On the Optimization of the Aggregate Packing for the Design of Self-Blocking High-Performance Asphalts

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ABSTRACT: In the framework of a partnership between the European EIFFAGE Travaux Publics Group and the Ecole de Technologie Supérieure (ETS) from Montreal, some basic concepts associated with granular combinations and aggregate packing characteristics enabled the development and design of high-performance self-blocking asphalt concretes. The aggregate packing methods first developed in the field of high-performance cement concretes were successfully transposed to the field of asphalt concretes. Laboratory assessment consisted in the evaluation of the compacting ability using the French gyratory shear compactor (GSC), the resistance to moisture using the so-called Duriez test, the resistance to rutting thanks to the French wheel tracking tester at 60°C, the secant stiffness modulus at 15°C and the fatigue resistance at 10°C. The paper concludes that the proposed principles can be used to develop more specific guidelines for aggregate structure selection of high-performance asphalt concretes.

KEY WORDS: mix design, optimal aggregate packing, high-performance asphalts (HPAs).

1 INTRODUCTION

Controlling the volumetrics and the compactability of asphalt concretes is the first step of any mix design procedure. The aggregate packing characteristics, which are of prime importance, are mainly influenced by the four following parameters (Caquot 1937, Baron 1982, de Larrard et al. 1988, 1994, Corté & Di Benedetto 2004):

- 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)

This paper is dealing with the first parameter (gradation) by specifically optimizing the combination of fine and coarse fractions in such a way that results in an interactive network of coarse particles in asphalt concrete, providing indirectly the strongest mix resistance (Roque *et al*., 1997; Kim *et al.*, 2008).

2 BASIC CONCEPTS OF AGGREGATE PACKING CHARACTERISTICS FIRST DEVELOPED IN THE FIELD OF CEMENT CONCRETES

Some basic concepts of aggregate packing characteristics were first developed by Caquot in 1937, then by many researchers since the 1970's. A state-of-the-art was recently presented by Perraton et al. (2007) transposing those concepts into the field of asphalt mix design.

2.1 Basic notions associated with granular combinations

When filling a container with an aggregate, one fraction of the volume is occupied by the particles and the other one by interstices. It is noteworthy that for an infinite medium, the void index (*e*) of an aggregate composed of one-dimensional particles remains independent of particle size (Ben Aïm 1967, Cumberland & Crawford 1987).

When studying the porosity of mixes composed of two aggregates with differing yet one-dimensional individual sizes, Caquot (1937) evidenced two types of interparticle interaction: the so-called "wall effect" & "interference effect" –the latter is also called "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 void index of the blend is reduced when adding a few coarse particles into an infinite volume of fines. Nevertheless, the coarse particles locally, at the interface, disturb the arrangement of fines whose void index is increasing. This local porosity increase is proportional to the particle surface area of the incorporated coarse aggregate (Caquot 1937, Chanvillard 1999), cf. Figures 1 (left) & 2.

In continuing to increase the part 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. Thus, outside of the wall effect, the fine aggregate void index increases due to interference: the arrangement of fine particles will not just depend on the surface areas of coarse particle walls (the wall effect), but also on the actual layout of these particles.

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 is present. 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_{FINE}) is small enough compared to that of coarse particles (d_{COARSE}) (e.g. $d_{FINE}/d_{COARSE} \leq 0.2$), the wall effect is linear and satisfies the superposition principle (Baron & Sauterey 1982). In contrast, the interference/loosening effect is never linear and therefore difficult to frame simplistically (Baron & Sauterey, 1982).

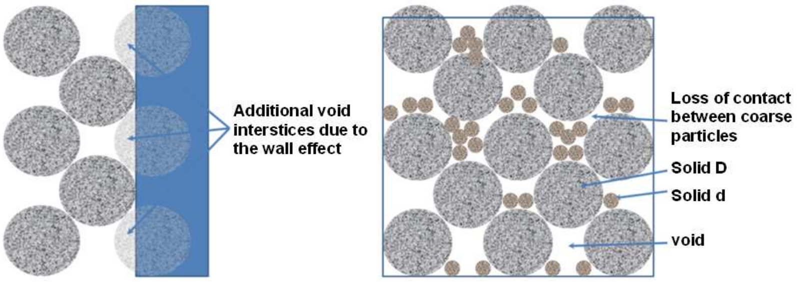

Figure 1: (Left) Schematic of the wall effect. (Right) Schematic of the loosening effect (loss of stone-to-stone contact due to the all too high content of fine particles).

