GB5: ECO-FRIENDLY ALTERNATIVE TO EME2 FOR LONG-LIFE & COST-EFFECTIVE BASE COURSES THROUGH USE OF GAP-GRADED CURVES & SBS MODIFIED BITUMENS

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ABSTRACT

Aggregate packing concepts developed in the field of high-performance cement concretes, initially by Caquot (1937) then by contemporary researchers since the 1970s, were transposed to the field of asphalts. These concepts, associated with gyratory compactor use on aggregates only, enabled the development of a new laboratory design procedure of dense high-modulus asphalts. These mixes are characterized by single or double gap-graded curves and great coarse aggregate interlock, as well as no need for hard bitumens to obtain the European EME2 specifications requirements, in particular the 14,000 MPa stiffness modulus value at 15°C.
Furthermore, the use of polymer modified binders (PMB's), at a content of about 4% to 4.5%, combined with this sort of optimized aggregate packing, led to the design of the so-called high-performance asphalts (HPAs) characterized by great compactability, a very high stiffness modulus and a high fatigue resistance in a single formulation, allowing for reduced pavement thickness and increased longevity. Moreover, the proposed mix design and the 4%-4.5% binder content makes PMB's affordable in base courses.
The laboratory assessment of such materials consisted in the evaluation of compactability, moisture resistance, rutting resistance at 60°C, complex stiffness modulus at 15°C and fatigue resistance at 10°C. The paper also addresses the successful application of this new material on different work sites, located mainly in France.
The paper illustrates that the proposed HPA material may be potentially considered as a relevant solution for sustainable long-life pavements that do not deteriorate structurally, needing only timely surface maintenance.

Keywords: mix design, aggregate packing optimization, dense gap-graded materials, PMB, SBS, high-performance asphalts, perpetual pavements

1. INTRODUCTION

Controlling the volumetrics of asphalt mixes is the first step of any mix design procedure. Apart from binder-related considerations, as the aggregate component represents about 95% of the weight of asphalt, predicting and controlling packing properties of aggregates is of prime importance. Aggregate packing is mainly influenced by five parameters (e.g. Caquot [1], Baron [2], Larrard [3-6], Corté & Di Benedetto [7]):

- Gradation (continuously-graded, gap-graded, etc.)
- Shape (flat & elongated, cubical, round)
- Surface micro-texture (smooth, rough)
- Type & amount of compaction effort (static pressure, impact or shearing)
- Layer thickness (e.g. Cooper et al. [8])

This paper mainly focuses on the first parameter (gradation) by optimizing the combination of fine and coarse fractions, resulting in an interactive network of coarse particles in the asphalt, indirectly providing the strongest mix resistance (Roque [9], Kim et al. [10]) and in particular the highest mix modulus.

Apart from the previous gradation-related considerations, the ability of SBS polymer modification to reduce fatigue cracking and aging is well recognized (Baaj [11], Dressen [12]), but the high modulus required for perpetual pavement base structures usually calls for hard binders (and thus slightly higher binder content to preserve fatigue resistance), which have viscosity and compatibility issues with conventional SBS. Therefore, at EIFFAGE Travaux Publics we set out to combine both optimal aggregate interlock and the use of SBS polymers, in order to obtain both very stiff and fatigue-resistant polymer modified base or binder course material in a single formulation.

2. THEORETICAL BACKGROUND ON AGGREGATE PACKING

Many researchers have developed empirical methods of relating void content in mineral aggregate to the gradation or proposed "ideal" theoretical gradations which aim for maximum solid volume density. These theoretical curves are always continuously-graded curves, and they generally have a parabolic shape [13-14]. They have a similar shape when placed on the same plot. The most prevalent theoretical "ideal" gradation is based on the following empirical equation:

- $P = 100(d/D)^b$ equation (1)

where P: percentage of aggregate, by weight, passing through a particular sieve;
d: size of openings in the particular sieve, in millimetres;
D: maximum size of aggregate particles in the gradation, in millimetres;
b: coefficient. Nijboer [13] & Yoder [14] found that the maximum density of any continuously-graded compacted mix is obtained when b equals about 0.45 or 0.5.

Despite equation (1), Lees [15] emphasized that the correct proportions for minimum void content must inevitably be affected by changes of aggregate shape from source to source and from size to size, by the level of compaction effort applied, by the presence of lubricating coatings, and by size and shape of the section in which the material is to be used. Some more general concepts of aggregate packing were first developed by Caquot in 1937 [1], and then by contemporary researchers since the 1970s, especially in the field of cement concrete [3-6, 16]. A state of the art of basics has been recently presented by Perraton [17] and Olard & Perraton [18-19], transposing these concepts to the field of asphalt mix design. The following sub-sections are partially drawn from these papers.

2.1. Basic notions associated with binary gradings

The first essential step, before studies of multi-component systems may be undertaken, is to understand the factors involved in the relationship between aggregate proportions and porosity in 2-component systems.

When studying porosity of mixes composed of two aggregates with differing yet one-dimensional individual sizes, Caquot [1] first highlighted in 1937 the importance of two types of interparticle interaction on the void index (e=(volume of voids)/(volume of particles)): the so-called "wall effect" and "interference effect" –the latter is also known as the "loosening effect".

