GB5 mix design: high-performance and cost-effective asphalt concretes by use of gap-graded curves and SBS modified bitumens

François Olard

a EIFFAGE Travaux Publics, Research and Development Division, 8 rue du Dauphiné BP 357, 69960, Corbas Cedex, France

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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 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 single or double gap-graded curves, great coarse aggregate interlock and no need for low penetration grade bitumens to fulfil the European EME2 specification requirements, in particular the 14,000 MPa stiffness modulus value at 15°C.

In addition, the use of polymer modified binders (PMBs), at a content of about 4% up to 4.5%, combined with such an optimized aggregate packing leads to the design of the so-called high-performance asphalt concretes (HPAs) characterized by great compactability, very high stiffness modulus and 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 PMBs use affordable in base courses. 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 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; optimal aggregate packing; gap-graded asphalts; polymer modified binders (PMBs); high-performance asphalt mixes (HPAs)

1. Introduction

Controlling the volumetrics and the compactability of asphalt concretes is the first step of any mix design procedure. Apart from the binder-related considerations, as the aggregate component represents 90 to 95% of the weight of asphalt mixtures, predicting and controlling the packing properties of aggregates is thus of prime importance. Broadly speaking, the aggregate packing characteristics are mainly influenced by the following five parameters (Caquot, 1937; Baron, 1982; de Larrard, 1988; de Larrard, Sedran, & Angot, 1994; de Larrard & Sedran, 1994, 2002; Corté & Di Benedetto, 2004):

- gradation (continuously-graded, gap-graded, etc.),
- shape (flat and elongated, cubical, round),

*Email: francois.olard@eiffage.com
This paper mainly focuses on the first parameter (gradation) by specifically optimizing the combination of fine and coarse fractions: the result is an interactive network of coarse particles in asphalt concrete, providing indirectly the strongest mix resistance (Roque, Huang, & Ruth, 1997; Kim, Guarin, Roque, & Birgisson, 2008) and in particular the highest mix modulus.

Apart from the previous gradation-related considerations, the ability of SBS polymers to reduce fatigue cracking and aging is well recognized (Baaj, di Benedetto, & Chaverot, 2005; Dreessen, Ponsardin, Planche, Dumont, & Pittet, 2011) 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) that have viscosity and compatibility issues with conventional SBS. Under those circumstances, at EIFFAGE Travaux Publics we set out to combine both optimal aggregate interlock (using aggregate packing methods initially developed in the field of high-performance cement concretes) and the use of SBS polymers, in order to obtain both very stiff and fatigue-resistant polymer modified base course material in a single formulation.

2. Theoretical background on aggregate packing

Many researchers developed empirical methods of relating air voids content in mineral aggregates to the gradation, or proposed ‘ideal’ gradations, which aim at maximum solid volume density. These theoretical curves are always continuously-graded curves and they generally have a parabolic form (Nijboer, 1948; Yoder, 1959). They all have a similar shape when placed on the same plot. The most prevalent theoretical ‘ideal’ gradation is based on the following empirical equation:

\[
P = 100(d/D)^b
\]  

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 (1948) and Yoder (1959) found that the maximum density of any continuously-graded compacted mix is obtained when \( b \) equals 0.45 or 0.5.

Despite equation (1), Lees (1970) 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. In addition, some more general concepts of aggregate packing were first developed by Caquot in 1937, and then by contemporary researchers since the 1970s, especially in the field of cement concrete (de Larrard, 1988; de Larrard, Sedran, & Angot, 1994; de Larrard & Sedran, 1994, 2002; Andersen & Johansen, 1993). A state of the art of basics has been recently presented by Perraton, Meunier, and Carter (2007) and Olard and Perraton (2010), transposing those concepts in the field of asphalt mix design. The following sub-sections are partially drawn from these papers.
2.1. Basic concepts associated with granular combinations

When filling a container with an aggregate or granular mix, just a fraction of the volume is occupied by the particles and the remainder is composed of interstices. It is worthwhile to remark that for an infinite medium, the void index ($e = \text{volume of air voids/volume of solid particles}$) of an aggregate mix composed of one-dimensional particles remains, for all practical purposes, independent of particle size (Ben Aim, 1967, 1970; Cumberland & Crawford, 1987).

When studying the porosity of mixes composed of two aggregates with differing yet one-dimensional individual sizes, Caquot first highlighted in 1937 the importance of two types of interparticle interaction on the void index: the so-called ‘wall effect’ and ‘interference effect’ – the latter is also called the ‘loosening effect’.

The ‘wall’ effect is tied to the interaction between particles and any type of wall (pipe, formwork, etc) placed in contact with the granular mass. The case of a uniform, two-aggregate mix can be considered in order to understand the concept. The two composing fractions only differ by their average particle dimension, i.e. one for the coarse aggregate particles and another for the fines. When adding a few coarse particles into an infinite volume of fines, the void index of the blend is reduced. Nevertheless, the 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 the incorporated coarse aggregate (Caquot, 1937; Chanvillard, 1999). Figure 1 (left) and Figure 2 indicate the wall effect on the void index of a granular combination when raising the coarse fraction at the expense of fine aggregate within a binary mix.

