EXPERIENCE WITH OPTIMISED HARD GRADE BITUMENS IN HIGH MODULUS ASPHALT MIXES

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ABSTRACT

In the early nineteen eighties, new generations of French asphalt mixes were developed to reduce roadbase thicknesses and subsequently to strengthen some binder/base courses and selected wearing courses. High modulus asphalt mixes “EME” and “BBME” were introduced. To achieve the required performance (high stiffness; fatigue resistance; high rutting resistance; resistance to brittle thermal cracking; ageing resistance; workability;...), appropriate asphalt mix designs were found which resulted in the first set of performance-based specifications in 1992. Among the key components were the hard special bitumen grades “HMB”, mostly 10/20 and 15/25 penetration, with characteristics that resulted in compromises between optimised thermal susceptibility and ageing resistance. This is only achievable through tailor made refinery processes as illustrated with the evaluation of 2 extreme HMB with “SOL” and “GEL” type colloidal structures. A review and recommendations to interpret the draft CEN prEN 13924 specifications for HMB are provided. The example of a successful implementation of the “EME” technology from France to another European country is described, including the effect of recycled asphalt mix addition on “EME” performance.

Keywords: Hard grade bitumens (10/20, 15/25), high modulus asphalt mixes (EME, BBME), performance testing, implementation of technology, recycling.

1. INTRODUCTION

In the early nineteen eighties, new generations of asphalt mixes were developed in France to reduce pavement thicknesses (roadbase layers from 7 cm to 15 cm thick to answer technical, economical and ecological requirements) and in the nineteen nineties to strengthen certain thick binder/base courses and selected wearing courses in a context of increased traffic stresses. High modulus asphalt mixes, Enrobés à Module Elevé “EME” and Béton Bitumineux à Module Elevé “BBME” respectively, were introduced for reinforcement and rehabilitation or new pavement construction purposes. To achieve the required asphalt mix performance (high stiffness but sufficient fatigue resistance at pavement design temperature; high rutting resistance; sufficient resistance to brittle thermal cracking but good hardening & ageing resistances; good workability at limited high compaction temperature;...), appropriate asphalt mix designs based on compromises were found which resulted in the first set of performance-based specifications NF P 98-140 and NF P 98-141 published by AFNOR in 1992 covering respectively EME & BBME applications.

Although the EME standard distinguishes two classes of performance, this study deals with the single EME class 2 “EME2” (corresponding to the first generation of these asphalt mixes based on continuous aggregates grading (0/14 or 0/20 mm) and on high binder content for increasing their compactness and resistance to fatigue) and only refers to BBME applications based on HMB without providing additional data [14], [15], and [16].
A complete historical review on the development of EME/BBME and the presentation of their formulations and performances being provided in ([1], [3], [4], [5], [6] and other referenced documents), they will not be further discussed in this paper.

Among the key components of EME and of some BBME asphalt mixes are the hard special bitumen grades, mostly 10/20 and 15/25 penetration, presently named High Modulus Bitumens “HMB”. According to the survey carried out by the World Road Association PIARC in 1996 [21], their production in France reached 50,000 tons at the time and since has considerably increased positioning the French market in a leading position. The chemical composition and the colloidal structure of the hard grades being strongly dependent on their manufacturing process, their rheological and ageing properties could vary within a wide range. Consequently, the specific characteristics of the current HMB used in France for EME & BBME applications resulted in compromises between optimised thermal susceptibility and ageing resistance that is only achievable through tailor made refinery processes.

The main aim of this paper being to demonstrate the effect of the thermal susceptibility of the HMB (strongly influenced by their colloidal structure) on their rheological & ageing characteristics and on the performance of the corresponding EME, 2 HMB with extreme “SOL” & “GEL” colloidal types were evaluated. It is also intended to evaluate the relevance of the draft CEN specification pr EN 13924 for HMB (focusing on their thermal susceptibility criteria appreciated via the ring and ball softening point and the Pfeiffer penetration index ranges) so as to optimise the choice of HMB for EME application. Some recommendations to interprete these draft CEN specifications are provided.

The last part of this paper covers the technology exchanges between European countries that exhibit an increasing interest for the EME technique (e.g. Benelux, Spain, UK,). The example of a successful implementation of the EME technology from France to another European country is described, including the evaluation of the effect of recycled asphalt mix addition on EME performance.

2. EXPERIMENTAL

2.1 Materials

2.1.a Binders

2 HMB were selected on the basis of their extreme colloidal structures (defined from the colloidal instability index “CII”

\[
CII = \left( \frac{\% \text{ Asphaltenes} + \% \text{ Saturates}}{\% \text{ Aromatics} + \% \text{ Resins}} \right)
\]

- Grade 10/20 named "B" with an n-heptane asphaltenes content of 10 % (m/m) and a CII of 0.14 considered as a “SOL” type HMB which complied with the draft CEN specifications standard pr EN 13924 for hard paving grade bitumens (07/2003 version).
- Grade 15/25 named "F" with an n-heptane asphaltenes content of 21 % (m/m) and a CII of 0.43 considered as a “GEL” type HMB that fitted with most of the pr EN 13924 requirements although its ring and ball softening point of 78 °C (expressed as an into water measured softening point) is borderline.