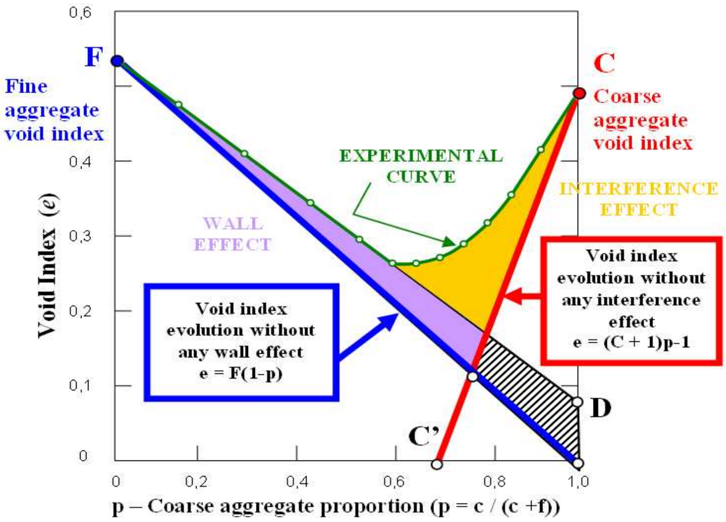

Figure 2: Wall & interference effects (Powers 1968). f & c are resp. the solid volumes of fine & coarse aggregates (f+c=1); F (resp. C)=void index of fine (resp. coarse) aggregate.

2.2 Evolution in aggregate porosity Vs. average particle dimension

Powers (1968) noted that Furnas had formerly evidenced the dependence of the evolution in void index (e) Vs. coarse aggregate portion in a one-dimensional binary combination on the ratio of average particle sizes. Figure 3 –from Furnas' work–, reveals that as the ratio of average fine aggregate dimension-to-average coarse aggregate dimension rises, interaction effects become more significant as well. To minimize interactions of the intermediate particle fraction on the coarsest particles in the asphalt concrete, it is crucial to limit both their size and amount and fill voids instead by a higher fraction of fines. Let's point out the experimental evidence showing that the minimum void volume of a granular mix depends first and foremost on the ratio of the coarsest particle dimension to the finest and that the range of intermediate dimensions exerts only a slight influence (Baron, 1982).

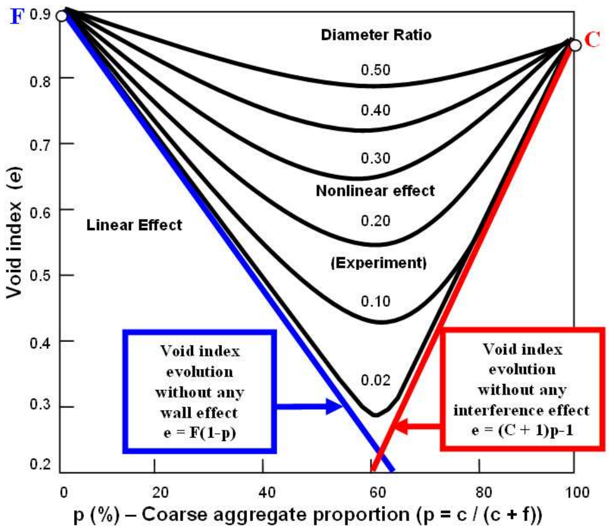

Figure 3: Evolution in the Furnas void index (e), as established on a binary combination of coarse (c) and fine (f) aggregates Vs. the proportion of coarse aggregate in the combination for various d_{COARSE}/d_{FINE} ratios (Powers 1968, Perraton et al. 2007).

