GB5: INNOVATIVE DESIGN OF HIGH-PERFORMANCE ASPHALT MIXES FOR LONG-LIFE & COST-EFFECTIVE PAVEMENTS BY OPTIMIZING AGGREGATES & USING 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 1970's, were transposed to the field of asphalt concretes. These concepts, associated with the use of the gyratory compactor on aggregates only, enabled the development of a new laboratory design procedure of dense high-modulus asphalt concretes. These mixes are characterized by great coarse aggregate interlock and no need for low penetration grade bitumens to obtain the EME2 specifications requirements, in particular the 14,000MPa stiffness modulus value at 15°C.
Besides, the use of only 3.9% of SBS modified bitumen combined with such an optimized aggregate packing leads to the design of the so-called GB5 material, showing excellent compactability, very high stiffness modulus and above all high fatigue resistance in a single formulation, allowing for reduced pavement thickness and greater longevity.
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. Apart from these results, the paper also addresses the successful application of this new material on different job sites, located mainly in France.
The paper illustrates that the proposed innovative material may be potentially considered from now on as a relevant solution for sustainable long life pavements that do not deteriorate structurally, needing only timely surface maintenance.

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 an asphalt mix, 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 mix, providing indirectly 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 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), having 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 developed empirical methods of relating void content in mineral aggregate to the gradation or proposed "ideal" theoretical gradations which aim at maximum solid volume density. These theoretical curves are always continuously-graded curves and they generally have a parabolic form [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 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 [16] emphasized that 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], then by contemporary researchers since the 1970's, especially in the field of cement concrete [3-6, 15]. A state of the art of basics has been recently presented by Perraton [17] and Olard & Perraton [18-19], transposing those concepts in 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 called "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 composing fractions only differ by their average particle dimension, i.e. one for the coarse aggregate particles and another one for the fines. When adding a few coarse particles into an infinite volume of fines, the void index of the blend reduces. Nevertheless, coarse particles disturb locally (at the interface) the arrangement of fines whose porosity is increasing (i.e. an increasing void index). This local porosity increase is proportional to the particle surface area of incorporated coarse aggregate (Caquot [1], Chanvillard [20]). Figure 1 (left) indicates the wall effect on the void index of a granular combination when raising coarse fraction within a binary mix.

By increasing the fraction of coarse particles within the overall mixture, at a certain point a specific quantity of small particles ends up entrapped in the interstices delimited by coarse particles. Fine aggregate void index increases due to interference: the arrangement of fine particles will depend not only on surface areas of coarse particle walls (wall effect), but also on the actual layout of these particles, i.e. the shape of their interstices.