By increasing the fraction of coarse particles within the fines, at a certain point a specific quantity of small particles winds up entrapped in the interstices delimited by the coarse particles. Therefore, outside of the wall effect, the fine aggregate void index increases due to interference: the arrangement of fine particles will depend not only on the surface areas of coarse particle walls (the 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 the coarse particles are forced apart by means of loosening, thus modifying their spatial configuration: interference occurs. Figures 1 (right) and 2 also display the interference effect on the void index of a binary granular combination.

If the average particle dimension of fines ($d_{\text{FINE}}$) is small enough compared with the one of coarse particles ($d_{\text{COARSE}}$) (e.g. when the $d_{\text{FINE}}/d_{\text{COARSE}}$ ratio is lower than 0.2), the wall effect is linear and satisfies the superposition principle: the effect of two walls amounts to the sum of effects.

![Figure 1](image1.png)  
*Figure 1. (Left) Schematic of the wall effect (case of the contact of fine particles at the surface of a coarse particle). (Right) Loosening effect (loss of stone-to-stone contact due to the all too high content of fine particles).*
of each wall taken individually (Baron & Sauterey, 1982). In contrast, the interference/loosening effect is never linear and consequently difficult to frame simplistically (Baron & Sauterey, 1982).

2.2. Evolution in aggregate porosity versus average particle dimension

Furnas (1928), Powers (1968) and Oger (1987) showed the dependence of the shift in void index ($e$) versus coarse aggregate portion in a binary combination on the ratio of average particle sizes. Figure 3 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 with 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 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.

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 ($d_{\text{FINE}}/d_{\text{COARSE}} \sim 0.008$), Baron (1982) proposed describing the void index variation of a mix by means of three straight lines (Figure 4). 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 mixture has a high ($p < p_X$), medium ($p_X < p < p_T$) or low ($p > p_T$) content of fine aggregate, void index variation can be defined according to three
distinct laws, as shown in Figure 4:

- 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 (Figure 4).
Low content of fines in the mix, \( p > p_T \):

\[
\implies e = (C + 1)p - 1
\]  

where \( C \) is the void index of coarse particles (Figure 4).

Medium content of fines in the mix, \( p_X < p < p_T \):

\[
\implies e = E p
\]  

where \( E \) is a coefficient without any simple physical significance.

2.4. Transposition of Baron’s approach to the design of stone-matrix asphalts with an optimal coarse aggregate packing according to Perraton et al. (2007)

By applying the concepts initially developed by Baron for the design of high-performance cement concretes, Perraton and his colleagues from the Ecole de Technologie Supérieure (University of Quebec) have recently illustrated that the laboratory performances of some SMA mixes may be substantially enhanced by means of a maximized coarse aggregate packing (Perraton et al., 2007).

The proposed mix design method was then applied to producing the so-called ‘SMA-Cpack’ (acronym for SMA with an optimal coarse aggregate packing) mixes with various NMPS (nominal maximum particle size) values using materials available in Montreal. Figure 5 shows a schematic diagram of the macrostructure in asphalt mix section cuts obtained using digital imaging. It may be noticed that the coarse particle content is high for each of the SMA-Cpack mixes produced.

First, the initial set of laboratory results suggests a potential binder saving of nearly 15% since the maximized coarse aggregate packing brings about a reduced void content in the granular skeleton. Second, based on Perraton’s results, compactability and resistance to rutting of such mixes are remarkable.

3. Objective of the present study

The previous concepts associated with granular combinations and packing characteristics were used in the EIFFAGE Travaux Publics research centre in France. Baron’s approach for optimal aggregate packing, developed in the field of high-performance cement concrete in 1982, was transposed and adapted to the field of asphalt concrete. The main goal was to evaluate the relevance of such an approach in the asphalt field, especially with typical French aggregates. The underlying questions were: can we develop high-performance dense asphalts with multiple-gap grading mainly thanks to aggregate packing optimization? And, likewise, can we use more specific guidelines for aggregate structure selection?

Figure 5. Illustration of the coarse aggregate proportion in the SMA-Cpack mixes (Perraton et al., 2007).
After the publication of the first encouraging results obtained by Perraton et al. (2007) and after some technical exchanges with Perraton and his colleagues, EIFFAGE Travaux Publics has launched a large experimental program at its research centre, including the evaluation of moisture resistance, stiffness modulus and fatigue resistance as well. Laboratory tests consisted of the assessment of compactability using the French gyratory compactor (GC), moisture resistance using the Duriez test, rutting resistance using the French wheel tracking tester (FWTT) at 60°C, stiffness modulus at 15°C and finally fatigue resistance at 10°C.