The "wall" effect relates to the interaction between particles and any type of wall (pipe, formwork, etc.) placed in contact with the granular mass. Let us consider a uniform, two-aggregate mix. The two component fractions only differ by their average particle dimension, i.e. one for the coarse aggregate particles and another one for the fine particles. When a few coarse particles are added to an infinite volume of fine particles, the void index of the blend decreases (Figure 1, left). Yet, coarse particles disturb locally (at the interface) the arrangement of fine particles, whose porosity increases in proportion to the particle surface area of incorporated coarse aggregate (Caquot [1], Chanvillard [20]).

The "interference" (or "loosening") notion can be illustrated by focusing on the effect induced by introducing a few fine particles into an infinite volume of coarse particles. As the amount of fine particles increases, at some point coarse particles are forced apart by loosening, thus modifying their spatial configuration (Figure 1, right).

If the average particle dimension of fine particles (d_{FINE}) is small enough compared to the one of coarse particles (d_{COARSE}) ($d_{FINE}/d_{COARSE} < 0.2$), the wall effect is linear and satisfies the superposition principle. Otherwise, the interference/loosening effect is never linear and therefore difficult to frame easily (Baron [2]).

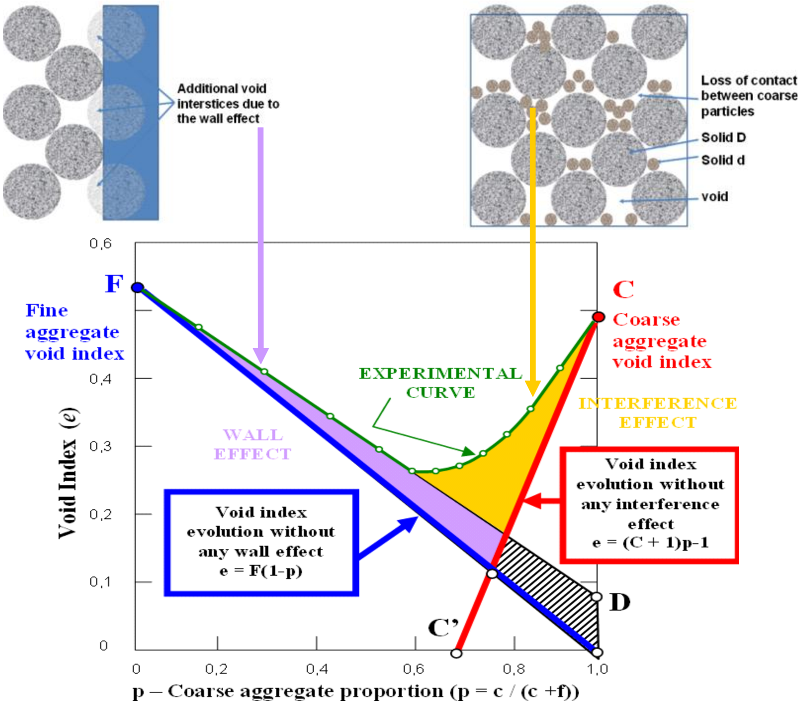

Figure 1: Wall and interference effects, Powers [21]. f and c are respectively the solid volumes of fine and coarse aggregates (f+c=1); F (resp. C) = void index of fine (resp. coarse) aggregates.

2.2. Evolution in aggregate porosity vs. average particle dimension

Powers (21), Furnas (22) and Oger (23) showed the dependence of the shift in void index (e) vs. the coarse aggregate portion in a binary combination on the ratio of average particle sizes. Figure 2 reveals that as the ratio of average fine aggregate dimension to average coarse aggregate dimension rises, the interaction effects also become more significant. In order to reduce interactions of intermediate particles on the coarsest ones in the mix, it is crucial to limit both their size and quantity, and fill air voids by a higher fraction of fine particles instead. In addition, it appears that if the ratio between successive sizes in a gap gradation is chosen so as to give the most drastic reduction in voids, that reduction would be equal to, or possibly greater than, the most drastic reduction in voids for a continuous gradation.

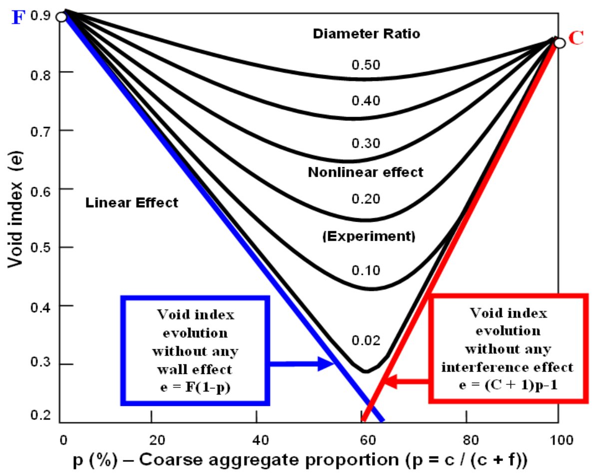

Figure 2: Effect of diameter ratio (d_{FINE}/d_{COARSE}) on void index (e) of binary granular blends [21-23].