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

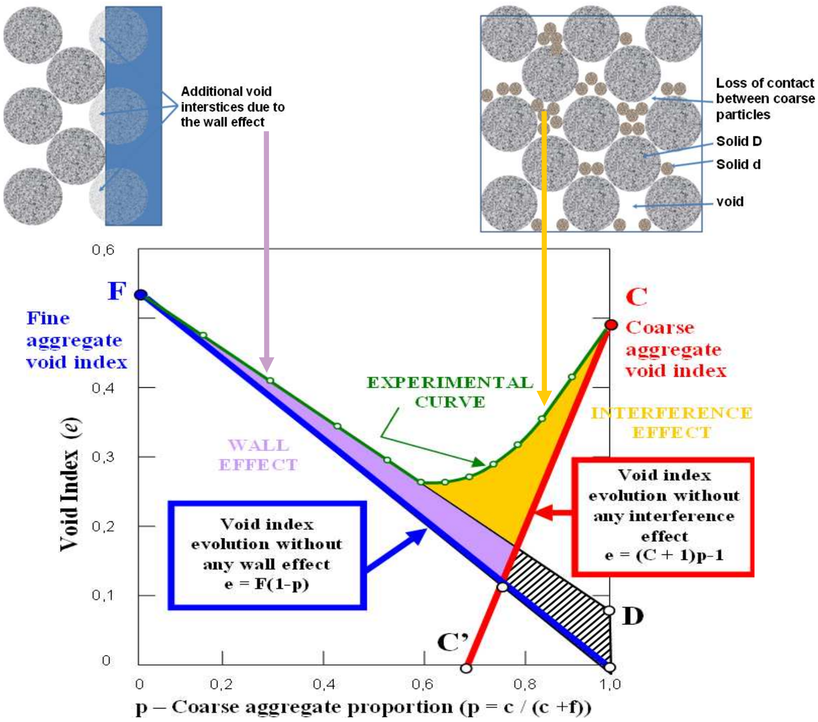

Figure 1 – Wall and interference effects, Powers [21]. f and c are respectively the solid volumes of fine and coarse aggregates (f+c=1); F (resp. C) = void index of fine (resp. coarse) aggregates.

2.2. Evolution in aggregate porosity Vs. average particle dimension

Furnas [12] showed the dependence of the shift in void index (e) Vs. 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, interaction effects become more significant as well. In order to reduce interactions of intermediate particles on the coarsest ones in the mix, it is crucial to limit both their size and amount and fill air voids by a higher fraction of fines instead. In addition, it appears that if the ratio between successive sizes in a skip 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.

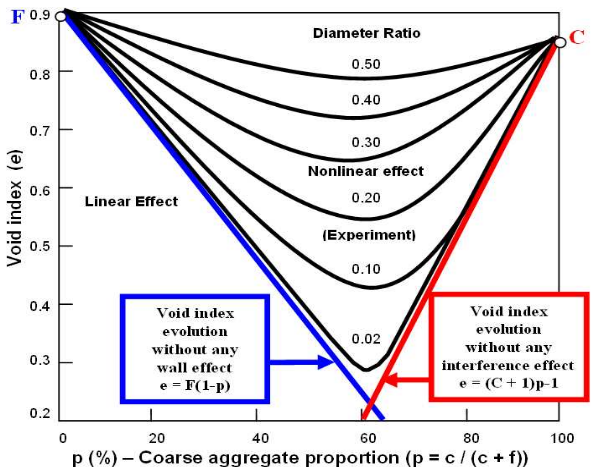

Figure 2 – Effect of diameter ratio (d_{FINE}/d_{COARSE}) on void index (e) of binary combinations of coarse (c) and fine (f) aggregates (Furnas [12], Powers [21], Oger [22] and Perraton [17]).

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 (d_{FINE}/d_{COARSE} ~ 0.008), 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, which indicate the critical concentrations that allow eliminating interference effects. Within a binary mix with 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 fines, void index variation can be defined according to three distinct laws:

- High content of fines in the mix, $p < p_X$:
  - $e = F(1 - p) + Dp$ [2]

  where F is the void index of fines and D is a parameter of the wall effect (Fig. 3).
- Low content of fines in the mix, $p > p_T$:
  - $e = (C + 1)p - 1$ [3]

  where C is the void index of coarse particles (Fig. 3).
- Medium content of fines in the mix, $p_X < p < p_T$:
  - $e = Ep$ [4]