2.1.b Asphalt mixes

The high modulus asphalt mixes complying with the formulation requirements of the AFNOR specifications standard NF P 98-140 (Enrobé à Module Elevé for road base high modulus asphalt concrete - 11/1999 version) for EME2 were constituted with these 2 extreme HMB. The formulation of the reference EME2 was: 0/14 mm aggregates (Diorite from LA NOUBLEAU French quarry meeting the XP P 18-540 AFNOR standard requirements) with a binder content in weight (with respect to the
aggregates weight) of 5.5 pph (equivalent to 5.2 % (m/m): ratio by weight of the binder to the asphalt mix). The richness factor K for the binder content was 3.65 complying to the min. request of 3.4 from NF P 98-140. The aggregates grading curve is of a continuous standard type according to NF P 18-560 AFNOR standard:

<table>
<thead>
<tr>
<th>SIEVE SIZE (mm)</th>
<th>16</th>
<th>14</th>
<th>12.5</th>
<th>10</th>
<th>8</th>
<th>6.3</th>
<th>5</th>
<th>4</th>
<th>3.15</th>
<th>2</th>
<th>1</th>
<th>0.315</th>
<th>0.080</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUMULATIVE % (m/m) of PASSING AGGREGATES</td>
<td>100</td>
<td>96.5</td>
<td>92.5</td>
<td>78.5</td>
<td>69</td>
<td>59</td>
<td>49</td>
<td>42</td>
<td>39</td>
<td>33</td>
<td>23.5</td>
<td>13.5</td>
<td>7.5</td>
</tr>
</tbody>
</table>

2.1.c Recycled materials added to EME2
The recycled materials added to EME2 as discussed in §3.2 were 0/16 mm crushed asphalt concrete containing 5.3pph (5.0%-m) of aged binder. The aged binder (after extraction) had a PEN25°C of 21 mm/10.

2.2 Equipment
2.2.a Binder evaluation
The basic binder characteristics measured according to the pr EN 13924 draft specifications complied with its referenced test methods (EN standards).
The following test methods were also used:
- The chemical composition was assessed with:
  - The dosage of n-heptane asphaltenes with the NF T 60-115 standard.
  - The thin film liquid chromatography on alumine rods IATROSCAN specific procedure [12] which allows the polar separation between the saturates, aromatics and resins generic families from the maltenes phase extracted according to the previous NF T 60-115 standard.
- The complex modulus was evaluated according to the AFNOR draft test method pr NF T 66-065 (04/2003 version) with the 2 following rheometers:
  - METRAVIB Elastometer with the 2 following controlled strain (5 µm amplitude longitudinal oscillation) procedures: tensile-compression and annular shearing for the temperature ranges of (-30 °C to around +20 °C) and of (around +20 °C to +60 °C) respectively. Although the measurements were monitored for a wide range of frequencies (from 7.8 Hz to 250 Hz), only the isochronal 7.8 Hz data are reported here.
  - BOHLIN Dynamic Shear Rheometer "DSR" with angular oscillatory load for only the 15/25 F HMB. Although the measurements were monitored within wide ranges of temperatures (from around +10 °C to +80 °C) and frequencies (from 0.1 Hz to 10 Hz), only the +60 °C; 1.6 Hz data are reported here.

2.2.b Asphalt mix evaluation
The performance of the EME2 asphalt mixes were assessed according to the NF P 98-140 specifications standard that refers to the following AFNOR test methods:
- The workability of the asphalt mix was measured with the Gyratory shear Compaction Press test ("PCG" NF P 98-252 standard). Air voids contents for 100 gyrations of the PCG between 4.7% and 5.7% were measured for the EME2 based on some of the HMB maintained at Equi-Viscosity 200 mPa.s Temperatures "E.V.T. 200 mPa.s". This confirms the low sensitivity of the workability of a given asphalt mix formulation versus the binder characteristics as far as the PCG temperature is monitored at the binder equi-viscosity temperatures. These air voids contents matched with the 6% max. NF P 98-140 specification.
- The resistance to water was measured with the DURIEZ compression test (NF P 98-251-1 standard). Wet/dry compression ratios (r/R) above 0.95 were measured for some of the HMB. They fully satisfied
the 0.75 min. NF P 98-140 specification and, more globally, no adhesion concern was noticed for the EME2 asphalt mixes combining the LA NOUBLEAU aggregates and the HMB.

- The resistance to rutting was evaluated with the LCPC wheel tracking rutting test (NF P 98-253-1 standard) performed at 60 °C; 1 Hz.
- The resistance to fatigue cracking was assessed by the LCPC two points bending test (NF P 98-261-1 standard) performed at 10 °C; 25 Hz on trapezoidal samples with controlled strain (oscillatory displacement with 3 levels of imposed constant amplitude at the top of the beam).
- The stiffness of the EME2 based on pure HMB was measured with the LCPC two points bending test (NF P 98-260-2 standard) performed in the (-10 °C; +40 °C) temperature range and (1Hz; 30 Hz) frequency range on trapezoidal samples with controlled strain (oscillatory displacement with imposed constant low amplitude at the top of the beam).
- The stiffness of the asphalt mixes of the comparative study between the EME2 containing or not recycled materials (§3.2) was measured according to the NF P 98-260-1 standard requirements on cylindrical samples cored from laboratory prepared slabs. The procedure of the LCPC direct tensile test “MAER” based on an imposed and increasing strain law was adapted on one of the MTS multifunctional servo-hydraulic presses as part of the ExxonMobil Road Design Technology “ERDT” (this includes also tensile-compression stiffness, tensile-compression fatigue, dynamic creep and restrained cooling down tests performed on MTS presses). Although the measurements included wide ranges of temperatures (from 0 °C to 15 °C) and tensile loading times (from 1 s to 300 s), only the data at 0.02 s extracted from the master curve at 15 °C are reported here.