4. The proposed way of aggregate packing optimization

To make the simplest possible selection of an optimal granular combination with a maximized coarse fraction, it is herein proposed to separate the granular skeleton into three phases: fine, intermediate and coarse particles. The latter constitute the granular fraction that provides continuity in handling the force transfer within the mix macrostructure. This phenomenon is commonly referred to as coarse-on-coarse particle contact.

To enhance compactability, this method proposes monitoring the choice of granular combination in order to overcome the loosening effect by the intermediate fraction on the coarse fraction layout. In particular, the intermediate particles’ dimension must be held below a certain critical value. With respect to Furnas’ work (Figure 3), it is advised to limit the ratio of intermediate particle diameter ($d_{\text{INT}}$) to coarse particle diameter ($d_{\text{COARSE}}$) to 20% ($d_{\text{INT}} \leq 0.20d_{\text{COARSE}}$) (see particle dimensions in Table 2). Likewise, $d_{\text{FINE}} \leq 0.20d_{\text{INT}}$.

Using the French GC on aggregates only – without any bitumen – the respective void index of coarse, intermediate and fine aggregate particles is first determined after 20 gyrations. Indeed, after 100 gyrations, attrition, segregation and abrasion may be observed (Figure 6).

Depending on the NMPS of the designed mix and thus on the number of used granular fractions ($n$), the optimization sequence is performed during $n - 1$ steps. For instance, in the case of a three-fraction mix with fine, intermediate and coarse aggregates, the optimization sequence is performed during two steps.

- Step 1: granular optimization of the intermediate aggregate–coarse aggregate blend (i.e. determination of the corresponding optimal ratio according to Baron’s approach illustrated in Figure 4).
- Step 2: granular optimization of the blend between the previous optimized aggregate blend and the fine aggregates (same methodology, Figure 4).

![Figure 6. Example of attrition, segregation and abrasion phenomena observed at 100 gyrations using the gyratory shear compactor.](image)
The only slight difference with Baron’s original approach is that a sensitivity study is realized around threshold \( p_T \) (Figure 7). Two additional points are performed around \( p_T \) value \((p_T \pm 3\%)\). Moreover, for each step \((i)\), equation (2) is defined by carrying out two GC tests: the first one with \( p = 0\% \), the second one with \( p = 40\% \). As illustrated in Figure 7, six GC tests are performed for each step \((i)\). In the case of a three-fraction mix with fine, intermediate and coarse aggregate particles, granular optimization is performed with a series of 12 GC tests on this tertiary configuration.

Eventually, considering the effect of diameter ratio \((d_{\text{FINE}}/d_{\text{COARSE}})\) on void index \((e)\) of binary granular blends (illustrated in Figure 3), it has been decided to introduce single or double gaps in granular gradations in order to obtain very dense aggregate packings with great coarse aggregate interlock (maximization of contact between coarse particles) and without any risk of the loosening effect (related to rutting issues).

5. Materials

Two pure paraffinic bitumens coming from the same crude and refinery were investigated: a straight run 35/50 and a semi-blown 35/45B (‘B’ stands for ‘semi-blown’) Pen grade bitumens. In addition, two PMBs made from these two pure bitumens with 2.5% SBS (proprietary crosslinking process) were also investigated. The analysis of the recovered aged binder of two RAP (reclaimed asphalt pavement) aggregates, both of them being studied hereafter, was also realized. Table 1 presents the results of conventional tests (Penetration at 25°C, Softening Point Ring and Ball and Fraass brittle point) initially performed on these different binders.

Because of the great number of aggregate combinations tested in the framework of this laboratory study, only two typical French aggregate natures are presented here: the diorite crushed aggregate fractions \((0/2, 0/4 \text{ and } 10/14 \text{ mm})\) coming from the ‘La Noubleau’ quarry and the limestone crushed aggregate fractions \((0/2, 6/10 \text{ and } 14/20 \text{ mm})\) coming from the ‘Obourg’ quarry. In both cases, added limestone filler coming from the ‘St Hilaire’ quarry in France was considered. Moreover, some RAP aggregates coming from either the ‘Touraine Enrobés’ asphalt plant (EIffAGE TP Centre Ile-de-France) or the ‘MEN’ asphalt plant (EIffAGE TP Nord) were used, respectively with the diorite and the limestone aggregate formulas. Table 2 and Figures 8 and 9 give the gradation curves of each granular fraction.
### Table 1. Conventional results on the studied binders.

