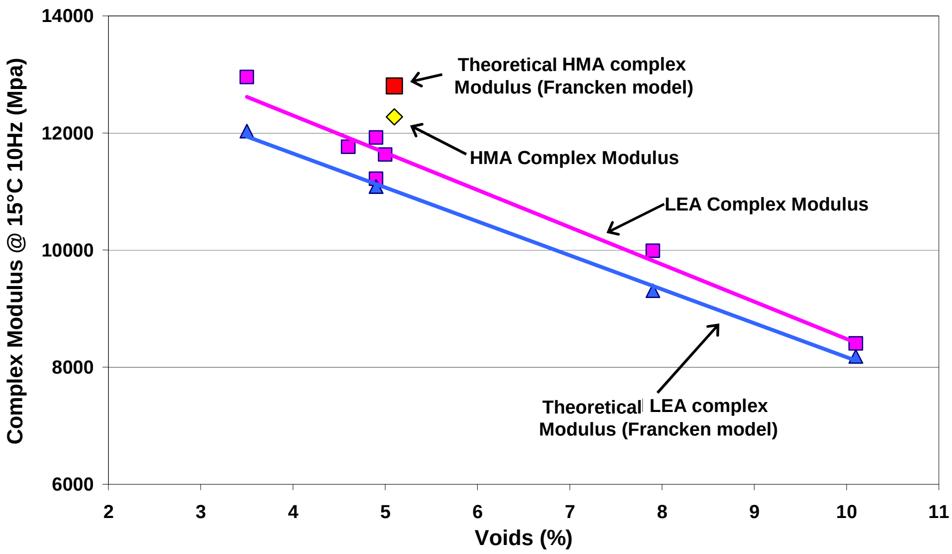

FIGURE 6: Complex modulus results for HMA and H-WMA mixes

In the case of a mix void content equal to 7%, the complex modulus values lie in a range from 10,200 to 11,600 MPa (Fig. 7).

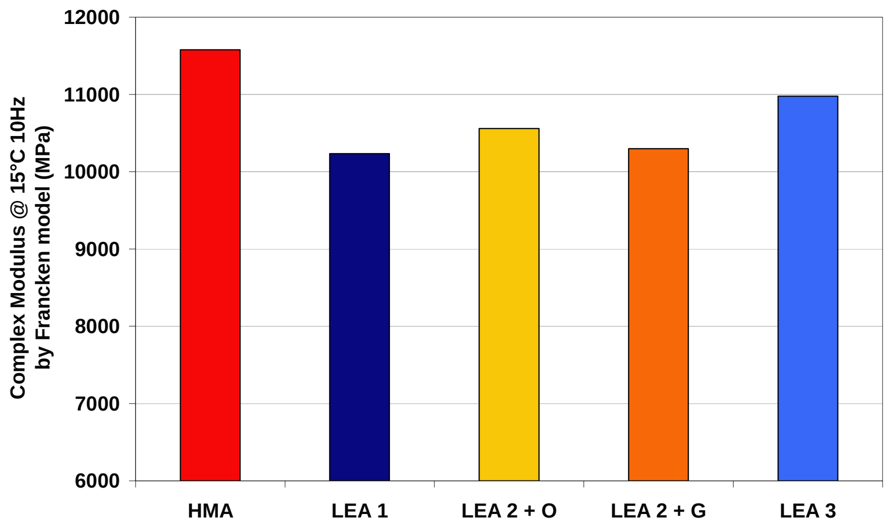

FIGURE 7: Complex modulus values from a two-point bending test for HMA and H-WMAs, as obtained from the Francken model (with a void content of 7%)

The hma value is higher than the various h-wma values, yet they still remain close with a difference of approx. 700 MPa observed between the hma value and the mean h-wma value. This difference may be explained by the complex modulus test repeatability as well as less binder ageing due to a lower manufacturing temperature for h-wmas, as shown in Fig. 8.