The wheel tracking, fatigue and stiffness tests were carried out by maintaining the air voids contents of the test slabs in the narrowest range possible so as to accurately compare their performances.

3. RESULTS AND DISCUSSION

3.1 Relation between the thermal susceptibility of HMB and their performance in EME2

The aim of this study is to establish the relationship between the thermal susceptibility (linked to the colloidal structure) of the HMB and the performance of the corresponding EME2 asphalt mixes in order to:

- Demonstrate that the optimal choice for a HMB binder, from the developers point of view or that of road contractors having to select the most suitable binder, is (as always, as far as asphalt mixes are concerned) the result of a compromise between incompatible/lanternogistic performances.
- Provide guidelines to the EU countries and to the HMB suppliers in their selection of classes, options and declared TRB ranges for the future EN 13924 specifications for HMB. The negotiations actually hold at CEN TC337 WG1 between certain countries proposing an increase of the maximum TRB values and other countries requesting a decrease of the minimum TRB values highlight the difficulty to obtain a general consensus.

3.1.a Characterisation of HMB with extreme colloidal structures

As stated in §2.1.a, 2 HMB were selected on the basis of their extreme colloidal structures and consequently their thermal susceptibility: 10/20 B “SOL” type and 15/25 F “GEL” type although its 78 °C TRB was borderline according to the pr EN 13924 specifications. Their characteristics are described into table 1.

These 2 extreme HMB were extracted from a matrix of 6 HMB with intermediate colloidal structures between “SOL” and “GEL” (obtained by blending) that had been evaluated in terms of binder properties and EME2 performance. When measurements have not been performed on the 10/20 B and 15/25 F in the laboratory but data were extrapolated from the full matrix of 6 HMB, they are indicated between brackets.
3.1.b Thermal susceptibility of the HMB versus their colloidal type

The decrease of the thermal susceptibility of the HMB when moving from a “SOL” to a “GEL” colloidal type was appreciated with:

- The increase of the Pfeiffer Penetration Index "PPI" (calculated from PEN25°C & TRB according to the EN 12591 or pr EN 13924 annexes A). Consequently, the optional specification of max. PPI (+0.7) from the pr EN 13924 would reject HMB with a too important “GEL” colloidal fingerprint although meeting the TRB specified range. Nevertheless, the relevance of the PPI range (-1.5 to +0.7) of the current pr EN 13924 is questionable as discussed in §3.1.h.
- Flatter E* modulus isochrons @ 7.8 Hz of the binder and flatter E* stiffness isochrons @ 10 Hz of the corresponding EME2 as described into figures 1 & 2 respectively. The shape of the binder E* isochrons between -30°C & 0°C is such that, the lower the CII, the higher the E* showing a greater low temperature brittleness (the isochrons focusing towards the brittle modulus of the binders). The isochrons crossover around 45°C leading to lower E* from 45°C to 60°C for the “SOL” type HMB (predicting a poorer resistance to permanent deformation at high temperature). The phase angle δ isochrons @ 7.8 Hz for the binders and @ 10 Hz for the corresponding EME2 vary versus the CII of the HMB in the same way than that of the E* isochrons: the lower the CII, the lower the phase angle δ at low temperature showing a higher elastic rheological behaviour and the lower the CII, the higher the phase angle δ at high temperature showing a higher viscous rheological behaviour that impair respectively their low and high temperature performances. The prediction of the complex modulus data for HMB from their PPI with the Van Der Poels model [19] would also reflect these variations.

Table 1: Characterisation of 2 extreme HMB in terms of colloidal structure/thermal susceptibility
3.1.c Mixing temperature of the HMB versus their colloidal type

The E.V.T. 200 mPa.s of the HMB increased from 175 °C to 192 °C when moving from the “SOL” to the “GEL” type HMB but that range remained compatible with the EME2 industrial mixing temperatures.

3.1.d Hardening/ageing resistances of the HMB versus their colloidal type
- RTFOT hardening resistance

The RTFOT test practised @ 163 °C led to satisfactory hardening resistances for the 2 extreme HMB commented as follows:
- Changes (losses) of mass were far below -0.1% (m/m) and fully in line with the +/-0.5% (m/m) max. specification from the prEN 13924. Such a behaviour was expected taking into consideration the production routes used for formulating the "SOL" & "GEL" type HMB, that guarantee, as for much of the HMB available in France, a very low content of low volatility components.
- % of retained PEN25°C also far exceeded the 55% min. optional specification from the prEN 13924.
- The RTFOT increase in TRB criterion increased from +3.5 °C to +8 °C (borderline value when compared to the 8 °C max. optional specification (class 2) from the prEN 13924) when moving from the “SOL” to the “GEL” type HMB.