2.3. Ideal case of a mix of an extremely fine aggregate with a coarse aggregate

For a situation in which one aggregate is very fine in comparison with the other, Baron [2] proposed to describe the void index variation of a mix by means of three straight lines (Fig. 3). Baron defined two thresholds, p_X and p_T, indicating the critical concentrations enabling elimination of interference effects. Within a binary mix of coarse and fine particles, threshold p_X corresponds to the maximum coarse aggregate concentration that can be combined with fine aggregate without altering the fine aggregate arrangement, whereas threshold p_T is equal to the maximum fine aggregate concentration ($1-p_T$) for combination with coarse aggregate so as not to interfere with the coarse particle layout.

Depending on whether the granular mix has a high ($p < p_X$), medium ($p_X < p < p_T$) or low ($p > p_T$) content of fine particles, void index variation can be defined according to three distinct laws:

- High content of fine particles in the mix, $p < p_X$:
  - $e = F(1 - p) + Dp$ equation (2)

where F is the void index of fine particles and D is a parameter of the wall effect (Fig. 3).

- Low content of fine particles in the mix, $p > p_T$:
  - $e = (C + 1)p - 1$ equation (3)

where C is the void index of coarse particles (Fig. 3).

- Medium content of fine particles in the mix, $p_X < p < p_T$:
  - $e = Ep$ equation (4)

where E is a coefficient determined graphically (Fig. 3).

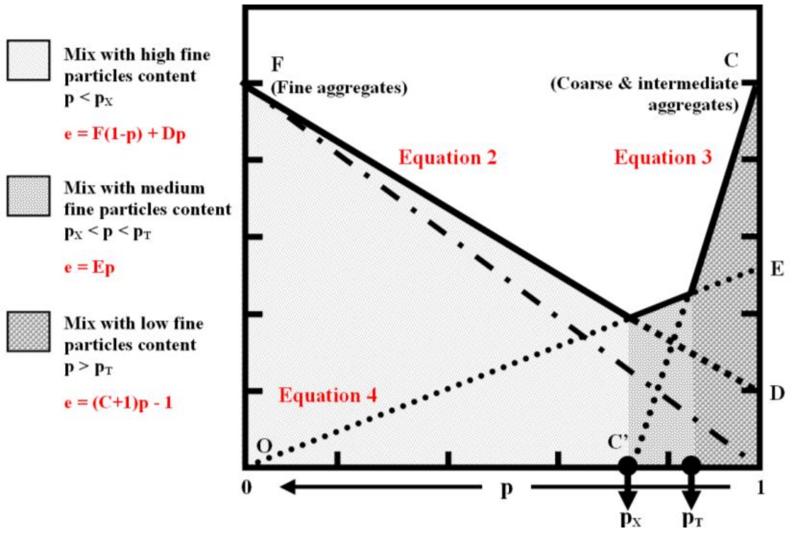

Figure 3: Void index variation (e) in the case of a two-aggregate mixture, one of which is very fine compared to the other (according to Baron [2]).

3. OBJECTIVE OF THE PRESENT STUDY

Baron's approach for optimal aggregate packing, first developed in the field of high-performance cement concrete in 1982 [2], was transposed to the field of asphalt concrete at the EIFFAGE research centre in France. The main goal was to evaluate the relevance of such an approach in the asphalt field with typical French materials. The underlying question was: can we develop high-performance dense asphalt by means of optimized gap grading? And, likewise, can we use more specific guidelines for aggregate structure selection?

After publication of the first encouraging results obtained by Perraton [17] and Olard & Perraton [18-19], a large experimental program has been launched at the EIFFAGE research centre, including the evaluation of compactability, moisture resistance, rutting resistance, stiffness modulus as well as fatigue resistance.

4. MATERIALS

Two pure paraffinic bitumens coming from the same crude and refinery were investigated: 35/50 and 35/45B ("B" stands for "semi-blown") pen grade bitumens. Two PMB's made from these two pure bitumens with 2.5% SBS (proprietary crosslinking process) were also investigated. Eventually, the analysis of recovered aged binder from RAP aggregates was also carried out. Table 1 presents the results of conventional tests (Penetration at 25°C and Ring and Ball Softening Point) performed on these different binders.

Only one typical French aggregate nature was considered: diorite crushed aggregate fractions (0/2, 0/4 and 10/14 mm) from the "Noubleau" quarry. Limestone filler from the "S^t Hilaire" quarry in France was also considered. Moreover, some reclaimed asphalt pavement (RAP) aggregates from the "Touraine Enrobés" asphalt plant (EIFFAGE TP Centre) were used. Table 2 gives gradation curves of each granular fraction. The average dimension of filler was determined by means of a Coulter® particle size analyzer.