2.3 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 ($d_{FINE}/d_{COARSE} \sim 0.008$), Baron (1982) proposed describing the void index variation of a mix by means of three straight lines (Fig. 4). Baron defined two thresholds, p_X & p_T, which indicate the critical concentrations that allow eliminating interference effects. Within a binary mix (containing coarse and fine particles), p_X corresponds to the maximum coarse aggregate concentration that can be combined with fine aggregate without adversely altering the fine aggregate layout, while p_T allows establishing the maximum fine aggregate concentration (i.e. $1-p_T$) for combination with coarse aggregate without interfering 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, the void index variation can be defined as follows:

- High content of fines in the mix, $p < p_X$:

$$e = F\,(1 - p) + Dp \tag{1}$$

- Low content of fines in the mix, $p > p_T$:

$$e = (C + 1)\,p - 1 \tag{2}$$

- Medium content of fines in the mix, $p_X < p < p_T$:

$$e = Ep \tag{3}$$

where F is the void index of fines and D a coefficient of the wall effect, C is the void index of the coarse particles, and E is a coefficient without any simple physical significance.

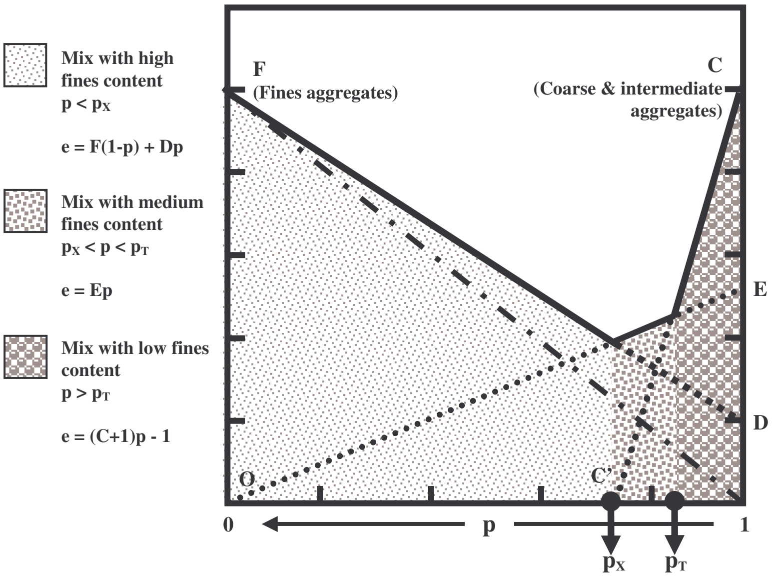

Figure 4: Void index variation (e) in the case of a two-aggregate mixture, one of which is very fine compared to the other (according to Baron (1982)).

2.4 Transposition of the "Baron's approach" to the design of Stone-Matrix Asphalts with an optimal coarse aggregate packing according to Perraton (2007)

By applying the concepts initially developed by Baron for designing high-performance cement concretes, Perraton has recently evidenced that the SMA lab performances may be enhanced by means of a maximized coarse aggregate packing (Perraton et al., 2007). The proposed mix design method was then applied to produce the so-called "SMA-Cpack" (acronym for SMA with an optimal coarse aggregate packing) mixes with various NMPS values using materials available in the Montreal area. Figure 5 shows a schematic diagram of the macrostructure in asphalt mix section cuts obtained using digital imagery. It may be observed that the coarse particle content is high for each of the SMA-Cpack mixes produced. The initial set of laboratory results suggests great compacting ability and rutting resistance of such mixes.

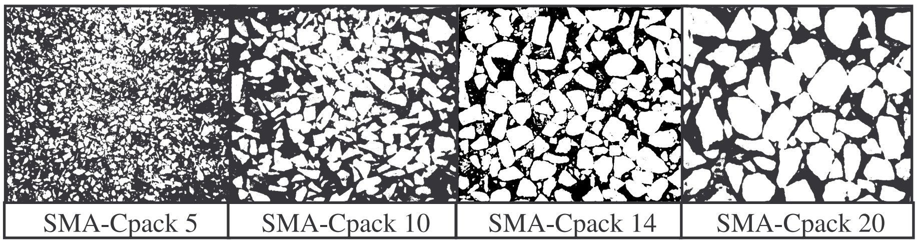

Figure 5: Illustration of the coarse aggregate proportion in the SMA-Cpack (Perraton 2007).

3 OBJECTIVE OF THE PRESENT STUDY

The previous concepts associated with granular combinations and packing characteristics were used in the EIFFAGE research centre in Corbas (France). The Baron's approach for optimal aggregate packing was transposed to the field of asphalt concretes by using very typical French aggregates. The underlying question was: can we develop high-performance dense asphalts with multiple-gap grading mainly thanks to aggregate packing optimization?