Nevertheless, like for some Polymer Modified Bitumens, there is a concern with the relevance of the RTFOT test practised at only 163 °C instead of the higher E.V.T. 200 mPa.s mixing temperatures of the HMB measured between 170 °C and 185 °C for the main current 10/20 & 15/25 grades supplied on the French market and included in a 175°C - 192°C range for the present 2 extreme HMB from this study. For HMB with too high E.V.T. 200 mPa.s such a low 163 °C temperature can lead to thicker and less homogeneous binder films in the RTFOT bottles (due to the higher binder viscosities) and consequently to a less severe hardening than expected in a standard asphalt mixing plant run at E.V.T. 200 MPa.s mixing temperature.
• **PAV ageing resistance**

Table 1, although limited to the evaluation of the “GEL” type HMB, demonstrates that its PAV long term ageing resistance is impaired when taking into consideration some SHRP Bending Beam Rheometer “BBR” criteria.

As also noticed in [1], the rise of temperature of iso-modulus S=300 MPa “$T = 300 \text{ MPa}$” between the fresh HMB and the RTFOT + PAV aged HMB was very limited (+1 °C) but the increase in the temperature of the iso-slope $m = 0.3$ “$T = 0.3$” was much greater (from +4 °C to +7 °C for the commercial French HMB tested in [1]) and +21 °C for the extreme “GEL” type HMB from this study. The main variation of the BBR $T_m=0.3$ criterion occurred during the PAV ageing process (around 70%) and not during the RTFOT hardening process (around 30%).

Nevertheless, one could argue that the PAV ageing procedure is irrelevant for the HMB applied to EME (the road base being protected by a wearing course and possibly a binding/base course and the EME being relatively dense asphalt mixes) and to BBME for a binding/base course (being protected by a wearing course).

3.1.e **Low temperature performance of the HMB versus their colloidal type**

The low temperature performance of the 2 extreme HMB was assessed with the TFRAASS and with the BBR tests on fresh binders as recommended by the prEN 13924 plus the SHRP criteria of BBR on RTFOT + PAV aged binder as discussed in §3.1.d. The low temperature performance (decrease of TFRAASS and of BBR $T = 300 \text{ MPa}$) rises with the CII for the fresh HMB. The BBR “$T_m=0.3$” criterion, supposed to reflect the ability of the binder to relax at low temperature (for avoiding brittle thermal cracking or thermal fatigue leading to surface cracking) is still acceptable for the fresh “GEL” type HMB although there is a gap of +6 °C with the corresponding $T = 300 \text{ MPa}$. As opposed to this, after RTFOT + PAV ageing procedures, the $T_m=0.3$ criterion led to a positive temperature (+6 °C) for this HMB that is considered as critical.

Nevertheless, the relevance of the PAV ageing procedure (supposed to simulate 5 to 10 years of ageing for a softer binder in a wearing course asphalt concrete) and of the BRR criteria $T_m=0.3$ will need to be established also for HMB by calibrating with the pavement performance of EME & BBME (as part of the process for second generation performance driven CEN specifications?).

The French criterion (critical temperature for phase angle $\delta @ 7.8 \text{Hz} = 45^\circ$ corresponding to the transition between predominant elastic behavior and predominant viscous behavior) related to the cracks healing capacity of the fresh binder raised from +27 °C to +40 °C when moving from the “SOL” to the “GEL” type HMB. The “GEL” type HMB is supposed not to achieve a sufficient viscous state for temperatures of the asphalt mix below 40 °C in order to allow the healing of the thermal (or structural fatigue) cracks. In addition, this critical temperature is expected to increase with the ageing of the binder...

As far as HMB applied to EME (the road base being thermally protected by a wearing course and possibly a binding/base course) and to BBME for base courses (being thermally protected by a wearing course) are concerned, the risk for low temperature cracking failure is low with HMB having a medium (not extreme) colloidal type. That means excluding the extreme “SOL” type HMB considered as too brittle at very low temperature (resulting in brittle thermal cracking) and excluding the extreme “GEL” type HMB considered as having insufficient long term ageing resistance, too limited ability to relax at low temperature and very low cracks healing capacity at medium temperature (resulting in thermal fatigue surface cracking) although they can pass the prEN 13924 basic specifications (see 3.1.h).

EME2 have proven [1] under the French climatic conditions that they were not impaired by low temperature brittle thermal cracking or thermal fatigue cracking (when not rapidly covered). In order to compensate a lower healing capacity of the HMB as compared to the softer conventional paving grades, the EME2 are designed with a relatively high binder content and low air voids content that prevent
fatigue failure and can also enhance the thermal cracking resistance. In the case of BBME for wearing courses, HMB with a moderate “GEL” colloidal type provide a sufficient low temperature performance (when also confirmed with restrained cooling down test and low temperature tensile test for the asphalt mixes) could be used on sites where climatic conditions generally allow the standard use of conventional paving bitumen 35/50 in wearing courses.

3.1.f Performance of EME based on HMB versus their colloidal type

The performance of the reference EME2 asphalt mixes based on the 2 extreme HMB was assessed according to the NF P 98-140 specifications standard as described into §2.2.b and table 2.