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

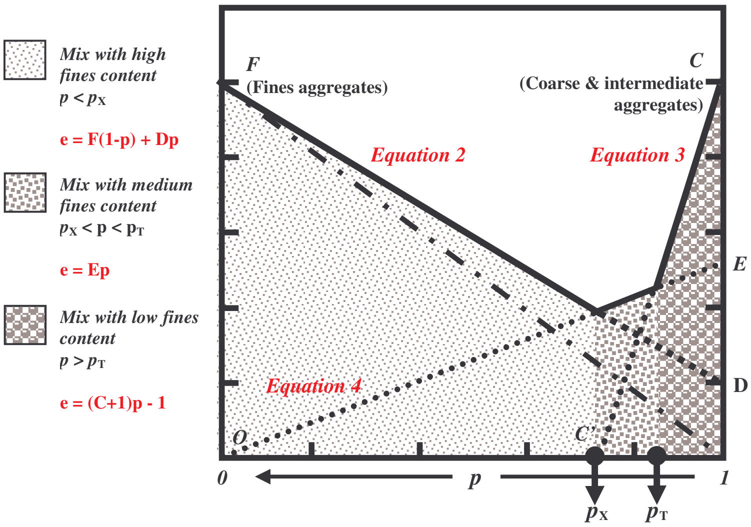

Figure 3 – Void index variation (e) in the case of a two-aggregate mixture, one of which is very fine compared to the other (according to Baron [2]).

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 relevancy 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 [16] and Olard & Perraton [17-18], a large experimental program has been launched at the EIFFAGE research centre, including the evaluation of compactability, moisture resistance, rutting resistance, stiffness modulus and fatigue resistance as well.

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) coming from the "Noubleau" quarry. Limestone filler coming from "S^{t} Hilaire" quarry in France was also considered. Moreover, some reclaimed asphalt pavement (RAP) aggregates coming from "Touraine Enrobés" asphalt plant (EIFFAGE TP Centre) were used. Table 2 gives gradation curves of each granular fraction. 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℃ (mm/10) NFEN1426	Softening Point R&B (℃) 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 ASPHALT CONCRETES

Many laboratory tests were conducted on asphalt concretes, including:

• Compactability, measured with the gyratory compactor (GC), following the requirements of NFEN 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 or screening of mixes, and to optimize asphalt mix composition (Harman et al. [23]).

• Water resistance, measured from the so-called Duriez test (NFEN 12697-12) which consists of a direct compression test on two sets of six cylindrical samples, one set of whom tested after conditioning in water. If 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℃ with the French Rut Tester in accordance with NFEN 12697-22 (specimens subjected to repeated passes at 1Hz of a wheel fitted with a tyre, inducing permanent deformation).

• Complex modulus at 15℃-10Hz (NFEN 12697-26) using cylindrical specimens.

• Fatigue resistance at 10℃-25Hz (NFEN 12697-24 standard) using strain-controlled test on trapezoidal specimens. Classical fatigue criterion, referenced as N_{f50}, was used. According to it, fatigue life corresponds to the number of cycles for which stiffness modulus decreases to 50% of its initial value. Strain amplitude value leading to failure at one million cycles is hereafter called ε_6 (used in French design method SETRA-LCPC [24]).

6. AGGREGATE PACKING OPTIMIZATION RESULTS

The use of a single-gap or even a double-gap graded curve [25] may be helpful to get very dense asphalt mixes with great coarse aggregate packing (lower interaction between intermediate and coarse particles, cf. Figure 3). Such 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 (10/14mm, 0/4mm, 0/2mm and filler), by using gyratory compactor (GC) on aggregates only – without any bitumen – as detailed before. This packing optimization 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):

• 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 one hand, and experimental data, on the other hand, because of $d_{50}(0/4)/d_{50}(10/14)$ = 0.165 ratio causing some interference (cf. Fig. 3);

• second set of GC tests 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%;

• third and last set of GC measurements is performed in order to determine the optimal 10/14-0/4-0/2-filler quaternary blend (in this case, p_T=86.5%, cf. Figure 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 on the asphalt plant (metering of 10% added filler is not convenient on batch plants and even impossible on most drum mix plants), filler content was fixed to 5%. Finally, two skip 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. This figure shows in particular that the passing of proposed aggregate gradations at the 2-mm sieve is above SMA window (NF EN 13108-5, 2006), which is indirectly due to the 4/10 gap gradation.

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 during *n*-1 steps.