<table>
<thead>
<tr>
<th>Binder</th>
<th>Pen 25°C (mm/10) NFEN1426</th>
<th>Softening R&amp;B (°C) NFEN1427</th>
<th>Fraass (°C) NFEN12593</th>
</tr>
</thead>
<tbody>
<tr>
<td>35/50</td>
<td>38</td>
<td>53.5</td>
<td>−15</td>
</tr>
<tr>
<td>35/45B</td>
<td>37</td>
<td>62</td>
<td>−15</td>
</tr>
<tr>
<td>35/50 + crosslinked 2.5%SBS</td>
<td>38</td>
<td>62.2</td>
<td>−15</td>
</tr>
<tr>
<td>35/45B + crosslinked 2.5%SBS</td>
<td>33</td>
<td>71</td>
<td>−15</td>
</tr>
<tr>
<td>aged RAP binder ‘Touraine Enrobés’ plant</td>
<td>10</td>
<td>71.2</td>
<td>0</td>
</tr>
<tr>
<td>aged RAP binder ‘MEN’ plant</td>
<td>19</td>
<td>61.4</td>
<td>−5</td>
</tr>
</tbody>
</table>

### Table 2. Passing percentage and average particle size for each granular fraction.

<table>
<thead>
<tr>
<th>Sieve (mm)</th>
<th>Noubleau aggregates</th>
<th>Obourg aggregates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>filler</td>
<td>0/2</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>16</td>
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<tr>
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<td></td>
<td>83</td>
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<td></td>
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<td>83</td>
</tr>
</tbody>
</table>

**Average particle dimension, hereafter named d50**

| Diameter (mm) | 0.025 | 0.6  | 1.9  | 11.5 | 5    | 0.85 | 7.9  | 15.8 | 6.5  |

Figure 8. Gradation curves for each tested Noubleau granular fraction.
Apart from the average dimension of added filler being determined by means of a Coulter particle size analyzer (NF ISO 13320-1, 2000), the average particle dimension of the other fractions was determined by sieve passing (cf. Table 2).

6. Description of the tests used for characterizing asphalt concretes

Many laboratory tests were conducted on asphalt concretes, including the following.

- Compactability, measured with the gyratory compactor (GC), following the requirements of NF EN 12697-31 standard (2005). This test gives a good idea of the job-site density values, according to course thickness. Conducted ahead of the other mechanical tests, this test is used to make a preliminary selection or screening of mixes, and for optimizing the asphalt mix composition (Harman, Bukowski, Moutier, Huber, & McGennis, 2002).
- Water resistance, measured from the so-called Duriez test (NF EN 12697-12, 2002) which consists of a direct compression test on two sets of six cylindrical samples, one set of six samples tested after conditioning in water. If the ratio of average compression strengths after and before conditioning is above a certain value, the material is deemed to be acceptable. This ratio is the French counterpart of the TSR (Tensile Strength Ratio) value with Marshall samples.
- Resistance to rutting at 60°C, determined with the FWTT following NF EN 12697-22 standard (rectangular samples subjected to repeated passes at 1 Hz of a wheel fitted with a tyre, inducing permanent deformation, 2004).
- Complex stiffness modulus measured at 15°C–10 Hz, in accordance with the NF EN 12697-26 requirements (strain-controlled test on cylindrical specimens, 2004). Complex modulus test was also performed for some high-performance asphalt mixes (HPAs) from –30°C to 45°C with a frequency ranging from 0.01 to 10 Hz.
- Complex stiffness modulus and fatigue resistance at 10°C–25 Hz, following the NF EN 12697-24 standard (controlled-strain test on trapezoidal specimens with unconfined conditions, see Figure 10, 2005). The fatigue criterion that is used in this paper is the classical one, referenced as Nf50. It corresponds to the number of cycles for which either the complex
7. Aggregate packing optimization results

The use of a single-gap or even a double-gap gradation may be very helpful in obtaining very dense asphalt concretes with an outstanding coarse aggregate packing (there is far less interaction between intermediate and coarse particles, cf., for example, Figure 3). Thus, such single-gap and double-gap gradations were respectively investigated with Noubleau and Obourg aggregates.

7.1. Optimization of single-gap-graded granular curve with Noubleau aggregates

Figure 11 illustrates the three-step iterative aggregate packing optimization of a quaternary 10/14-0/4-0/2-filler aggregate combination (4/10 mm gap), by using the gyratory compactor (GC) on aggregates only—at ambient temperature and without any bitumen—as previously detailed.

The 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)

At the very last stage of such optimization, when determining the optimal content of added filler, the three theoretical straight lines described by Baron are clearly validated (Figure 4 and equations (2) to (4) in the particular case of a binary blend of very fine particles and coarse particles). Nevertheless, even if the addition of 13.5% of filler is quite convenient and relevant in the field of cement concretes, where final air voids are close to zero and production is realized on discontinuous batch plants, the added filler content was arbitrarily fixed at 5% in order to avoid overfilled asphalt concretes in the end and as the production may be realized on continuous drum mix plants. Table 3 and Figure 12 show gradation curves of each tested asphalt concrete.
Figure 11. Three-step iterative optimization of the 10/14-0/4-0/2-filler blend.
Table 3. Passing percentage for each tested asphalt mix made from the Noubleau aggregates.

<table>
<thead>
<tr>
<th>Sieve (mm)</th>
<th>Reference Grave</th>
<th>HPA 0/14 with 5% added filler (4/10 gap-graded)</th>
<th>HPA 0/14 with 5% added filler (4/10 gap-graded) + 10% RAP</th>
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<tbody>
<tr>
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Table 4. Passing percentage for each tested asphalt mix made from the Obourg aggregates.