Table 1: Conventional Results on the Studied Binders

Binder	Pen 25°C (mm/10) NFEN1426	Softening Point R&B (°C) NFEN1427
35/50	38	53.5
35/45B	37	62

35/50+crosslinked 2.5%SBS	38	62.2
35/45B+crosslinked 2.5%SBS	33	71
aged RAP binder	10	71.2

Table 2: Passing Percentage and Average Particle Size for Each Tested Granular Fraction

Sieve (mm)	Passing (%)				
	filler	Noubleau aggregates			RAP Tours
		0/2	0/4	10/14	
16				100	100
14				93	97
12.5				77	89
10				22	72
8				5	63
6.3			100	1.7	55
4		100	96	0.4	45
2		97	54	0.3	32
1		68	37	0.2	23
0.5		45	25	0.2	17
0.25	100	31	18	0.2	10
0.125	94	22	13	0.2	10
0.08	83	17	10	0.2	9
Average particle dimension, hereafter named d_{50}					
Diameter (mm)	0.025	0.6	1.9	11.5	5

5. TESTS USED FOR CHARACTERIZING ASPHALTS

Many laboratory tests were conducted on asphalt concretes, including:

• Compactability, measured with a gyratory compactor (GC), as per the requirements of NF EN 12697-31 standard. This test gives a good idea of job-site density values. Conducted ahead of other mechanical tests, this test is used to make a preliminary selection of asphalts and to optimize asphalt composition (Harman et al. [24]).

• Water resistance, measured from the so-called Duriez test (NF EN 12697-12) which consists of a direct compression test on two sets of six cylindrical samples, one set of which was tested after conditioning in water. If the mean ratio of results after and before conditioning is greater than a certain value, the material is deemed to be acceptable. This ratio is the French counterpart of Tensile Strength Ratio value with Marshall samples.

• Rutting resistance, evaluated at 60°C with the French Rut Tester in accordance with NF EN 12697-22 (specimens subjected to repeated passes at 1 Hz of a wheel fitted with a tyre, inducing permanent deformation).

• Complex modulus at 15°C-10 Hz (NF EN 12697-26) using cylindrical specimens.

• Fatigue resistance at 10°C-25 Hz (NF EN 12697-24) using a strain-controlled test on trapezoidal specimens. A conventional fatigue criterion, referred to as N_{f50}, was used; according to which, fatigue life corresponds to the number of cycles for which stiffness modulus decreases to 50% of its initial value. The strain amplitude value leading to failure at one million cycles is hereafter referred to as ε_6 (used in French design method SETRA-LCPC [25]).

6. AGGREGATE PACKING OPTIMIZATION RESULTS

The use of a single-gap or even a double-gap graded curve [26] may help obtain very dense asphalt mixes with high coarse aggregate packing (lower interaction between intermediate and coarse particles, cf. Figure 3). This sort of single-gap graded curve was investigated with Noubleau aggregates in the framework of this study. Figure 4 illustrates the iterative aggregate packing optimization of a quaternary 10/14-0/4-0/2-filler blend (10/14 mm, 0/4mm, 0/2 mm and filler), using a gyratory compactor (GC) on aggregates only – without any bitumen – as detailed before. This packing optimization procedure consists of three sets of GC measurements at 20 gyrations (after 20 gyrations without any bitumen, phenomena such as abrasion or attrition do occur, see Figure 5):

• the first set of GC tests is performed to determine the optimal 10/14-0/4 binary blend (p=80% (*i.e.* 80% 10/14 and 20% 0/4), cf. Figure 4). A slight difference is found between calculated $e(p_X)$ and $e(p_T)$, on the one hand, and experimental data, on the other hand, because of the ratio $d_{50}(0/4)/d_{50}(10/14) = 0.165$ causing some interference (Fig. 3);

• the second set of GC measurements is performed so as to determine the optimal 10/14-0/4-0/2 tertiary blend, which is considered as a binary blend: the previous 80% 10/14-20% 0/4 blend is considered as the "coarse fraction", while the 0/2 fraction is considered as the "fine fraction". The optimal amount of coarse particles is 80%;

• the third and last set of GC tests is performed to determine the optimal 10/14-0/4-0/2-filler quaternary blend (in this case, p_T=86.5%, Fig. 4). Therefore, the resulting optimal 10/14-0/4-0/2-filler quaternary blend is the following:

- 10/14 content: 55.3% (=0.865*0.64)
- 0/4 content: 13.9% (=0.865*0.16)
- 0/2 content: 17.3% (=0.865*0.2)
- added filler content: 13.5% (=1-0.865)

For both practical and economical reasons at the asphalt plant, filler content was fixed at 5%. Finally, two gap gradations were studied: the first one without RAP as determined above, the second one with 10% RAP. Figure 6 gives the gradation curves of each tested asphalt mix, along with the one obtained with 10% added filler.
Let us generalize the aggregate packing optimization technique in the case of a multi-component system: depending on nominal maximum particle size of the designed mix and therefore on the number of used granular fractions (*n*), the optimization sequence can be performed in *n*-1 steps.