After the publication in the French Bulletin de Liaison des Ponts et Chaussées of the first encouraging results obtained by Perraton et al. (2007), EIFFAGE Travaux Publics launched a large experimental campaign in its laboratory consisting in evaluating the compacting ability, the moisture resistance, the rutting resistance at 60°C, the stiffness modulus at 15°C and finally the fatigue resistance at 10°C.

4 THE PROPOSED WAY OF AGGREGATE PACKING OPTIMIZATION

The granular skeleton assembly is separated into three phases: fine, intermediate and coarse particles. The latter actually constitute the granular fraction that provides for continuity in handling the force transfer within the mix macrostructure, otherwise known as coarse-on-coarse contact. These particles on their own serve to define aggregate NMPS. To enhance compacting ability, our method proposes monitoring the choice of granular combination so as to overcome the loosening effect from the intermediate fraction on the coarse fraction arrangement. In particular, the intermediate particle dimension must be held below a certain critical value. With respect to Fig. 3, it is advised to limit the ratio of intermediate particle diameter (d_{INT}) to coarse particle diameter (d_{COARSE}) to 20% ($d_{INT} \leq 0.20\ d_{COARSE}$) (cf. average particle dimension of the respective fractions in section 4). Likewise, $d_{FINE} \leq 0.20\ d_{INT}$.

Using the French gyratory shear compactor (GSC) on aggregates only –without any bitumen–, the respective void index of coarse, intermediate and fine aggregate particles is first determined using the GSC after 20 gyrations. Indeed, after 100 gyrations, attrition, segregation and abrasion may be observed. Depending on the NMPS of the designed mix and thus on the number of used granular fraction (n), the optimization sequence is performed during n-1 steps. For instance, in the case of a 3-fraction mix with fine, intermediate and coarse aggregates, the optimization sequence is performed during two steps:

- Step 1: optimisation of the intermediate aggregate-coarse aggregate blend (determination of the corresponding optimal ratio according to Baron's approach illustrated in Fig. 4).
- Step 2: granular optimisation of the blend between the previous optimized aggregate blend and the fine aggregates (same methodology, described in Fig. 4).

For each step (i), the only slight difference with the original Baron's approach is that a sensibility study is realized around the thresholds p_T. Two additional points are performed around the p_T value ($p_T \pm 3\%$). Moreover, for each step (i), Equation (1) is defined by carrying out two GSC tests: the first one with $p=0\%$, the second one with $p=40\%$. Thus, six GSC tests are performed for each step (i).

For a 3-fraction mix with fine, intermediate and coarse aggregate particles, the granular optimization is performed with a series of twelve GSC tests on this ternary configuration.

5 MATERIALS

The diorite crushed aggregate fractions (0/2, 0/4 & 10/14 mm) came from the "La Noubleau" quarry in France. The added limestone filler came from the "S^t Hilaire" quarry in France. In addition, some reclaimed asphalt pavement (RAP) aggregates coming from the "Touraine Enrobés" plant were used. An analysis of the recovered aged binder of the RAP showed that the content, penetration and Ring and Ball value were respectively 5.1%, 10 (mm/10) and 65°C. Table 1 gives the gradation curves of each granular fraction. The average particle dimension of the fractions was determined by sieve passing, except for the added filler whose average dimension was determined thanks to the Coulter® particle size analyzer.

Sieve (mm)	**Passing (%)**				
	Added filler	**0/2**	**0/4**	**10/14**	**RAP**
16				100	100
14				93	97
12.5				77	89
10				22	72
8				5	63
5			100	0.8	50
4			96	0.4	45
3.15		100	85	0.3	41
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					
Diameter (mm)	0.025	0.6	1.9	11.5	5

Table 1: Passing percentage for each tested granular fraction.