<table>
<thead>
<tr>
<th>Sieve (mm)</th>
<th>Reference Grave</th>
<th>HPA 0/20 with 5% added filler (2/6 &amp; 10/14 gap-graded)</th>
<th>HPA 0/20 with 5% added filler (2/6 &amp; 10/14 gap-graded) + 10% RAP</th>
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</tbody>
</table>

shows in particular that the passing of the different HPA aggregate gradations at the 2-mm sieve is above the SMA window (NF EN 13108-5, 2006), which is indirectly due to the 4/10 mm gap gradation.

A typical gradation curve of a ‘Grave Bitume 2’ material (GB2) is also presented, for comparison.

### 7.2. Optimization of double-gap-graded granular curve with Obourg aggregates

The proposed methodology was applied to optimize the double-gap-graded granular curve with the so-called Obourg aggregates. To the extent that four granular fractions were investigated (14/20 mm, 6/10 mm, 0/2 mm and filler), optimization of aggregate packing was realized in three steps:
14 F. Olard

Figure 12. Gradation curves for the optimal 10/14-0/4-0/2-filler quaternary Noubleau aggregate blends versus typical gradation curve of the reference ‘GB2’.

• Step 1: optimization of the binary blend composed by 14/20 and 6/10 (p = 60% (i.e. 60% 14/20 and 40% 6/10), cf. Figure 13). As \(d_{50}(6/10)/d_{50}(14/20) = 0.50\), a true interference occurs in the case of the 14/20-6/10 binary aggregate composition (see Figure 3). The optimal content of coarse aggregate 14/20 may be arbitrarily fixed at 60% (leading to the densest binary blend).

• Step 2: the optimal blend obtained in Step 1 (60% 14/20-40% 6/10) is considered as the ‘coarse fraction’, whereas the 0/2 fraction is considered as the ‘fine fraction’. Optimal coarse ratio is \(p_T = 70\%\). It is noteworthy that \(d_{50}(0/2)/d_{50}(6/10) \approx 0.11\), leading to negligible interference between 0/2 and 6/10 particles (see Figure 3).

• Step 3: the optimal blend obtained in Step 2 (42% 14/20-28% 6/10-30% 0/2) is considered as the ‘coarse fraction’, whereas the filler is then considered as the ‘fine fraction’. Optimal coarse ratio is \(p_T = 95\%\). Note that \(d_{50}(filler)/d_{50}(0/2) \approx 0.03\), hence next to no interference between filler and 0/2 particles is observed (see Figure 3). In addition, the three straight lines from Baron’s approach cannot be obtained (Figure 4 and equations (2) to (4)).

The optimal 14/20-6/10-0/2-filler quaternary blend is the following:

• 14/20 content: 40% (\(= 0.95 \times 0.42\))
• 6/10 content: 26.5% (\(= 0.95 \times 0.28\))
• 0/2 content: 28.5% (\(= 0.95 \times 0.30\))
• added filler content: 5% (\(= 1-0.95\))

Figure 14 shows in particular that the passing of the different HPA aggregate gradations at the 2-mm sieve is above the SMA window (NF EN 13108-5, 2006), which is indirectly due to the 2/6- and 10/14-gap gradation.

8. Performance characterization and related discussion

In the framework of our study with Noubleau or Obourg mixtures, a 4% binder content by weight of aggregate (10% vol.) was used. Tables 5 and 6 respectively present the performances of HPAs
made from Noubleau and Obourg aggregates, compared with the reference continuously-graded ‘Grave Bitume 2’ (GB2) material normally used in France.

French specifications for a continuously-graded GB2 and ‘Enrobé à Module Elevé 2’ (EME2) are given as well. The reference EME2 material consists of 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 Europe and, in particular, in France.
Figure 14. Gradation curves for the optimal 14/20-6/10-0/2-filler quartertiary Obourg aggregate blends versus typical gradation curve of the reference ‘GB2’.

Table 5. Performances of HPA’s and reference GB2 material. Noubleau aggregates with a 4% binder content by wt of aggregate (%vol. = 10%).

<table>
<thead>
<tr>
<th>Formula</th>
<th>GC 100 gyrations</th>
<th>Duriez Test</th>
<th>Rut Depth</th>
<th>E (MPa)</th>
<th>$\varepsilon$ ($10^{-6}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Binder nature</td>
<td>%RAP</td>
<td>%Air</td>
<td>VMA</td>
<td>R (MPa)</td>
</tr>
<tr>
<td>Specifications for ‘Grave Bitume 2’ (GB2)</td>
<td>&lt;10%</td>
<td>-</td>
<td>-</td>
<td>&gt;70%</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Specifications for ‘Enrobé à Module Elevé 2’ (EME2)</td>
<td>&lt;6%</td>
<td>-</td>
<td>-</td>
<td>&gt;70%</td>
<td>&lt;7.5</td>
</tr>
<tr>
<td>GB2 35/50</td>
<td>0</td>
<td>9.7</td>
<td>19.7</td>
<td>10.1</td>
<td>93</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>5.9</td>
<td>15.9</td>
<td>11.8</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>7.2</td>
<td>17.2</td>
<td>12.1</td>
<td>91</td>
</tr>
<tr>
<td>HPA 35/50 + 2.5%SBS</td>
<td>0</td>
<td>5.7</td>
<td>15.7</td>
<td>12.3</td>
<td>93</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>
</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>
</tr>
</tbody>
</table>