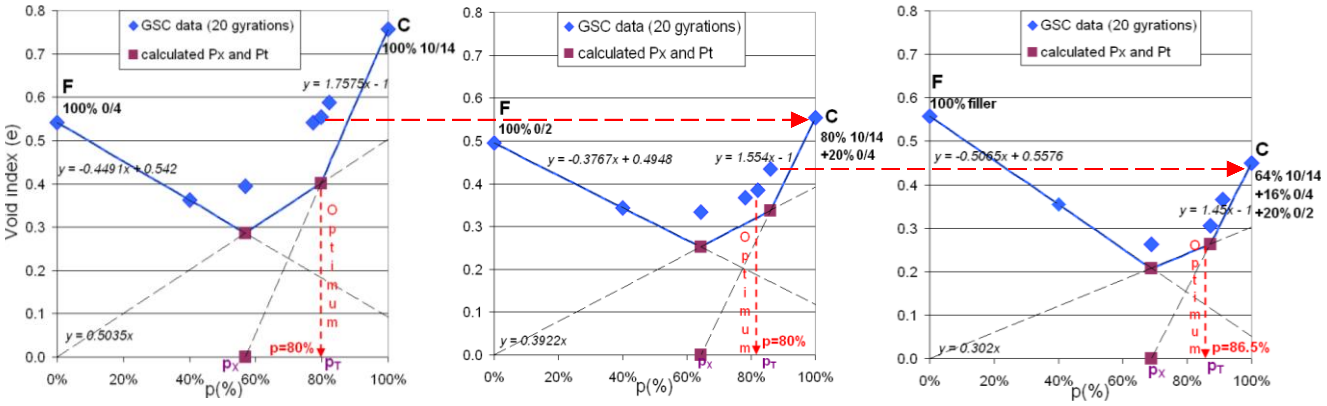

Figure 4: 3-step iterative optimization of the 10/14-0/4-0/2-filler quaternary Noubleau aggregate blend.

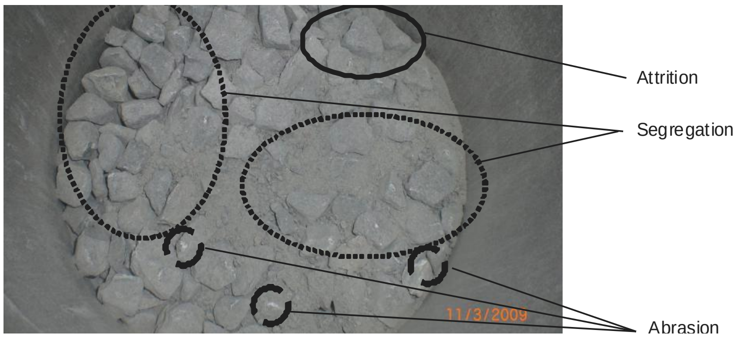

Figure 5: Attrition, segregation and abrasion observed at 100 gyrations in the gyratory shear compactor (GC).

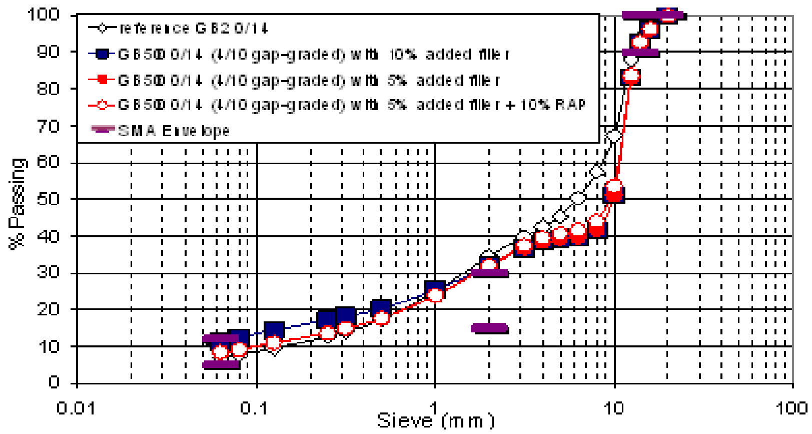

Figure 6: Gap-gradation curves (referred to as "GB5") for the optimal quaternary aggregate blends vs. that of the continuously graded reference "GB2".

7. PERFORMANCE-RELATED CHARACTERIZATION AND RELATED DISCUSSION

In the framework of our study with Noubleau mixtures, a 4% binder content by weight of aggregate (10% vol.) was used. Table 3 presents the performances of the so-called GB5® (gap-graded curves) made from Noubleau aggregates, compared to the reference continuously-graded Grave Bitume GB2 material normally used in France. The French specifications for the continuously-graded "Grave Bitume 2" (GB2) and "Enrobé à Module Elevé 2" (EME2) are given as well. The reference EME2 material consists in a continuously-graded curve and relies on the use of hard binders (penetration at 25°C < 30 dmm) at a content of 5.5-6.0% by weight of aggregates to preserve fatigue resistance. EME2 is traditionally used as base course material in Perpetual Pavement design in France.

Table 3 – Performances of the GB5 materials compared to the reference GB2 material. Noubleau aggregates with a 4% binder content by weight of aggregate (%vol.=10.0%). 'VMA' stands for Voids in Mineral Aggregates