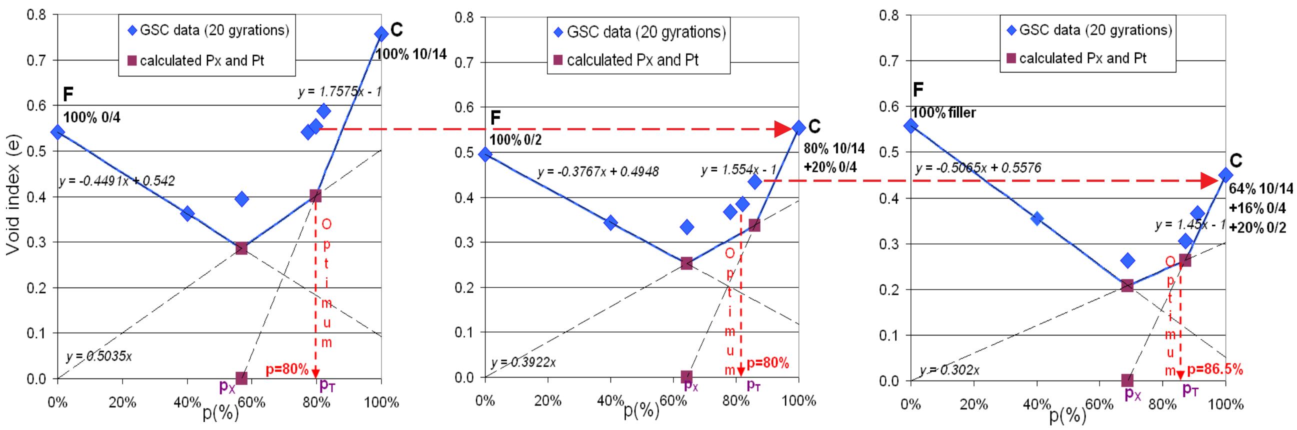

Figure 4 – 3-step iterative optimization of the 10/14-0/4-0/2-filler quaternary Noubleau aggregate blend.

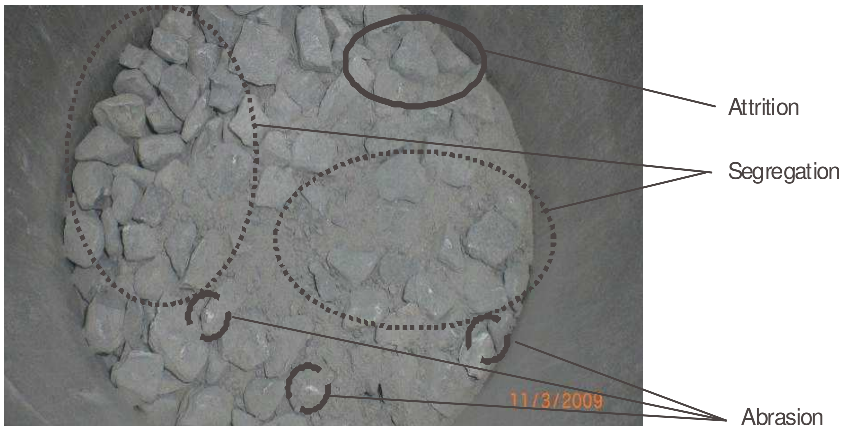

Figure 5 – Example of the attrition, segregation and abrasion phenomenons observed at 100 gyrations using the gyratory shear compactor (GC).