<table>
<thead>
<tr>
<th>HMB GRADE</th>
<th>UNIT</th>
<th>STANDARD</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 - CHARACTERISATION OF THE REFERENCE EME2 ASPHALT MIXES BASED ON THE HMB BLENDS</td>
<td>10/20 B</td>
<td>15/25 F</td>
</tr>
<tr>
<td>WHEEL TRACKING TEST LCPC @ +60°C</td>
<td>% RUT @ 30000 cycles</td>
<td>%</td>
</tr>
<tr>
<td>STIFFNESS 2 POINTS BENDING TEST LCPC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>STIFFNESS E* @ 15°C; 10Hz</td>
<td>MPa</td>
<td></td>
</tr>
<tr>
<td>FATIGUE 2 POINTS BENDING TEST LCPC @ +10°C; 25Hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EPSILON 6 @ 1 million cycles</td>
<td>µstrain</td>
<td></td>
</tr>
<tr>
<td>SLOPE (LOG EPSILON / LOG N)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Characterisation of EME2 based on 2 extreme HMB in terms of colloidal structure/thermal susceptibility

- **High temperature performance of the HMB versus their colloidal type**

As well known for conventional paving bitumens, the higher their CII for a limited PEN25°C range (e.g. comparison at equi-grade), the higher the resistance to permanent deformation of the corresponding asphalt mixes (justifying the development of the multigrade bitumens). In the case of the HMB, the same trend was noticed making the HMB with the highest TRB & PPI the best performers at high temperature. The increase of the standard high temperature criteria for fresh binders (TRB, E* @60°C;7Hz from METRAVIB complex modulus and SHRP critical temperature for G*sinδ @1.6Hz = 1 KPa from BOHLIN complex modulus) versus their CII is important when moving from the "SOL" to the "GEL" type HMB.

The LCPC wheel tracking tests performed at 60 ° only confirmed a slight trend for increasing rutting resistance with higher CII without sufficient differentiation (possibly due to the limited reliability of the tests for such low rut depths). The 2 EME2 fully complied with the NF P 98-140 specifications (7.5% max. rut depth) and could be labelled as “Anti-Rutting” asphalt mixes recommended for heavy duty applications (e.g. French motorways generally requesting less than 5% rut depth).

- **Medium temperature performance (stiffness) of the HMB versus their colloidal type**

In §3.1.b, the effect of the CII of the HMB on the thermal susceptibility of their modulus (and the corresponding EME stiffness as illustrated in figure 2) was established including its consequences for their high and low temperature performances.

As far as EME stiffness is concerned, the NF P 98-140 specification only deals with the pavement design criteria E* @+15°C; 10Hz requested by the French methodology. It is well known that the stiffness of asphalt mixes at equi-formulation is well correlated with the modulus of the corresponding binders measured for the same temperature - frequency conditions [9].
The higher the CII of the HMB blends, the lower the EME2 $E^* \pm 15^\circ C; 10Hz$ because of the lower thermal susceptibility of "GEL" type HMB leading to flatter stiffness curves in the $-10^\circ C$ to $+40^\circ C$ temperature range. Consequently, the lower thermal susceptibility of the "GEL" type HMB that is perceived as an advantage for EME high and low temperature performances due to its respectively higher stiffness (associated to predominant elastic behaviour) and lower stiffness (associated to predominant viscous behaviour), disadvantages the stiffness at ambient temperature ($+15^\circ C$, defined as the French average reference temperature for pavement design). In the context of the present study, EME2 based on the "GEL" type HMB would not satisfy the 14000 MPa min. $E^*$ specification from NF P 98-140.

![Figure 2: Variation of STIFFNESS (E* isochron @ 10Hz) of EME2 based on 2 extreme HMB in terms of colloidal type](image)

- **Medium temperature performance (fatigue resistance) of the HMB versus their colloidal type**

  The NF P 98-140 specification for EME requests a minimum fatigue resistance measured with the LCPC 2 points bending test expressed as the admissible strain for failure achieved after 1 million of cycles ($\varepsilon_6 \pm 10^\circ C; 25Hz$) that is also used as the second major criteria in the French pavement design methodology. Fatigue resistance and stiffness being generally antagonistic properties (when measured for the same conditions of temperature and frequency), opposite strengths and weaknesses are expected for the 2 extreme HMB. The higher the CII of the HMB, the lower the HMB $E^* \pm 10^\circ C; 25Hz$ and the higher the EME2 $\varepsilon_6 \pm 10^\circ C; 25Hz$. In the context of the present study, EME2 based on the "GEL" type HMB would not satisfy the 130 $\mu$strain min. $\varepsilon_6$ specification from NF P 98-140.