8.1. **Compactability evaluated from the gyratory compactor**

Compactability, measured from the gyratory compactor (GC) at 100 gyrations, is significantly improved:

- regarding HPAs made from Noubleau aggregates (with single-gap-graded curve), densities are increased by 2.3% up to 3.8%. Nonetheless, the use of 10% (continuously graded) RAP slightly decreases the compactability of the HPA (7.2% air voids at 100 gyrations, instead of 5.9%), which indicates that non-negligible interference effects do occur between aggregate particles. Further work with 25% RAP will be set out to confirm this point;
- regarding the HPAs made from Obourg aggregates (with twice-gap-graded curve), densities are indeed increased by about 5%. The use of such optimized double-gap-graded granular curves appears as most promising.
Table 6. Performances of HPAs and reference GB2 material. Obourg aggregates with a 4% binder content by wt of aggregate (% vol. = 10%).

<table>
<thead>
<tr>
<th>Formula</th>
<th>GC 100 gyrations</th>
<th>Duriez Test</th>
<th>Rut Depth (mm)</th>
<th>E 15C-0.02 s</th>
<th>ε6 10C-25 Hz (10−6)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>R (MPa)</td>
<td>Moist. Res. (%)</td>
<td>3 × 10⁴ cycles</td>
<td></td>
</tr>
<tr>
<td>Specifications for 'Grave Bitume 2' (GB2)</td>
<td></td>
<td></td>
<td>&gt;70%</td>
<td>&lt;10</td>
<td>&gt;9000</td>
</tr>
<tr>
<td>Specifications for 'Enrobé à Module Elevé 2' (EME2)</td>
<td></td>
<td></td>
<td>&gt;70%</td>
<td>&lt;7.5</td>
<td>&gt;14000</td>
</tr>
<tr>
<td>GB2</td>
<td>35/50</td>
<td>8.7</td>
<td>11.8</td>
<td>83</td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td>35/45B</td>
<td>8.9</td>
<td>11.3</td>
<td>84</td>
<td>3.3</td>
</tr>
<tr>
<td>HPA</td>
<td>35/45B</td>
<td>3.8</td>
<td>12.7</td>
<td>85</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>35/45B + 2.5%SBS</td>
<td>3.8</td>
<td>12.5</td>
<td>83</td>
<td>2.1</td>
</tr>
</tbody>
</table>

It is worthwhile pointing out that such an excellent compactability of HPAs made from either Noubleau or Obourg aggregates has been confirmed on site during experimental roadworks near Blois, Tours and Arras (France) using the same asphalt formulas.

Eventually, even with a somewhat low value of binder content (% vol. = 10%), the proposed single- or double-gap graded curves allow one to obtain very encouraging VMA results (from 13.8% to 15.8%).

8.2. Compressive strength and moisture resistance assessed from the Duriez test

Direct compressive strength (determined on the first set of cylindrical samples kept 8 days in the air at 18°C), measured from the so-called Duriez test, is also improved (an increase from 1.2 MPa to 2.5 MPa is obtained).

In addition, 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 innovative gradations and PMBs used.

8.3. Rutting resistance assessed from the French wheel tracking test

The HPAs exhibit great resistance to rutting (low values of rut depth at 60°C after 30,000 cycles, cf. Tables 5 and 6) for two main reasons: the first reason is due to the well-interlocked and dense mixtures obtained from the optimization of aggregate packing, whereas the second reason lies on the fact that semi-blown and polymer modified bitumens give high resistance to rutting at high temperatures, in particular at 60°C.

8.4. Complex Modulus

For a fixed bitumen nature and content, the complex stiffness modulus of such well-interlocked and dense mixtures, measured at 15°C–10 Hz, is significantly increased (in the range of 20% to 26%). Further work with different aggregate natures and fractions remains to be done so as to confirm this encouraging result. Indeed, the proposed procedure to optimize the aggregate packing characteristics could be used in the framework of high-modulus mix design with slightly softer
grades than usual (Penetrability at $25^\circ > 30$ in contrast with the reference European EME2 mix design), thus enhancing both the reclaiming ability and fatigue resistance of asphalts concretes.

In addition, in order to assess the influence of the proposed gap-gradation on both glassy and static modulii, complex stiffness modulus tests were also performed for the GB2 reference material and the proposed gap-graded HPA with Noubleau aggregate, with the same binder (35/50) at the same amount (4% binder content by weight of aggregate), from $-30^\circ$ to $45^\circ$ with a frequency ranging from 0.01 Hz to 10 Hz (see Figure 15).