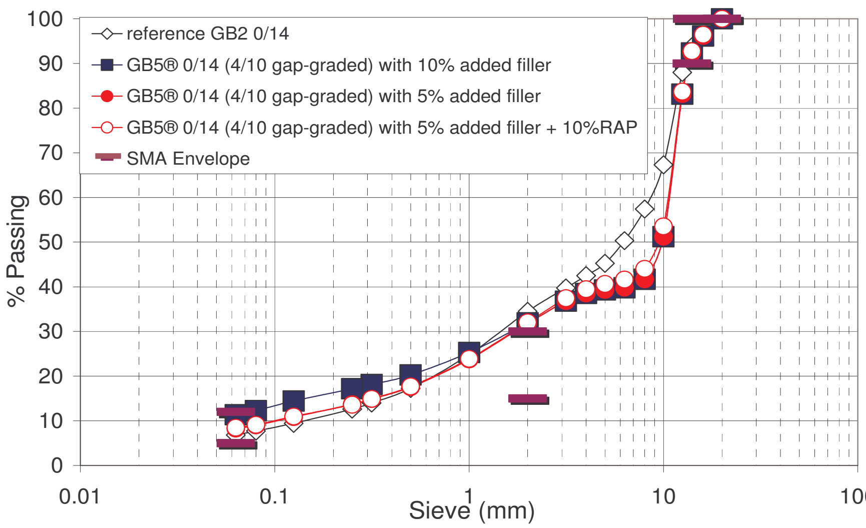

Figure 6 – Skip gradation curves (referred to as "GB5") for the optimal quaternary aggregate blends Vs that of the continuously graded reference "GB2".

7. PERFORMANCE-RELATED CHARACTERIZATION AND RELATED DISCUSSION

Richness modulus (*k*) is basically the ratio of bitumen content to surface area of aggregates and thus an estimation of binder film thickness. For more details, reader can refer to Corté & Di Benedetto [7] or Fontana et al. [26]. This parameter, of primary importance in France, was kept constant and equal to 2.55. This somehow low value for richness modulus corresponds to 3.9% binder content by weight of aggregates (10% vol.) for Noubleau mixtures. Table 3 shows the performances of the innovative GB5 gap-graded dense mixes compared to the reference Grave Bitume GB2 material usually used as base course material in France.

Table 3 – Performances of the GB5 materials compared to the reference GB2 material. Noubleau aggregates with a 3.9% binder content by weight of aggregate (%vol.=10.0%)

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

7.1. Compactability evaluated from 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 from Duriez test

Direct compressive strength is increased by 1.2MPa to 3MPa. Besides, moisture resistance ("Duriez ratio"), which is far above the minimum specification value for typical Grave Bitume GB2, does not seem to be influenced by the gradations and PMB's used.

7.3. Rutting resistance assessed from French Wheel Tracking test

GB5 mixes exhibit great 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 on 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℃-10Hz, is increased by approximately 17%. 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℃>30), thus enhancing both reclaiming ability and fatigue resistance of asphalts mixes.

Furthermore, Figure 7 illustrates the very positive influence of the proposed aggregate optimization upon the values of E_0 (static modulus) and E_∞ (glassy modulus). E_0 is the asymptotic value of complex modulus at high temperatures and low frequencies, whereas E_∞ (glassy modulus) is the asymptotic value of complex modulus at low temperatures and high frequencies. E1 (resp. E2) is the real part (resp. imaginary part) of the complex modulus E*.