**3.1.g Selection of optimum HMB based on their thermal susceptibility related to their colloidal type**

In the previous § it was demonstrated that both HMB with extreme colloidal types "SOL" & "GEL" could not fully satisfy the NF P 98-140 specification for EME although they met most of the basic requirements of the pr EN 13924 specifications for HMB. This means that, because part of the performances for HMB and EME2 are incompatible/antagonistic, a compromise must been found to optimise the binder choice. The HMB thermal susceptibility, approached by the means of their colloidal type, is a way to achieve that optimisation.
Indeed, the trends established in this study can be summarised as:

- The higher the PPI and the CII of the HMB, the lower its ageing resistance (appreciated with the RTFOT increase in TRB and PAV increase in BBR Tm=0.3 criteria) and the lower the EME stiffness at +15°C.
- The lower the PPI and the CII of the HMB, the lower its resistance to low temperature brittle cracking (appreciated with the TRAASS of the fresh binder), the lower the EME fatigue resistance at +10°C and the lower the EME rutting resistance at +60°C.

Consequently, a window for optimum HMB colloidal type must be found in order to guarantee the requirements of pr EN 13924 (with its most severe classes) and of NF P 98-140 (for the considered reference EME2 formulation). Because there is no univocal relationship between the thermal susceptibility of the bitumens and their colloidal type (HMB being potentially produced by various process routes), such an optimum window must be defined case by case in accordance with the considered application EME or BBME. Optimum HMB may result from compromises between the two thermal susceptibility and ageing resistance criteria that is only achievable through tailor made refinery processes and formulations. In addition, it is obvious that, because the contribution of the binder properties to the EME performance decreases from the low to the high temperatures, the optimisation of an EME asphalt mix design can compensate some of the defaults (from medium to high temperatures performances) of the considered HMB.

3.1.1 Recommendation for the interpretation of the pr EN 13924 draft specifications for HMB

An intention of this publication was to review the draft pr EN 13924 draft specification (07/2003 version) and to provide guidelines to the EU countries in their selection of the ring and ball softening point “TRB” classes for HMB (and choice of classes for other optional properties) and to the HMB suppliers in their declaration of TRB ranges (+/- 5°C around a mid-point, the overall range having to be within the national class).

As proven for the 2 HMB with extreme “SOL” & “GEL” colloidal types in § 3.1.g and for one HMB representative of the French market that has been characterized according to a separate study (evaluation of a portfolio of 5 HMB 10/20 & 15/25 supplied into the French market not reported here), the satisfaction by a hard grade bitumen of the pr EN 13924 specification does not guarantee the compliance with the NF P 98-140 specification for French EME, even if a standard reference asphalt mix formulation is considered. This draft specification will still allow the choice of HMB with too extreme thermal susceptibilities (linked to too low or too high TRB & consecutive PPI) and too low ageing resistance if HMB with a too pronounced “GEL” colloidal type are selected.

The following recommendations for the interpretation of the draft CEN specification pr EN 13924 (focusing on the HMB thermal susceptibility criteria appreciated via the ring and ball softening point and the consecutive PPI ranges) are provided so as to optimise the choice of HMB for EME & BBME applications:

<table>
<thead>
<tr>
<th>HMB GRADE</th>
<th>TRB CLASS (°C)</th>
<th>TRB INTERVAL (+/−5°C)</th>
<th>RESULTING PPI INTERVALS (considering min.PEN/max.TRB &amp; max.PEN/min.TRB expected cases)</th>
<th>RESULTING PPI INTERVALS (considering min.PEN/min.TRB &amp; max.PEN/max.TRB extreme unexpected cases)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/20</td>
<td>C.4 : 60/76</td>
<td>60/70</td>
<td>-0.9/-0.4</td>
<td>-1.9/+0.8</td>
</tr>
<tr>
<td>15/25</td>
<td>C.2 : 55/71</td>
<td>60/70</td>
<td>-0.5/+0.3</td>
<td>-1.4/+1.2</td>
</tr>
</tbody>
</table>

Surprising TRB range for the 15/25 grade identical (but still negotiable) to that of the 10/20 grade is recommended in order to avoid the exclusion of a HMB 15/25 whose good reputation for EME but also BBME (including application in wearing courses due to its premium high temperature performance) has been recognised in several European markets since 1988 [14], [15], [16].
3.2 Implementation of the EME technology between European countries - Example of the evaluation of EME2 including recycled materials

France having the longest expertise (more than 20 years now) on HMB and resulting high modulus asphalt mixes and being the world-wide market leader, its road authorities (SETRA, LCPC...), road contractors and oil companies that supply HMB are often consulted by other European countries (such as Benelux, Spain, UK...) increasingly interested in this technique. Nevertheless, [1] and the present paper explained that:

- The EME & BBME technologies are not based on a simple substitution of the binder (from a conventional softer paving grade as paving bitumens 35/50 or 50/70 pen to a HMB) in a standard asphalt concrete formulation. They require a specific asphalt mix design built on performance driven specifications.
- The hard grades produced within the adequate pen ranges (10/20, 15/25 or in the neighbour of these official grades) do not systematically guarantee the compliance with the performances required for EME or BBME applications even if they satisfy the pr EN 13924 specifications.

Cases of too partial expertise transfer (with risky technical adaptations, with too many limitations by local constraints/habits and insufficient access to relevant performance tests) that led to failure of high stiffness asphalt concrete have been reported in Europe. As opposed to this, the successful example of a direct implementation of the EME technology from France to another European country is described hereafter.