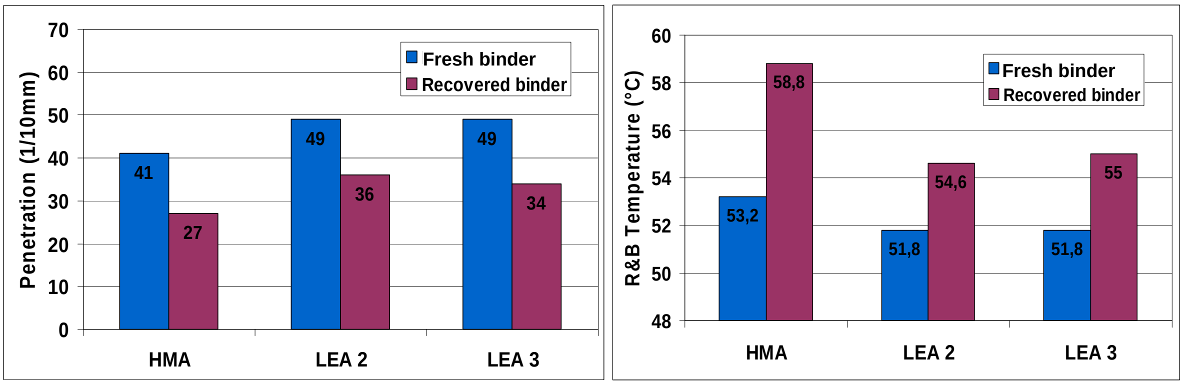

FIGURE 8: Results of penetration (left) and ring and ball temperature (right) for bitumen (both fresh and recovered) from HMA and H-WMAs.

Fatigue resistance tests were also performed in the laboratory. Table 2 indicates the number of cycles attained for each tested strain level along with the ε_6 result obtained.

In accordance with the French specification on characterising fatigue resistance at 10°C-25Hz, the result for hma (at 160°C) equals $92 \cdot 10^{-6}$, whereas results for the LEA® mixes (at 95°C) lie in the range of $71\text{-}96 \cdot 10^{-6}$. These very encouraging results naturally remain highly dependent on the density of tested samples.

Influence of manufacturing and process parameters on fume emissions

The three LEA® variants and hma were all characterised in order to demonstrate the influence of manufacturing process on fume emissions with a GB 0/14 formula (see Table 1), composed of the same bitumen (35/50 paraffinic) for hma and LEA®.

The TOC(e) emission results over time per kilogramme of bitumen and the EP under experimental design conditions, along with the characteristics of binders extracted to describe bitumen ageing during the manufacturing process, have been gathered in Table 3. TOC(e) emissions are also presented in Figures 9 and 10.

TABLE 3: Results from experiments on Hot and Half-Warm Asphalt Mixes: fume emissions, penetration, ring and ball values of the extracted bitumen

Experiment	Process	Additive	$TOC(e)_{max}$ ($mg/m^3/kg$)	Time (s) at $TOC(e)_{max}$	EP ($mg.s/m^3/kg$)	Pen-grade (1/10 mm)	R&B (°C)
E 1	HMA	-	233	492	$321\ 10^3$	27	58.5
E 2	LEA1	O	148	266	$152\ 10^3$	33	56.4
E 3	LEA2	-	132	293	$130\ 10^3$	n.m.	n.m.
E 4	LEA2	O	128	302	$134\ 10^3$	35	56.0
E 5	LEA3	O	236	250	$230\ 10^3$	31	57.2
E 6	LEA3	G	206	259	$213\ 10^3$	31	56.4

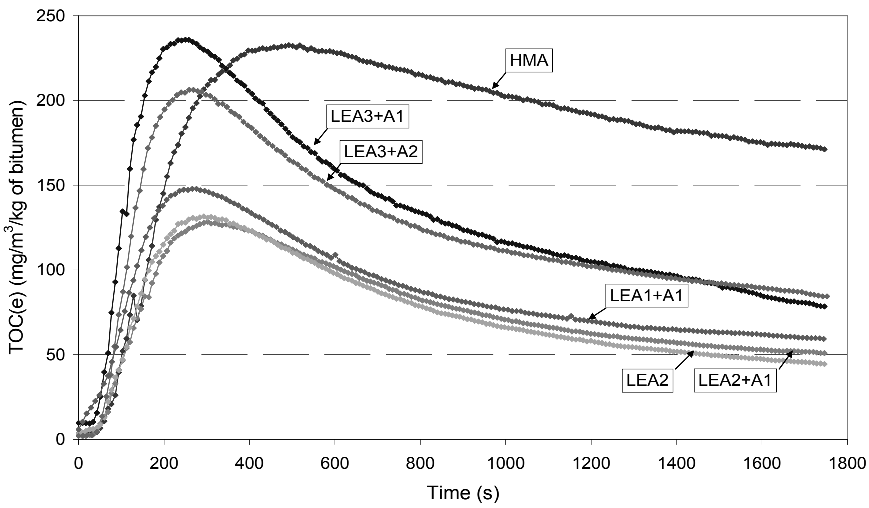

FIGURE 9: Process influence on TOC(e) emission results with a GB 0/14 La Noubleau formula for LEA® variants and HMA