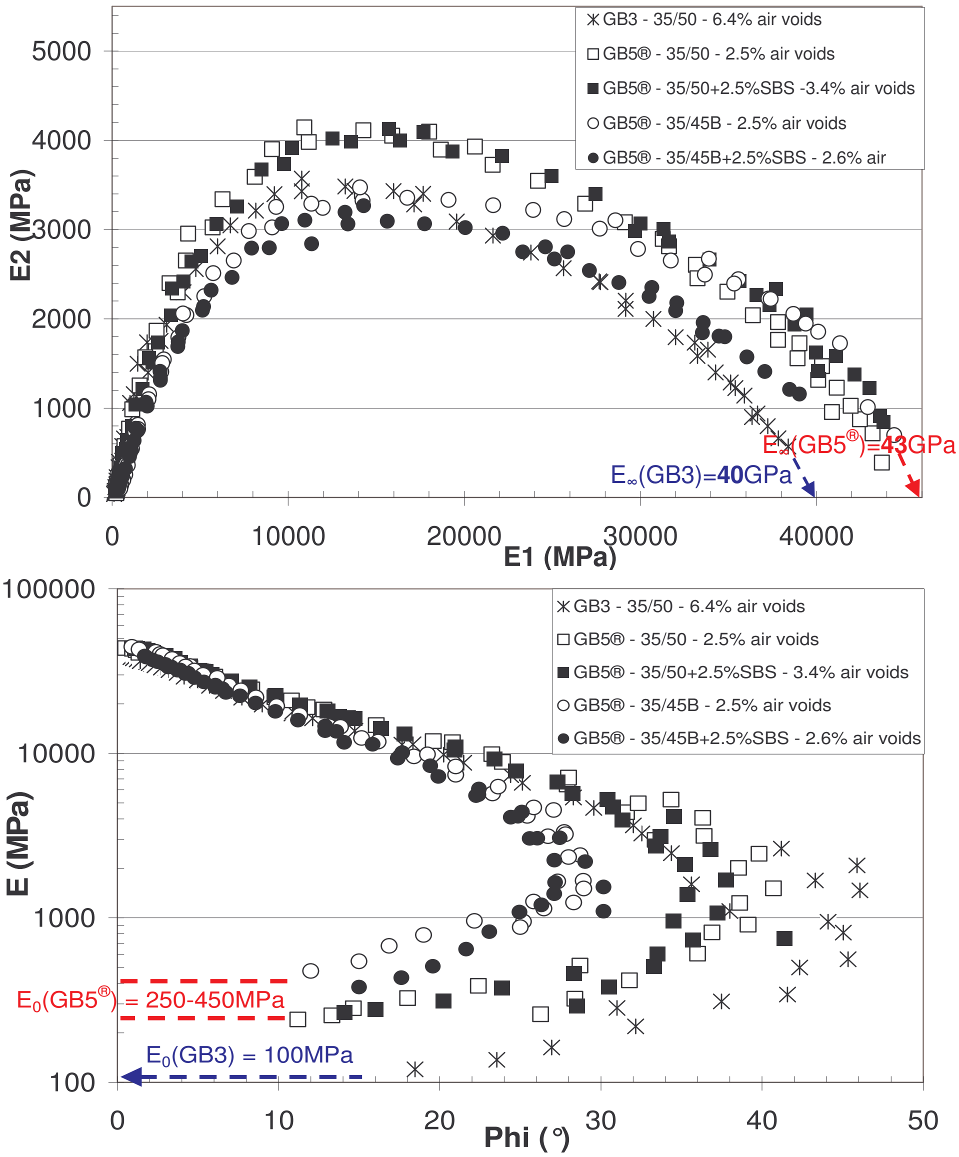

Figure 7 – Complex modulus results for GB3 & GB5 mixes (Cole-Cole and Black diagrams).

7.5. Fatigue resistance

For fixed bitumen nature and content, fatigue resistance measured at 10℃-25Hz is hardly influenced by aggregate packing optimization. On the contrary, 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℃-25Hz), obtained with 35/45B bitumen modified with 2.5% of cross-linked SBS, is an incredibly high value for an asphalt concrete with only 3.9% 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 3.9% 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. Obtained performances are close to the specifications required for EME2 (stiffness modulus of 14,000MPa at 15℃ and a fatigue resistance of 130 microstrains at 10℃) with a significantly lower bitumen content (in the range of 3.8% to 4.8% by weight of aggregate). Such 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, named 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℃ 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 [27].

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 specific gravities (ton/m^3) are:

- ρ(BBM): 2.42 t/m^3
- ρ(GB5): 2.47 t/m^3
- 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 4cm-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 economical impacts when considering the reduced base layer thickness and the reduced quantities of binder and aggregate required per square meter.

Insofar greenhouse gas emissions (GGEs) are concerned, the carbon dioxide (CO_2) quantity (main GGE generated during roadwork) associated to 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 by almost 30% in comparison with traditional EME2-based pavement design (see Table 4).