Regarding the glassy modulus (asymptotic value of complex modulus in the low-temperature and high-frequency domain), an increase by 20% was obtained, whereas for the static modulus (asymptotic value in the high-temperature and low-frequency domain), a threefold increase was obtained. These first results could make such HPAs interesting for heavy duty pavements, heavy duty bridge deck pavements, and so on.

8.5. Fatigue resistance

The very first results of HPA fatigue resistance tests appear comparable with those of the reference GB2 material, for a fixed bitumen nature and content. Fatigue resistance is indeed hardly influenced

Figure 15. Complex modulus of the gap-graded HPA versus that of the reference GB2 (Noubleau aggregate & 4% of 35/50 binder by wt of agg.): Master Curves at $15^\circ$C and Cole-Cole diagram.
by the developed aggregate packing optimization. On the contrary, binder nature highly influences fatigue resistance:

- with regards to the HPA with Noubleau aggregate (with single-gap-graded curve), the polymer modification (2.5% cross-linked SBS) of the 35/50 neat bitumen leads to an increase of the $\varepsilon_6$ value by 21 microstrains;
- regarding the reference ‘GB’ made from Obourg aggregates (with continuous gradation), moving from the neat 35/50 bitumen to the blown 35/45B bitumen brings about an increase of the $\varepsilon_6$ value by 20 microstrains;
- regarding the HPA with Obourg aggregates (double-gap-graded curve), the polymer modification (2.5% cross-linked SBS) of the blown 35/45B bitumen increases the value of $\varepsilon_6$ by 21 microstrains, leading to an $\varepsilon_6$ value of 135 microstrains, which is an incredibly high value for an asphalt concrete with only a 4% binder content in France.

An attempt was done to adjust the GB2 blends in order to lower VMA values close to those of the optimized blends to see the effect on the stiffness and fatigue performances. Yet it was impossible to get the 2.7% air voids target.

9. Economic and environmental outlook

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 Tables 5 and 6 (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 (mainly from France) 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 14,000 MPa at 15°C and a fatigue resistance of 130 microstrains at 10°C) with a
significantly lower bitumen content (in the range of 3.9% to 4.9% 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 and environmental impact.

9.1. Hypothesis for pavement design and 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 to determine 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 Grave Bitume (GB) 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 computational 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 (SÉTRA-LCPC, 1997).

In order to compare the costs of road structures with traditional EME2 or innovative GB5 base courses, the following orders of magnitude were taken into account for material costs:

- cost of 10/20 hard bitumen $\approx$ 35/50 pen grade bitumen + 40–60 €/t,
- cost of 35/45B $\approx$ 35/50 pen grade bitumen + 40–60 €/t,
- cost of 35/50 + 2.5% SBS $\approx$ 35/50 pen grade bitumen + 150–170 €/t,
- cost of 35/45B + 2.5% SBS $\approx$ 35/50 pen grade bitumen + 200–220 €/t.

The apparent specific gravities (ton/m³) are:

- $\rho$(BBM): 2.42 t/m³,
- $\rho$(GB5): 2.47 t/m³,
- $\rho$(EME2): 2.49 t/m³.

A ‘Béton Bitumineux Mince’ (BBM) is used as a 4 cm-thick overlay in France.

9.2. Comparative pavement design, corresponding costs and environmental impacts

Table 7 presents a comparative pavement design using the ALIZE software and considering a ‘TC620’ traffic category (cumulative traffic over 20 years in the range between 6.5 and 17.5 million 13-ton axles), a 4 cm-BBM overlay and a ‘PF3’ pavement formation class (120 MPa). Materials are the same ones listed in Table 5, together with their respective performance results. Table 7 shows that innovative GB5 mixes 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 metre.

Insofar as greenhouse gas emissions (GGEs) are concerned, carbon dioxide (CO₂) quantities (main GGE generated during roadwork) associated with aggregates, and pure bitumen and polymer modified binder are respectively equal to 10, 285 and 310 kgCO₂/t. Therefore, the proposed high-performance GB5 base layers may lead to a reduction in CO₂ emissions by almost 30% in comparison with traditional EME2-based pavement design (see Table 7).

However surprising it may seem, the proposed aggregate packing optimization makes the SBS affordable in base layer materials (its use was limited until now to surface courses for economic reasons).
### Table 7. Comparative pavement design with Noubleau materials (from Table 5), corresponding costs & related environmental impacts (per square meter).