<table>
<tr><th colspan="3">Formula</th><th colspan="2">GC
100 gyrations</th><th colspan="2">Duriez Test</th><th rowspan="2">Rut Depth (mm)
3 10^4 cycles</th><th rowspan="2">E (MPa)
15C-10Hz</th><th rowspan="2">ε_6□ (10^{-6})
10C-25Hz</th></tr>
<tr><th></th><th>Binder nature</th><th>%RAP</th><th>%Air</th><th>VMA</th><th>R(MPa)</th><th>Moist. Res.(%)</th></tr>
<tr><td colspan="3">Specifications for
"Grave Bitume 2" (GB2)</td><td><10%</td><td>-</td><td>-</td><td>>70%</td><td><10%</td><td>>9000</td><td>>80</td></tr>
<tr><td colspan="3">Specifications for "Enrobé à Module
Elevé 2" (EME2)</td><td><6%</td><td>-</td><td>-</td><td>>70%</td><td><7.5%</td><td>>14000</td><td>>130</td></tr>
<tr><td>GB2</td><td rowspan="3">35/50</td><td>0</td><td>9.7</td><td>19.7</td><td>10.1</td><td>93</td><td>4.1</td><td>14,200 at
4.1% air</td><td>86</td></tr>
<tr><td rowspan="5">GB5®</td><td>0</td><td>5.9</td><td>15.9</td><td>11.8</td><td>83</td><td>5.1</td><td>16,500 at
2.7% air</td><td>89</td></tr>
<tr><td>10</td><td>7.2</td><td>17.2</td><td>12.1</td><td>91</td><td>4.1</td><td>16,600 at
2.7% air</td><td>90</td></tr>
<tr><td>35/50
+2.5%SBS</td><td rowspan="3">0</td><td>5.7</td><td>15.7</td><td>12.3</td><td>93</td><td>2.4</td><td>15,600 at
3.2% air</td><td>110</td></tr>
<tr><td>35/45B</td><td>5.8</td><td>15.8</td><td>12.7</td><td>92</td><td>2.5</td><td>13,100 at
2.9% air</td><td>115</td></tr>
<tr><td>35/45B
+2.5%SBS</td><td>5.7</td><td>15.7</td><td>13.1</td><td>91</td><td>3.0</td><td>13,700 at
2.5% air</td><td>130</td></tr>
</table>

7.1. Compactability evaluated using Gyratory Compactor (GC)

Compactability is significantly improved: densities are increased by 2.3% up to 4.0%. Yet, the use of 10% (continuously graded) RAP slightly decreases compactability of the GB5 mix (7.2% air voids at 100 gyrations, instead of 5.9%), indicating that non-negligible interference effects occur between aggregate particles. This excellent compactability of such GB5 has been confirmed on site during many experimental roadworks in France and Spain.

7.2. Compressive strength & moisture resistance assessed by Duriez test

Direct compressive strength is increased by 1.2 to 3 MPa. Moisture resistance ("Duriez ratio"), which is far above the minimum specification value for a typical GB2 mix, does not seem to be influenced by the gradations and PMBs used.

7.3. Rutting resistance assessed from French Wheel Tracking test

GB5 mixes exhibit high resistance to rutting for two main reasons: the first reason is related to the well-interlocked and dense mixtures obtained from the optimization of aggregate packing; the second reason lies in the fact that semi-blown and polymer modified bitumens give high resistance to rutting at high temperatures, especially at 60°C.

7.4. Complex Stiffness Modulus

For a fixed bitumen nature and content, complex stiffness modulus of such well-interlocked and dense mixtures, measured at 15°C-10 Hz, is increased by almost 20%. The proposed aggregate packing optimization procedure could be used in the framework of high-modulus mix design with slightly softer grades than usual (Penetrability at 25°C>30), thus enhancing both the reclaimability and fatigue resistance of asphalts mixes.

7.5. Fatigue resistance

For a fixed bitumen nature and content, fatigue resistance measured at 10°C-25 Hz is hardly influenced by aggregate packing optimization. On the contrary, the binder nature greatly influences fatigue resistance: the use of both polymer modification (2.5% cross-linked SBS) and semi-blown bitumen lead to an increase of ε_6 value by about 24-29 10^{-6} individually and up to 44 10^{-6} when combined. Note that the ε_6 value of 130 10^{-6} (at 10°C-25 Hz), obtained with 35/45B bitumen modified with 2.5% cross-linked SBS, is an incredibly high value for an asphalt concrete with only 4% binder content in France.

8. ECO-FRIENDLY ALTERNATIVE TO EME2

An alternative to the traditional high-modulus and high-binder content EME2 (for which binder content is about 5.5% to 6%) may be proposed for long-lasting and cost-effective asphalt mixes. Considering the very encouraging results presented in Table 3 (with only 4% of bitumen by weight of the aggregate), at EIFFAGE Travaux Publics we set out to combine both optimal aggregate interlock and the use of semi-blown and/or SBS modified bitumens, so as to obtain both very stiff and fatigue resistant base/binder course material in a single formulation.
This has been done with many aggregate natures (from France and Spain) by using either single-gap or double-gap graded curves and a tremendous number of polymer modified and semi-blown bitumens. The performances obtained are close to the specifications required for EME2 (stiffness modulus of 14,000 MPa at 15°C and a fatigue resistance of 130 microstrains at 10°C), with a significantly lower bitumen content (in the range of 3.8% to 4.8% by weight of aggregate). This innovative mix design, which is referred to as GB5®, has been patented.
The two following sub-sections present a case study with comparative pavement design & environmental impact.

