Aggregate packing concepts initially developed in the field of high-performance cement concretes were adapted and transposed to the field of asphalts. These innovative 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 GB5® asphalts, 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. It is noteworthy that the proposed mix design and the 4% - 4.5% binder content makes PMB’s affordable in base courses. The proposed GB5® material may be potentially considered as a relevant solution for sustainable long-life pavements that do not deteriorate structurally, needing only timely surface maintenance.

The proposed innovative GB5® mix design was previously presented in ERR 18 [1], the present article mainly focuses on the different achievements of this new material on the field on different work sites in 2011, located mainly in France.

Introduction

Controlling the volumetrics of asphalt mixes is the first step of any mix design procedure, since the aggregate component represents about 95% of the weight of asphalt. Aggregate packing is mainly influenced by five parameters (e.g. Caquot [2], Baron [3], Larrard [4-6], Corté & Di Benedetto [8]):

- 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. [9]).

This article mainly focuses on the first parameter 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 [10], Kim et al. [11]) 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 [12], Dressen [13]), thus 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.

**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 [14-15]. They have a similar shape when placed on the same plot. The most prevalent theoretical “ideal” gradation is based on the following empirical equation:

$$P = 100(d/D)^b$$

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 [14] & Yoder [15] 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 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 [2], and then by contemporary researchers since the 1970s, especially in the field of cement concrete [4-7,17]. A state of the art of basics has been recently presented by Perraton [18] and Olard & Perraton [19-20], transposing these concepts to the field of asphalt mix design. The following sub-sections are partially drawn from these papers.

**Basic theoretical 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 [2] 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…) 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). Nevertheless, 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 [2], Chanvillard [21]).

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).
In other words, the ideal proportion of fine particles is that leading to the maximal density value without any loosening effect (minimization of the number of coarse aggregates contacts).

Proposed experimental method for the aggregate packing optimization

The use of a single-gap or even a double-gap graded curve [22-23] may help obtain very dense asphalt mixes with high coarse aggregate packing (lower interaction between intermediate and coarse particles). Figure 2 illustrates an example of the proposed iterative (step-by-step) aggregate packing optimization of a quaternary 10/14 - 0/4 - 0/2 filler blend (10/14 mm, 0/4mm, 0/2mm and filler), using a gyratory shear compactor (GSC) on aggregates only — without any bitumen — as detailed before. This packing optimization procedure consists of three sets of GSC measurements at 20 gyrations. Figure 3 shows an example of optimal gap-graded curves (referred to as GB5®) vs. that of the continuously graded reference "GB2".

Eco-friendly alternative to EME2

An alternative to the traditional high-modulus and high-binder content EME2 may be proposed for long-lasting and cost-effective asphalt mixes. Indeed, the great coarse aggregate interlocking and the very high density that may be obtained with the proposed GB5® mix design bring about improved compressive strength, rutting resistance and stiffness modulus [24-25], hence no need anymore for hard bitumens (i.e. low pen grade bitumens). Considering the very encouraging performances obtained with only 4% of bitumen by weight of the aggregate [24-25], 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 or above 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). This innovative GB5® mix design has been patented.

Let’s present in Table 1 a comparative pavement design using the Alizé software and considering a "TC620” traffic category, a 4cm-BBM overlay and a “PF3” pavement formation class. The materials are EME2 or GB5® mixtures made from Noubleau aggregates (diorite nature).
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 (CO2) quantity associated with aggregate, pure bitumen and modified binder is respectively equal to 10,285 and 310 kg CO2/t. Therefore, the proposed high-performance GB5® base layers may lead to a reduction in CO2 emissions of almost 30% in comparison with traditional EME2-based pavement design (Table 1).

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.

### 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. Five main nominal maximum particle sizes (NMPS) were used: 6mm, 10mm, 14mm, 16mm and 20mm.

<table>
<thead>
<tr>
<th>Traditional Solution Binder content=5.7%</th>
<th>Innovative GB5® Solutions Binder content=4.0%</th>
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<tbody>
<tr>
<td>EME2</td>
<td>GB5 35/45B</td>
</tr>
<tr>
<td>Overlay</td>
<td>Base course</td>
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<tr>
<td>4cm BBM</td>
<td>16cm EME2</td>
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<td>- 2cm (- 10%)</td>
<td>- 4cm (- 20%)</td>
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<td>- 10%</td>
<td>- 20%</td>
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<tr>
<td>- 30%</td>
<td>Reference</td>
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<tr>
<td>Difference in base layer thickness</td>
<td>Difference in aggregate quantity</td>
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<td>- 10%</td>
<td>- 28%</td>
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<tr>
<td>- 30%</td>
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<td>Difference in binder thickness</td>
<td>Difference in materials cost/m²</td>
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<td>- 38%</td>
<td>- 24%</td>
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<tr>
<td>Difference in kg CO2 eq./m²</td>
<td>- 17%</td>
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<tr>
<td>- 28%</td>
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</table>

### In-situ validation of the proposed mix design in the year 2010

10 full scale suitability tests were first carried out on several Eiffage plants in 2010 before generalizing the technique on each of the 160 Eiffage sites.

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 4.7%.

GB5® mixes were applied by the paver and very easily compacted by double-roll vibrating compactors (Photos 1 to 3). There was no need for pneumatic tyre rollers, with the final density in the range between 2% to 6%. The layer thickness was between 5 and 16 cm thanks to the gap gradations used. 150,000 tons of GB5® asphalts have been paved so far, corresponding to a saving of about 1,500 tons of bitumen in comparison with the reference EME2 (high-modulus high-binder content mix).
GBS®: eco-friendly alternative to EME2 for long-life & cost-effective base courses

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. Photos 2 and 3 illustrate two main large scale roadworks on French highly trafficked toll highways. Photo 2 specially shows a 31,000-ton GBS® 0/14mm roadwork on the A41N & A43 toll highways (AREA network) in the alpine area. A 0/14mm gradation with a 4/10mm 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:

- **GBS® Biprene®**: $E'(15^\circ C-10Hz) = 17,500$ MPa & fatigue resistance $\varepsilon_f(10^\circ C-25Hz) = 133 \times 10^{-6}$
- **GBS® Orthoprene®**: $E'(15^\circ C-10Hz) = 11,000$ MPa & fatigue resistance $\varepsilon_f(10^\circ C-25Hz) = 205 \times 10^{-6}$.

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 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 GBS project was awarded in 2010.

In 2011, a Road Innovation Charter was signed with several General Councils and companies in charge of toll highways. From then on, several GBS 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.

Photo 2
31,000-ton GBS® 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 GBS® 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.
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.

The first laboratory assessments of the optimal single or double-gap graded dense mixtures were found to be very encouraging since we obtained some great improvements in compactionability, compressive strength, rutting resistance at 60°C, and lastly in stiffness modulus measured at 15°C. In addition, 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 a single formulation, has been recently patented in a single formulation, has been recently patented by

References