<table>
<thead>
<tr>
<th></th>
<th>EME2 Solution</th>
<th>Innovative GB5® Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Binder</strong></td>
<td>Hard 10/20</td>
<td>35/45B</td>
</tr>
<tr>
<td><strong>Overlay</strong></td>
<td>4 cm BBM</td>
<td>4 cm BBM</td>
</tr>
<tr>
<td><strong>Base course</strong></td>
<td>16 cm EME2</td>
<td>14 cm GB5</td>
</tr>
<tr>
<td>Difference in base layer thickness</td>
<td>Reference</td>
<td>-2 cm (−10%)</td>
</tr>
<tr>
<td>Difference in aggregate quantity</td>
<td></td>
<td>−10%</td>
</tr>
<tr>
<td>Difference in bitumen quantity</td>
<td></td>
<td>−28%</td>
</tr>
<tr>
<td>Difference in materials cost/m²</td>
<td></td>
<td>−23%</td>
</tr>
<tr>
<td>Difference in kg CO₂eq./m²</td>
<td></td>
<td>−24%</td>
</tr>
</tbody>
</table>

10. **In-situ validation of the proposed mix design in the Year 2010**

Ten full-scale suitability tests were first carried out on several EIFFAGE asphalt plants in 2010 before generalizing the technique on each of the 180 EIFFAGE sites. These preliminary field trials allowed validating the technical choices with either single-gap or double-gap gradations initially studied in the laboratory. In particular, the great compactability of the proposed mixes was confirmed so far.

11. **Development and large-scale roadworks of 2011**

In 2011, the use of the proposed GB5 mix design was generalized 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, SBS content was in the range of 2.5% to 7%. The overall binder content (virgin + aged binders) was generally in the range of 4.0% to 4.5%.

The so-called GB5 mixes were applied by the paver and very easily compacted by double-roll vibrating compactors (Figures 17 and 18). There was no need for pneumatic tyre rollers, final density being in the range between 2% and 6%. Layer thickness was between 6 and 16 cm thanks to gap gradations used.

140,000 tons of GB5 mixes have been paved so far, corresponding to a saving of about 1400 tons of bitumen in comparison with the reference EME2 (high-modulus high-binder content mix) usually used as base course material in Perpetual Pavement design in Europe. On top of it, almost 4000 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.

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 in IDT (indirect tension) mode. This follow-up is very encouraging and confirms the great performances initially obtained in the laboratory.

One initial concern was to check the validity and effectiveness of the proposed approach with mixes containing high RAP contents. In 2011, some GB5 mixes were successfully designed and manufactured with 40% RAP: RAP aggregate size was 0/10 mm and the added crushed aggregate size was 14/20 mm, in order to get a single 10/14 mm gap in the 0/20 mm gradation. Further work is planned within the next few years on this issue, by using specially fractionated recycled materials. By fractionating RAP and combining high RAP contents with unaged SBS-modified binder, the GB5 mix design could produce a longer life pavement with a very interesting economic outlook.

Last but not least, in the framework of the so-called Road Innovation Charter procedure of SETRA (French acronym which stands for ‘Service d’Etudes Techniques des Routes et Autoroutes’), in France, 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 with toll highways. From then on, several GB5 projects were undertaken in different France’s climatic zones under very high traffic. A five-year follow-up by SETRA is planned for validation of this new technique.

12. 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, 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 from now on 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 through gyratory shear compaction, is remarkably improved. In the framework of this work, for the same compaction energy, density values are approximately 4% higher;

Figure 18. 12,000-ton GB5 0/14 roadwork on the French A43 toll highway (AREA network, Chignin-Francin section) in the alpine area. Budillon aggregate, 15% RAP (reclaimed asphalt pavement) and PMB’s Biprene 41 & Orthoprene were used.
• 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–0.02 s is significantly increased (in the range of 11% to 20%). The proposed procedure to optimize aggregate packing characteristics could be used in the framework of high-modulus mix design (e.g. French ‘EME’ (enrobé à module élevé)) with slightly softer bitumen grades than usual (Penetrability at 25°C > 30), thus enhancing both reclaiming ability and fatigue resistance of such asphalts concretes;
• fatigue resistance of GB5 mixes, 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 really enhanced stiffness moduli, the use of softer bitumen grades, semi-blown binders or PMBs yields great fatigue resistance. Such a particular combination of innovative single or double gap-graded curves with semi-blown and/or SBS modified bitumens, leading to very stiff and fatigue resistant polymer modified base or binder course materials in a single formulation, was recently patented by EIFFAGE Travaux Publics.

To some extent, such GB5 mixes 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, the on-site application of GB5 mixes on many experimental roadworks with or without RAP, at either hot (160°C) or warm (125°C) or even half-warm (90°C) temperature, was successfully realized mainly in 2011: almost 120,000 tons of GB5 mixes have already been paved in France on high traffic highways and toll motorways. This rapid development and the numerous large-scale roadworks of GB5 mixes, with SBS in base or binder courses, could be put into practice, particularly because 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 allows obtaining such rather low binder content, and thus, makes it economically possible to use SBS in base courses, leading to an alternative concept of perpetual pavement.

Acknowledgements
The author gratefully acknowledges the help provided by the staff of the EIFFAGE road research centre in Lyon, in particular P. Huon, F. Desvignes, R. Lictevout and C. Billet, for the performance of most aggregate packing optimizations and of many mechanical tests on HPAs. The author also thanks S. Dupriet for conducting all the fatigue tests on HPAs at the EIFFAGE road research centre in Ciry-Salsogne.

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