Table 4 – Comparative pavement design with Noubleau materials, corresponding costs & related environmental impacts (per square meter)

Thick Bituminous Pavement Structures. "TC620" Traffic Category. 4cm-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	4cm BBM	4cm BBM	4cm BBM	4cm BBM
Base course	16cm EME2	14cm GB5	12cm GB5	10cm GB5
Difference in base layer thickness	Reference	- 2cm (- 10%)	- 4cm (- 20%)	- 6cm (- 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. REFERENCES ROAD WORKS OF THE YEARS 2010-2011

Almost 10 full scale suitability tests were first carried out on several EIFFAGE plants in 2010. These preliminary field trials allowed validating the technical choices before generalizing GB5 mix design on each EIFFAGE site. The great compactability of GB5® mixtures was confirmed on more than 30 large scale roadworks so far.

Figure 8 – Paving GB5® 0/14mm high-performance asphalt with Noubleau aggregates and 35/45B bitumen in the Tours area. In-place density: 96.4% ; stiffness modulus measured in indirect tension configuration E*(15°C-10Hz): 14,100MPa.

Figure 9 – Paving GB5® 0/14mm high-performance asphalt with Cemex aggregates and 35/45B bitumen and 35% RAP (reclaimed asphalt pavement) near Toulouse. In-place density: 97% ; stiffness modulus in indirect tension mode E*(15°C-10Hz): 15,100MPa.

Several aggregate natures were studied in laboratory and used on the job sites. Four main nominal maximum particle sizes (NMPS) were tested: 11mm, 14mm, 16mm and 20mm. 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. Polymer modification was also carried out (SBS with or without a proprietary cross-linking procedure referred to as Biprene®) for most of our full scale suitability tests in 2010.

The use of reclaimed asphalt pavement (RAP) in GB5 is common in the 10-35% range.

GB5 mixtures were applied by the paver-finisher and were very easily compacted by double-roll vibrating compactors (Figures 8 and 9). By using GB5 mixture, there is no need for pneumatic tyre rollers, the final density being in the range between 2.5% to 6%. GB5 layer thickness was generally between 7cm and 16cm. Because of the skip gradations used, compaction of 6cm to 17cm layers with NMPS is possible.

After several months (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 laboratory.

10.CONCLUSIONS

The aggregate packing methods first developed in the field of high-performance cement concretes were successfully transposed to the field of asphalt concretes. They enabled development and design of high-performance asphalt mixtures based on single or double-gap-graded dense grading curves and the use of semi-blown and/or SBS modified binders.

Laboratory results on the so-called GB5® mixes were found to be very encouraging:

- the optimal skip gradations that were obtained from an innovative method based on gyratory shear compactor lead to improved compactability, increased compressive strength and enhanced modulus. The proposed procedure to optimize aggregate packing could be used in the framework of high-modulus mix design (e.g. French 'EME' (enrobé à module élevé)) with slightly softer grades than usual (Penetration at 25℃>30), thus enhancing both reclaiming ability and fatigue resistance of such asphalts concretes.
- the use of semi-blown and/or SBS modified binders leads to improved resistance to rutting and increased fatigue resistance as well.

Such combination of innovative single- or double-gap-graded curves with semi-blown and/or SBS modified bitumens (at such a low binder content as 3.9% by weight of the aggregate), leading to very stiff and fatigue resistant polymer modified base or binder course materials in a single formulation, has been patented. These materials could provide long-life pavements that do not deteriorate structurally, needing only timely surface maintenance to preserve their overall condition.

Up to now, several full scale roadworks were successfully realized in France and Spain as well, at either hot (170℃) or warm (125℃) or even half-warm (90℃) temperature.

Finally, the proposed approach is considerably different from those of SMA design and French EME2 design, since bitumen content is very low (about 4% instead of the more traditional range of 5.5%-6% by weight of the aggregate) with still very high performances. Reductions in binder quantity per ton of mix (despite the high cost of SBS modifier) and in base course thickness (due to enhanced stiffness and fatigue properties) lead to a cost-effective and eco-friendly perpetual pavement design.

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