At the end of the nineteen nineties, a foreign road contractor (HMB and high stiffness asphalt concrete having never been experienced in that European country) contacted several French companies (road contractors and bitumen suppliers) to obtain expertise on the EME technology. Its motivation was mainly ecological constraints (fresh aggregates saving) and cost reduction for roadbase applications. Bibliography, presentations, French road sites visits and training were proposed by the selected French company to achieve the most efficient possible technology implementation. The EME2 specification NF P 98-140 being adopted as the unique and complete reference, asphalt mix designs based on local aggregates and a French standard HMB 15/25 were undertaken by the selected French company. Complementary asphalt mix evaluations with tests (empirical or performance based) were carried out locally. Road trials of limited size were hold in the foreign country to gain experience with the mixing, laying and compaction conditions recommended in France and to convince the local road authorities. Since then, the EME2 technique has been fully recognised by the corresponding national road authorities and has became part of the asphalt mix techniques portfolio offered in that country.

At the request of the national road authorities, a further milestone must now be reached by agreeing to the introduction of recycled asphalt mix materials in EME after evaluating its impact on the EME2 performance. The local recycled materials described in § 2.1.c were added to a fresh EME with a 30%-m ratio for comparison between these materials “EME2 30%” and the reference pure EME2 based on 6.6pph (5.3%-m) of the standard HMB 15/25. The binder content (5.3pph) and the aggregates grading of the recycled materials were taken into account when blended with the fresh EME2 in order to achieve a total binder content (5.6pph) and an aggregates grading as close as possible to that of the reference pure EME2. The asphalt mix performance comparison provided in table 3 shows:

- Although the workability evaluated with the PCG tool at the same E.V.T. 200 mPa.s (185 °C) was similar (air voids content for 100 gyrations and corresponding curve slope) for EME2 without or with 30% recycled materials, the air voids contents measured on test pieces after DURIEZ compaction, on cylindrical cores (for “MAER type” stiffness test) and on trapezoidal test pieces (for fatigue testing) sawn from slabs prepared with the LCPC rolling wheel compactor (asphalt mixing being again monitored at the E.V.T. 200 mPa.s of 185 °C) far exceed the tolerances from the NF P 98-140 standard for the EME2 30%. These air voids contents confirm the low workability of the asphalt mix
noticed during the laboratory compactions. The difference of air voids contents measured between the two EME2 formulations associated with the risk for a certain heterogeneity in the EME2 30% may impair the following performance comparisons.

- The resistance to water evaluated with the DURIEZ test (wet/dry ratio r/R) was too low for the EME2 30% as a consequence of the higher porosity of the test pieces.
- The rutting resistance assessed with the LCPC wheel tracking test raised an exceptional level for the EME2 30% although the air voids content of the slabs far exceeded that of the reference pure EME2.
- Starting with a limited stiffness level (E* @+15°C; 0.02s) for the reference pure EME2, the introduction of 30% of recycled material, although based on an aged binder (PEN25°C = 21 mm/10) with the same hardness than the HMB 15/25, led to an insufficient stiffness slightly below the NF P 98-140 requirement explained by the too high air voids contents of the test cores (far exceeding 6%-volume).
- The evaluation of the fatigue resistance of the EME2 30% is still in a stand-by position as a result of the measurement of its deceiving stiffness. The use of a stiffer (@ +15 °C) HMB would have probably solved the stiffness issue but led to unsatisfactory fatigue resistance of the EME2 30% (due to a borderline performance of the pure EME2 associated to the too high air voids content).

Consequently, this first attempt to introduce 30% of recycled materials in EME2 according to the NF P 98-140 performance requirements failed due to issues with the asphalt mix compactness, resistance to water and search for a compromise between relatively incompatible stiffness and fatigue resistance requirements. The orientations in future investigations should be the optimisation of the EME2 30% asphalt mix design, the evaluation of the impact of other batches of recycled materials (various binder contents, levels of binder ageing and aggregates grading) on the workability of the EME blends and finally, if unsuccessful, the optimisation of the recycled materials ratio in the base EME2. This study demonstrated that it is impossible to introduce high amounts of recycled materials in EME2 in an uncontrolled manner due to the potential impacts on the EME2 performances.