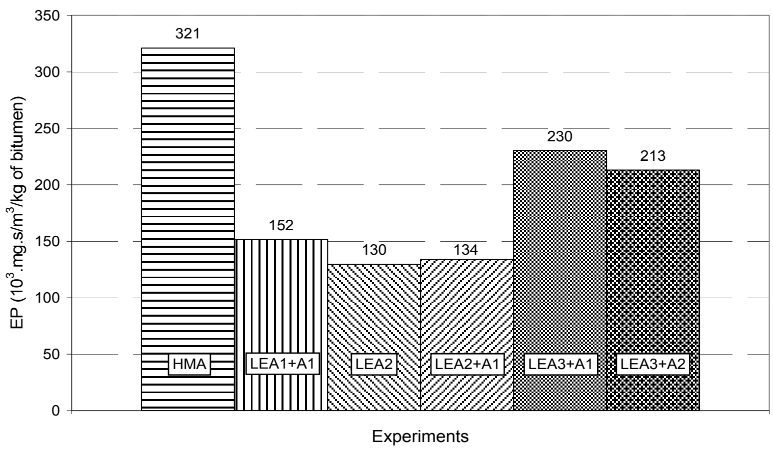

FIGURE 10: Process influence on Emissions Potential results with a GB 0/14 La Noubleau formula for LEA® and HMA

Figure 9 clearly reveals that the intensity of TOC(e) emissions depends on both the manufacturing temperature and the process employed.

Except for the E5 experiment, hma (E1 experiment) exhibits the highest TOC(e) emissions, i.e. equal to 233 mg/m^3/kg of bitumen. The high result found in the E5 experiment in terms of TOC(e)$_{max}$ at a similar level to hma can however be explained by the presence of internal water in the cold aggregate portion, which is capable of inducing a water stripping effect when in contact with hot bitumen *(9)(16)*.

According to Figure 10, the HMA EP value (321·10^3 mg.s/m3/kg of bitumen) exceeds the values of LEA® enhanced by the O additive (LEA1 (E2): 152·10^3 mg.s/m3/kg; LEA2 (E4): 134·10^3 mg.s/m3/kg; LEA3 (E5): 230·10^3 mg.s/m3/kg), thereby confirming the TOC(e) results and it suggests that in the presence of a high manufacturing temperature, asphalt mixtures tend to emit much greater TOC(e) and longer than a lower temperature. The TOC(e) and EP values are clearly tied to both the process and mix temperature.

This ranking can be interpreted by the chemical nature of the studied bitumen. Bitumen is known to be composed of different molecular weights. By taking into account the correlation existing between boiling point and molecular weight at higher manufacturing temperatures, a greater quantity of TOC(e) will be generated. As a consequence, TOC(e) intensity will be higher for hma than for LEA® mixes.

According to Figure 9, the initial results obtained from this preliminary study lead to concluding the following ranking in terms of TOC(e) generation in the laboratory for the LEA processes: LEA2 < LEA1 < LEA3. This laboratory observation can also be interpreted in terms of water stripping and thermodynamic phenomena. Nevertheless, this laboratory ranking still needs to be tested soon and then confirmed in a batch plant using the same asphalt mixture.

The use of vegetable-based additives O and G appears to exert very little influence on fume emission performance, as shown for additive O on the LEA2 mixture (for which maximum TOC(e) equals 128 mg/m^3/kg of bitumen with the O additive (E4) and 132 mg/m^3/kg without an additive. Moreover, the E5 and E6 experiments indicate that the type of additive (O or G) does not modify either maximum TOC(e) or EP (Table 3). These results have been obtained for both vegetable-based additives tested.

Bitumen ageing and fume emissions

After each mixing step, the manufactured mix was used to recover bitumen. Fresh and recovered bitumen were characterised by penetration tests and ring and ball temperature tests. According to this paper's references, the penetration and ring and ball temperature values, for mixing at various temperatures, are correlated with bitumen ageing *(17)*.

Table 3 shows that bitumen properties, as determined by penetration and by ring and ball temperature, are influenced by the process employed. In the case of hma, which is manufactured at 160°C (for bitumen and aggregate temperature), the bitumen properties are heavily influenced. Consequently, the pen-grade and ring and ball temperature are equal to 27° and 58.5°C, respectively. On the other hand, the properties of bitumen recovered from LEA® mixtures undergo less modification as a result of the laboratory manufacturing temperature (lower aggregate temperature than for hma). In LEA® laboratory production, the temperature after a sampling period is on the order of 90°C. Pen-grade and R&B temperature results lie respectively in the ranges of 31°-35°C and 56°-57.2°C.