6 TESTS USED FOR CHARACTERIZING ASPHALT CONCRETES

Many laboratory tests were conducted on asphalt concretes, including:

- Compactability, measured from the gyratory shear compactor (GSC), following the requirements of the standard NF EN 12697-31.
- Water resistance, measured from the so-called Duriez test (NF EN 12697-12) which consists of direct compression test on two sets of six cylindrical samples, one set of six samples tested after conditioning in water. If the mean ratio of the results after and before conditioning is above a certain value, the material is deemed to be acceptable.
- Resistance to rutting at 60°C, characterized with the French wheel tracking tester (FWTT) in accordance with NF EN 12697-22.
- Secant stiffness modulus at 15°C-0.02s, following the requirements of NF EN 12697-26.
- Complex stiffness modulus and fatigue resistance at 10°C-25Hz, following the NF EN 12697-24 requirements. The criterion that is used to determine the mix fatigue life is the classical one, referenced as N_{f50}. It corresponds to the number of cycles for which, either the complex modulus decreases of 50% of its initial value, or a sudden failure occurs. The value of the strain amplitude leading to failure at one million cycles is hereafter called ε_6.

7 AGGREGATE PACKING OPTIMIZATION RESULTS

Figure 6 left (resp. right) illustrates the iterative aggregate packing optimization of a ternary 10/14-0/2-filler (resp. a quaternary 10/14-0/4-0/2-filler) aggregate combination, by using the gyratory shear compactor (GSC) on aggregates only –without any bitumen– as already detailed in section 4.

Unlike Fig 6 left, Fig 6 right shows a noticeable difference between the calculated $e(p_X)$ and $e(p_T)$, from one hand, and the corresponding experimental data, from the other hand. The reason for such a difference mainly lies in the fact that $d_{0/2}/d_{10/14} = 0.052 < d_{0/4}/d_{10/14} = 0.165$, hence the slight interference in the case of the 0/4-10/14 binary aggregate composition.

For both 10/14-0/2-filler and 10/14-0/4-0/2-filler configurations, considering the packing optimization with the 0/2 fraction as "fines", the optimal p value (optimal proportion of coarse particles) was arbitrarily fixed to a slightly lower value than p_T. Indeed, the following and last stage of aggregate packing optimization with filler generally led to all too high filler contents (from both economic and practical outlook on the asphalt plant), far beyond 10%.

Insofar the 10/14-0/2-filler ternary combination is concerned, the aggregate packing optimization consists of two sets of GSC measurements at 20 gyrations:

- the first set of GSC tests is performed in order to determine the optimal 10/14-0/2 binary blend (in this case, p=70% (i.e. 70% 10/14 and 30% 0/2), cf. Fig 6 left);
- the second set of GSC tests is performed to determine the optimal 10/14-0/2-filler ternary blend, which is considered as a binary blend: the previous 70% 10/14-30% 0/2 blend is considered as the "coarse fraction", whereas the filler is considered as the "fine fraction". In this case, the optimal coarse ratio is found to be p_T=89.4%.

Therefore the optimal 10/14-0/2-filler ternary blend is the following:

- 10/14 content: 62.58% (=0.7*0.894)
- 0/2 content: 26.70% (=(1-0.7)*0.894=0.3*0.894)
- added filler content: 10.6% (=1-0.894)

As regards the 10/14-0/4-0/2-filler quaternary blend (Fig. 6 right), the packing optimization consists of three sets of GSC measurements at 20 gyrations.