8.1 Hypothesis for pavement design & material cost

The French method for pavement design has been used. Calculations presented hereafter rely on the use of the so-called ALIZE software. The adjustment factor, denoted k_c, that is used for determining the strain value $\varepsilon_{t,ad}$ considered acceptable at the bottom of the GB5® base course, is considered as equal to 1.3 (typical value for a French GB3/GB4 Grave Bitume base layer). Furthermore, the k_c=1 hypothesis is made when considering conventional high modulus asphalt concretes (referred to as EME2), which use very low-Pen grade bitumens (Penetrability at 25°C in the range 10-30 dmm). Broadly speaking, this k_c coefficient adjusts the results of the computation model in line with the behaviour observed on actual pavements of the same type. For more details, the value of this coefficient, for bituminous materials, is detailed in the French design manual for pavements structures [25].
In order to compare the costs of road structures with traditional EME2 or innovative GB5® base course, the following orders of magnitude were taken into account for material costs:

- cost of 10/20 ≈ 35/50 pen grade bitumen + 40-60 €/ t
- cost of 35/45B ≈ 35/50 pen grade bitumen + 40-60 €/ t
- cost of 35/50 + 2.5%SBS ≈ 35/50 pen grade bitumen + 150-170 €/ t
- cost of 35/45B + 2.5%SBS ≈ 35/50 pen grade bitumen + 200-220 €/ t

The apparent densities are respectively ρ(BBM)=2.42 t/m^3, ρ(GB5)=2.47 t/m^3 and ρ(EME2)=2.49 t/m^3.

8.2 Comparative pavement design, corresponding costs & related environmental impacts

Table 4 presents a comparative pavement design using the ALIZE software and considering a "TC620" traffic category, a 4 cm-BBM overlay and a "PF3" pavement formation class. The materials are the same ones listed in Table 3, together with their respective performances.
Innovative GB5 materials do have very positive environmental and economic impacts when considering the reduced base layer thickness and the reduced quantities of binder and aggregate required per square metre. Insofar greenhouse gas emissions (GGEs) are concerned, the carbon dioxide (CO_2) quantity (main GGE generated during roadwork) associated with aggregate, pure bitumen and modified binder is respectively equal to 10, 285 and 310 kgCO_2/t. Therefore, the proposed high-performance GB5 base layers may lead to a reduction in CO_2 emissions of almost 30% in comparison with traditional EME2-based pavement design (see Table 4).

Table 4: Comparative pavement design, corresponding costs & related environmental impacts (per m^2)

Thick Bituminous Pavement Structures with Noubleau materials. "TC620" Traffic Category. 4 cm-BBM Overlay. "PF3" Pavement Formation Class.				
	Traditional Solution	Innovative GB5® Solutions		
	EME2 Binder content=5.7%	**GB5 35/45B** Binder content=3.9%	**GB5 35/50+2.5%SBS** Binder content=3.9%	**GB5 35/45B+2.5%SBS** Binder content=3.9%
Overlay	4 cm BBM	4 cm BBM	4 cm BBM	4 cm BBM
Base course	16 cm EME2	14 cm GB5	12 cm GB5	10 cm GB5
Difference in base layer thickness	Reference	- 2 cm (- 10%)	- 4 cm (- 20%)	- 6 cm (- 10%)
Difference in aggregate quantity		**- 10%**	**- 20%**	**- 30%**
Difference in bitumen quantity		**- 28%**	**- 39%**	**- 48%**
Difference in materials cost/m^2		**-23%**	**-27%**	**-38%**

Difference in kg CO_2eq. /m^2		**-24%**	**-17%**	**-28%**

9. IN-SITU VALIDATION OF THE PROPOSED MIX DESIGN IN THE YEAR 2010

10 full scale suitability tests were carried out on several EIFFAGE plants in 2010 before generalizing the technique on each of the 180 EIFFAGE sites. These preliminary field trials were able to validate the technical choices. In particular, the high compactability of GB5 mixes (with either single-gap or double-gap gradations) has so far been confirmed.

Figure 7: Paving GB5® 0/14mm high-performance asphalt with Cemex aggregates, 35/45B binder and 35% RAP (reclaimed asphalt pavement) near Toulouse. In-place density: 97%; modulus E*(15°C-10 Hz): 15,100 MPa.

10. DEVELOPMENT AND LARGE SCALE ROADWORKS OF THE YEAR 2011

The Year 2011 consisted in generalizing the proposed GB5® mix design on most French EIFFAGE sites. Several aggregate natures were studied. Four main nominal maximum particle sizes (NMPS) were used: 11 mm, 14 mm, 16 mm and 20 mm. Both single-gap graded curves and double-gap graded granular curves were successfully investigated. Semi-blown 20/30, 35/50, 50/70 and 70/100 pen grade binders were used. SBS modification was also carried out (referred to as Biprene® and Orthoprene®, with a proprietary cross-linking procedure) for most of our full scale suitability tests so far. In PMB's compositions, the SBS content was in the range 2.5% to 7%. The overall binder content (virgin + aged binders) was generally in the range 4.0% to 4.5%.
GB5 mixes were applied by the paver and very easily compacted by double-roll vibrating compactors (Fig. 7, 8 & 9). There was no need for pneumatic tyre rollers, with the final density in the range between 2% to 6%. The layer thickness was between 6 and 16 cm thanks to the gap gradations used.
130,000 tons of GB5® asphalts have been paved so far, corresponding to a saving of about 1,300 tons of bitumen in comparison with the reference EME2 (high-modulus high-binder content mix) typically used as base course material in Perpetual Pavement design in France. Furthermore, more than 3,500 tons of PMBs have been produced and used so far in base courses, whereas their use was limited until now to surface courses for economic reasons.
Figures 8 & 9 illustrate two main large scale roadworks on French highly trafficked toll highways.
Figure 8 specially shows a 31,000-ton GB5® 0/14 mm roadwork on the A41N & A43 toll highways (AREA network) in the alpine area. A 0/14 mm gradation with a 4/10 mm single gap with ‘Budillon-Rabatel’ aggregate and 15% RAP was used. SBS-modified binders Biprene® and Orthoprene® were both used on different sections at a content of 3.5% by weight of the aggregate (overall binder content = 4.3%). Within the framework of these large scale roadworks, the laboratory results were found to be most encouraging:

- GB5® Biprene® 41: E*(15ºC-10Hz)=17,500 MPa & fatigue resistance ε_6(10°C-25Hz) =133 10^{-6}
- GB5® Orthoprene®: E*(15ºC-10Hz)=11,000 MPa & fatigue resistance ε_6(10°C-25Hz) =205 10^{-6}

Figure 8: 31,000-ton GB5® 0/14 roadwork on the French A41N & A43 toll highway (AREA network) in the Alpine area. SBS-modified binders Biprene® and Orthoprene® were both used.

Figure 9: 4,000-ton GB5® 0/14 roadwork on the French A13 toll highway (SAPN network, A13-RD613 section) in Normandy. 35/45B bitumen and SBS-modified binder Biprene® were both used.

After our trials in 2010-2011, these different sites were revisited in order to assess the condition of the pavement and/or to take cores to assess density and complex or secant modulus of these field cores in IDT (indirect tension) mode. This follow-up is very encouraging and confirms the great performances initially obtained in the laboratory.
Last but not least, in the framework of the so-called Road Innovation Charter procedure of SETRA (French acronym for the "Highways Technical Studies Department"), the innovative GB5 project was awarded in 2010. In 2011, a Road Innovation Charter was signed with SETRA and several General Councils and companies in charge of toll highways. From then on, several GB5 projects were undertaken in different French climate zones under very heavy traffic. A five-year follow-up by SETRA is planned for validation of this new technique.

11. CONCLUSIONS

Effective particle packing seeks to select proper sizes and proportions of small particle shaped materials to fill larger voids. These small particles in turn contain smaller voids that are filled with smaller particles, and so on. Such well-interlocked gap-graded mixtures have greater friction angles than the continuously dense-graded mixtures. Starting from such basic concepts associated with granular combinations, the aggregate packing methods first developed in the field of high-performance cement concretes were successfully transposed and adapted to the field of asphalt concretes, and enabled the development and design of high-performance asphalts. The proposed mix design method is now referred to as the GB5® mix design method in France.

A so-called "Grave Bitume GB2" (continuously-graded) mixture, traditionally used for base courses in France, was studied, acting as a "reference" material. The first laboratory assessments of the optimal single or double-gap graded mixtures designed in this study were found to be very encouraging:

- compactability, evaluated with gyratory shear compaction, is remarkably improved. In the framework of this work, with the same compaction energy, density values are more or less 4% higher,
- moisture susceptibility assessed using the so-called Duriez test does not appear to be influenced by the proposed optimal gradations. Further work is planned to confirm this point,
- compressive strength value at 18°C is increased by about 15%,
- rutting resistance at 60°C-1 Hz is hardly influenced by the optimal gradations used. Yet, the ability of blown bitumens or SBS polymers to reduce susceptibility to rutting was once again evidenced.
- secant stiffness modulus measured at 15°C-10 Hz is significantly increased by almost 20%. The proposed procedure to optimize the aggregate packing characteristics could be used in the framework of high-modulus mix design (e.g. French 'EME' ("enrobe à module élevé")) with slightly softer grades than usual (Penetrability at 25°C>30), thus enhancing both reclaiming ability and fatigue resistance of such asphalt concretes
- the fatigue resistance of GB5® asphalts, evaluated at 10°C-25 Hz and for a fixed considered bitumen, appears comparable to the one of the reference GB2 material. In addition, as the single or multiple gap-graded asphalt mixtures have really enhanced stiffness moduli, the use of softer bitumen grades or semi-blown binders or PMB yields obtaining great fatigue resistance. This particular combination of innovative single or double-gap graded curves with semi-blown and/or SBS modified bitumens, leading to highly stiff and fatigue resistant polymer modified base or binder course materials in a single formulation, has been recently patented by EIFFAGE Travaux Publics.

To some extent, such GB5® asphalts used for base or binder courses could provide real long-life pavements that do not deteriorate structurally, needing only timely surface maintenance to maintain their overall condition.

Finally, GB5® asphalts were successfully applied, mainly in 2011, on-site on many experimental roadworks with or without RAP, at either a hot (160°C) or warm (125°C) or even half-warm (90°C) temperature: almost 130,000 tons of GB5® asphalts have already been paved in France on highly trafficked highways and toll motorways.

This rapid development and the numerous large scale roadworks of GB5® asphalts, with SBS in base or binder courses, was possible to the extent that, in particular, the proposed GB5® mix design relies on a rather low binder content (from 4.0 to 4.5% generally). Indeed, the optimization of aggregate packing first of all enables this rather low binder content to be achieved, and thus makes it economically possible to use SBS in base courses, leading to an alternative concept of 'perpetual' or long-lasting pavement.

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