In conclusion, with an increase in bituminous mix temperature, more significant ageing occurs. This behaviour was similarly observed during manufacturing for TOC(e) and EP (Figs. 9 and 10).

According to Table 3, the results obtained for half-warm asphalt imply the following ranking in terms of bitumen ageing, which occurs during the bitumen heating and mixing steps: LEA2 < LEA1 < LEA3. This ranking has been confirmed by the EP values reported in Table 3 and shown in Figure 9.

The EP has been related to the values of penetration and of ring and ball temperature obtained on recovered binder after mixing (Fig. 11). A linear regression of these experimental points was carried out for the penetration and ring and ball temperature parameters. In both cases, the EP of TOC emissions progresses linearly with penetration and ring and ball temperature measurements on recovered bitumen stemming from hma and LEA® processes.

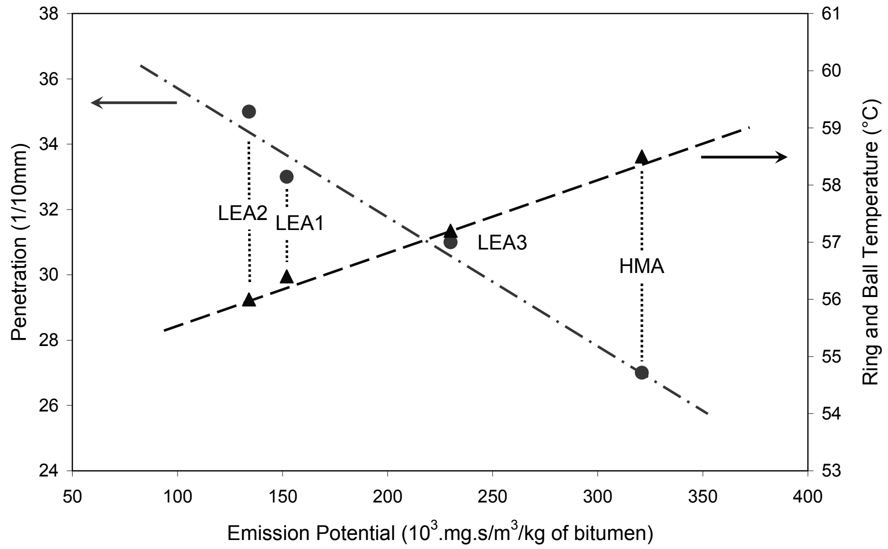

FIGURE 11: Penetration and ring and ball temperature vs. Emissions Potential results for HMA and LEA® enhanced by the O additive

With an increase in the TOC(e) EP, penetration decreases and ring and ball temperature increases for the GB formula tested. These findings point to an ageing of the bitumen due to a manufacturing temperature differential between hma and LEA® as well as to the process employed in the case of LEA® variants. Through this effort, a relation between fume emissions generated during the manufacturing of asphalt mixes and the ageing of bitumen can be derived; such a relation corresponds to what has already been stated on hma *(9).*

CONCLUSION

The purpose of this study has been to identify the effect of bituminous material composition on mechanical performance and emissions, as expressed in terms of TOC(e) and Emissions Potential of the various asphalt mix processes (hma and LEA®). The main set of conclusions can be drawn as follows:

- The values of stiffness modulus and fatigue resistance for the LEA mixes are very close to those obtained for hma, which highlights a similar durability between the series of LEA mixes and their hot-mix counterpart.
- This study has shown that a decrease in manufacturing temperature leads to an overall emissions reduction.

- When using the two vegetable-based additives provided by EIFFAGE Travaux Publics, the initial environmental results indicate no influence from additives with the compounds used in the half-warm mix asphalt. These results obviously must be examined further for other types of additives.
- Total Organic Compounds TOC(e) provided by the half-warm mix asphalts are less than hot mix asphalts, according to the manufacturing temperature differential.
- Both the penetration and ring and ball temperature values obtained from the bitumen recovered during the LEA processes have undergone less modification than the bitumen recovered from HMA, which would indicate slower ageing of the binder.
- A linear relation has been found between the Emissions Potential and penetration or ring and ball temperature value.
- Lastly, this study has highlighted the influence of mix parameters and processes, especially on TOC(e) emissions and the Emissions Potential for half-warm and hot mix asphalts.

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