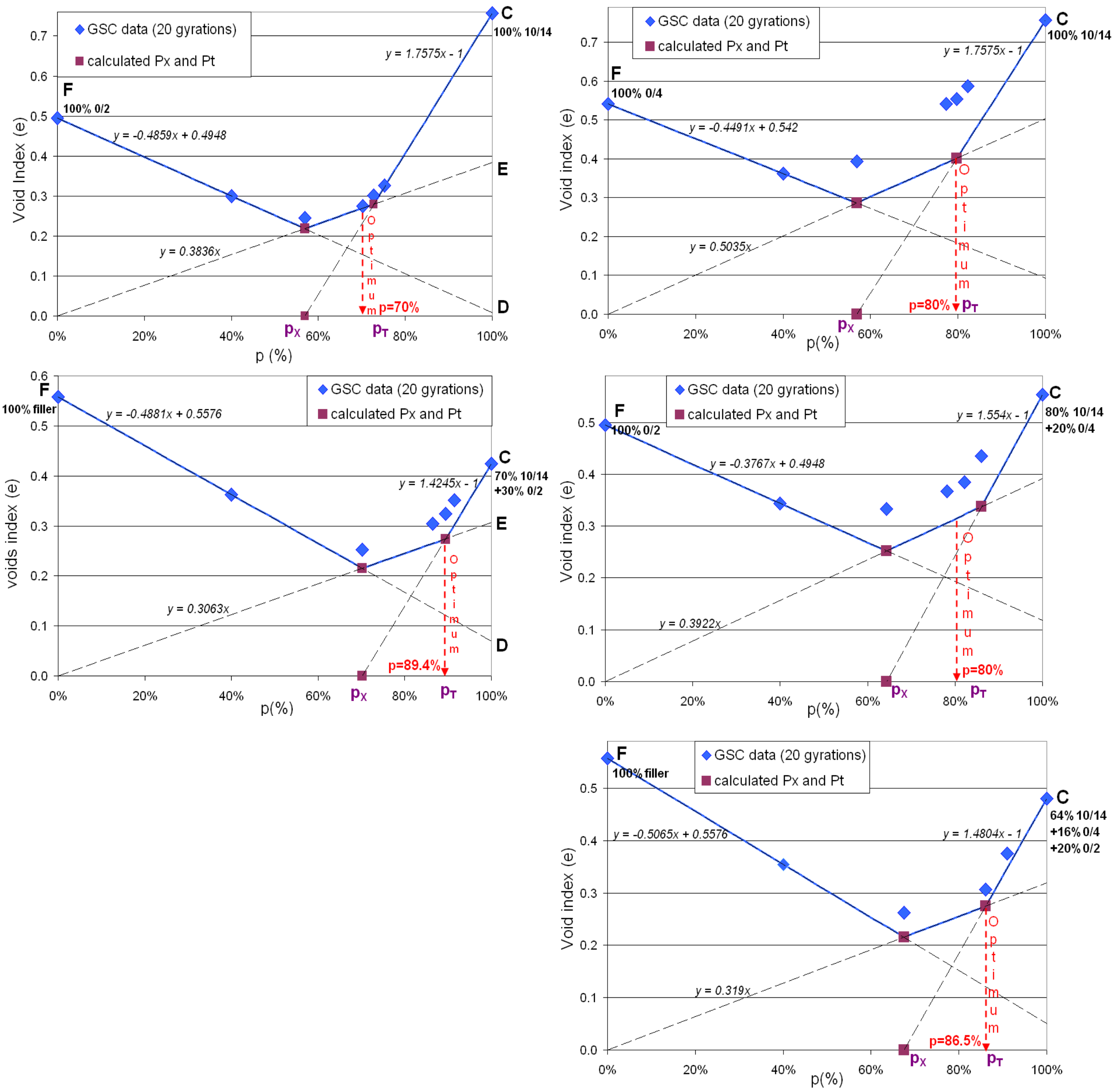

Figure 6: (left) two-step iterative optimization of the 10/14-0/2-filler ternary aggregate blend; (right) three-step iterative optimization of the 10/14-0/4-0/2-filler quaternary blend.

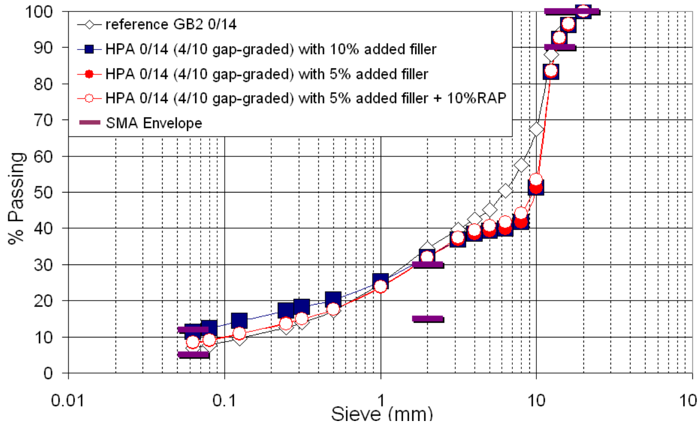

Figure 7: Gradation curves for the optimal 10/14-0/4-0/2-filler quaternary aggregate blends.

Owing to a slight segregation observed for the 10/14-0/2-filler ternary blend, the 10/14-0/4-0/2-filler quaternary blend was first preferred to start the laboratory campaign on asphalt concretes (cf. next section). For both practical and economical reasons, two additional gradations –very close to the optimal one– with only 5% filler content were studied: the first one without RAP, the second one with 10% RAP. Indeed, the metering of 10% added filler is not convenient on most asphalt plants. Figure 7 gives the gradation curves of each tested asphalt concrete.