<table>
<thead>
<tr>
<th>CHARACTERISATION OF EME2 ASPHALT MIXES WITH &amp; WITHOUT RECYCLED MATERIALS</th>
<th>EME2 0/16 GRANITE SPEC AFNOR</th>
<th>WITHOUT RECYCLED MATERIALS</th>
</tr>
</thead>
<tbody>
<tr>
<td>% HMB 15/25 INTO BASE EME2</td>
<td>5.6</td>
<td>5.7</td>
</tr>
<tr>
<td>% RECYCLED MATERIALS IN EME2</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>WORKABILITY with GYRATORY SHEARING PRESS PCG LCPC @ E.V.T. 200 mPas °C</td>
<td>NFP 98-252</td>
<td></td>
</tr>
<tr>
<td>AIR VOIDS CONTENT @ N=100 gyrations %%-volume</td>
<td>3.5</td>
<td>4.1</td>
</tr>
<tr>
<td>SLOPE K (V/LOG N)</td>
<td>-2.74</td>
<td>-2.60</td>
</tr>
<tr>
<td>DURIEZ COMPRESSION TEST LCPC @+18°C</td>
<td>NFP 98-251-1</td>
<td></td>
</tr>
<tr>
<td>AIR VOIDS CONTENT %%-volume</td>
<td>5.9</td>
<td>10.6</td>
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<tr>
<td>STRESS AT 18°C AFTER 7 DAYS DRY (R) MPa</td>
<td>12.8</td>
<td>12.2</td>
</tr>
<tr>
<td>STRESS RATIO WET/DRY (r/R)</td>
<td>0.90</td>
<td>0.70</td>
</tr>
<tr>
<td>WHEEL TRACKING TEST LCPC @+60°C</td>
<td>NFP 98-253-1</td>
<td></td>
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<tr>
<td>AIR VOIDS CONTENT %%-volume</td>
<td>5.2</td>
<td>13.5</td>
</tr>
<tr>
<td>% RUT @ 3000 cycles %</td>
<td>3.8</td>
<td>2.2</td>
</tr>
<tr>
<td>SLOPE (LOG RUT / LOG N)</td>
<td>0.149</td>
<td>0.112</td>
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<tr>
<td>STIFFNESS according to the principle of MAER TEST LCPC</td>
<td>NFP 98-260-2</td>
<td></td>
</tr>
<tr>
<td>AIR VOIDS CONTENT %%-volume</td>
<td>6.0</td>
<td>&gt;&gt; 6</td>
</tr>
<tr>
<td>STIFFNESS E* @+15°C; 0.02 s MPa</td>
<td>14300</td>
<td>13500</td>
</tr>
<tr>
<td>FATIGUE 2 POINTS BENDING TEST LCPC @+10°C;25Hz</td>
<td>NFP 98-260-1</td>
<td></td>
</tr>
<tr>
<td>AIR VOIDS CONTENT %%-volume</td>
<td>5.8</td>
<td>&gt;&gt; 3/6</td>
</tr>
<tr>
<td>EPSILON 6 @ 1 million cycles µstrain</td>
<td>152</td>
<td>130</td>
</tr>
<tr>
<td>SLOPE (LOG ε / LOG N)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Evaluation of the effects of the addition of 30% of recycled materials to an EME2 formulation.
4. CONCLUSIONS

To demonstrate the effect of the thermal susceptibility of the HMB (mainly resulting from their colloidal structure) on their rheological and ageing characteristics and on the performance of the corresponding EME2, 2 HMB with extreme “SOL” and “GEL” colloidal types were evaluated. Relationships or trends between the HMB thermal susceptibility (related to their colloidal type), the binder properties and the EME performances were established:

• The higher the PPI and the CII of the HMB, the lower its ageing resistance (appreciated with the RTFOT increase in TRB and PAV increase in BBR Tm=0.3 criteria) and the lower the EME stiffness @+15 °C.
• The lower the PPI and the CII of the HMB, the lower its resistance to low temperature brittle cracking (appreciated with the TFRAASS of the fresh binder), the lower the EME fatigue resistance @+10 °C and the lower the EME rutting resistance @+60 °C.

Both HMB with extreme colloidal types “SOL” & “GEL” did not fully satisfy the NF P 98-140 specification for EME2 although they met most of the basic requirements of the pr EN 13924 (07/2003 version) draft specifications for HMB. This means that, because part of the performances for HMB and EME2 are incompatible/antagonistic, a compromise must be found to optimise the binder choice. This is only achievable through tailor made refinery processes and formulations targeting adapted windows for optimum HMB colloidal type in order to guarantee the requirements of the pr EN 13924 (with its most severe classes) and of the NF P 98-140.

Because there is no univocal relationship between the thermal susceptibility of the bitumens and their colloidal type (HMB being potentially produced by various process routes) such an optimum window must be defined case by case in accordance with the considered application, EME or BBME. In addition, it is obvious that, because the contribution of the binder properties to the EME performance decreases from the low to the high temperatures, the optimisation of an EME or BBME asphalt mix design can compensate some of the defaults (medium to high temperatures performances) of the considered HMB.

As proven for the 2 HMB with extreme colloidal types “SOL” & “GEL” from this study and for one HMB representative of the French market (not reported here), the satisfaction by a hard grade bitumen of the pr EN 13924 specification does not guarantee the compliance with the NF P 98-140 specification for French EME, even if a standard reference asphalt mix formulation is considered. Recommendations for the interpretation of the draft CEN specification pr EN 13924 (focusing on the HMB thermal susceptibility criteria appreciated via the ring and ball softening point and the Pfeiffer penetration index ranges) were provided to optimise the choice of HMB for EME & BBME applications avoiding the exclusion of products whose good performances had been established for a long time on some European markets.

As several European countries (e.g. Benelux, Spain, UK...) are showing an increasing interest for EME techniques, an example of a successful, because direct and complete, implementation of the EME technology from France to another European country has been described. A first attempt to introduce 30% of recycled materials in that foreign EME2 according to NF P 98-140 performance requirements failed due to issues with the asphalt mix compactness, resistance to water and a search for a compromise between relatively incompatible stiffness and fatigue resistance requirements. The reported study demonstrated that it is impossible to introduce high amounts of recycled materials in EME2 in an uncontrolled manner due to the potential impacts on the EME2 performances.
5. ACKNOWLEDGEMENTS

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