8 PERFORMANCES OF ASPHALT MIXES PRODUCED WITH SUCH A METHOD

Richness modulus (k) is essentially the ratio of bitumen to surface area of aggregate and thus an estimation of binder film thickness (Corté & Di Benedetto 2004). This parameter was kept constant and equal to 2.6, whatever the tested asphalt concrete (binder content in volume is also given in Table 2). Table 2 presents the mechanical assessment of the developed high-performance asphalts (HPAs) compared to the reference Grave Bitume GB2 material:

- Density increased by 2.3% up to 3.8% at 100 gyrations. Yet, the use of 10% (continuously graded) RAP slightly decreases the compacting ability of the developed HPA, which indicates that non-negligible interference effects do occur between aggregate particles.
- Direct compressive strength, measured from the so-called Duriez test at 18°C, is also truly enhanced (a difference from 1.7MPa up to 2.5MPa is obtained).
- Moisture resistance (Duriez ratio) is far above the minimum specification value for typical GB2. Nonetheless, the moisture resistance of the three tested HPAs is slightly below that of reference GB2. Further work is needed since there is no clear reason for any decrease (even slight) in the moisture resistance of such well-interlocked and dense mixtures.
- Considering the rutting resistance at 60°C, the added filler content of 10% brings about a clear increase in the permanent deformation susceptibility (rut depth of 10.2% at 10,000 cycles). Even with very good compactability, compressive strength, moisture resistance and even stiffness modulus, such HPA with 10% of added limestone filler is bound to develop high accumulated plastic deformations, *i.e.* rutting problems. Yet, the HPAs with 5% added filler exhibit great rutting resistance. This confirms the previous work of Perraton (2007).
- Stiffness modulus at 15°C-0.02s is truly increased (in the range of 11% to 15%).
- The very first results of HPA fatigue resistance appear as comparable to those of the reference GB2 material. Additional fatigue tests are planned in the EIFFAGE Travaux Publics research centre.

Formula					**E** (MPa) 15°C-0.02s	ε_6 10°C-25Hz (µstrains)
	% added filler	k	%vol. binder	%RAP		
Specifications for "Grave Bitume 2" (GB2)					*>9000*	*>80*
GB2	-	2.6	10.0	0	14,300 at 4.1% void	86
HPA	10		10.6	0	16,400 at 2.6% void	to be done
	5		10.0	0	15,900 at 2.7% void	89
			10.0	10	16,400 at 2.7% void	90

Table 2: Mechanical performances of the three developed high-performance asphalts (HPAs) compared to the reference Grave Bitume GB2 material (constant richness modulus: k=2.6).

9 CONCLUSIONS

Starting from basic concepts associated with granular combinations, the aggregate packing methods first developed in the field of high-performance cement concretes were successfully transposed to the field of asphalt mixes and enabled the design of high-performance asphalts.

A continuously-graded dense "Grave Bitume" traditionally used for base courses in France, was studied, acting as a "reference" material. Lab assessment of the gap-graded dense mixes were found to be very encouraging:

- Compacting ability, evaluated with gyratory shear compaction, is somewhat enhanced. With the same compaction energy, density values are more or less 3% higher,
- Moisture resistance using the Duriez test does not appear to be highly influenced by the optimal gradations used in this study. Further work is planned to confirm this point,
- Compressive strength values, determined at 18°C, increase by about 20%,
- Rutting resistance is not influenced by the optimal gradations used on the condition that the filler addition does not exceed 5%. In the present study, a filler addition of 10% (close to the optimal value leading to a minimal porosity of the aggregate squeleton (after 20 gyrations at GSC), without any interference with the intermediate and coarse particles) makes the asphalt mixes bound to rutting. Further work with a 7.5% filler addition will be performed,
- Secant stiffness modulus at 15°C-0.02s is truly increased (in the range of 11% to 15%),
- The HPA fatigue resistance, evaluated at 10°C-25Hz, appears as comparable to those of the reference GB2 material. Further work is planned to confirm this point.

From our results, the use of "optimal" and dense gap-graded aggregate compositions brings about better compacting ability, better compressive strength and stiffness modulus of asphalt concretes. Additional aggregate natures and fractions are to be tested to confirm these results.

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