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

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A (very) long trip from Lyon to Melbourne
We won’t speak (a lot) about RUGBY...
Outline

✓ Theoretical background on aggregate packing
  ▪ Mix of an extremely fine aggregate with a coarse aggregate

✓ Use of Gyratory Compactor for aggregate packing optimization

✓ Innovative combination of skip gradings & PMB’s

✓ Testing of the so-called GB5® bituminous mixes & Results

✓ Conclusions
Objectives

✓ In the context of higher traffic intensities, both higher performances and increased longevity are needed

✓ In the context of ever-increasing economic & environmental pressures, decrease in the use of natural resources (aggregate & bitumen) is highly desired

« Make more with less »
« Pave for longer with lesser quantity of raw materials »
European experience of 2 “parallel worlds”

✓ The world of asphalt concretes

- 1980’s: development of high-modulus asphalts in order to decrease the base course thickness
  - use of hard bitumens (Pen@25°C<30dmm)
  - increase in binder content
  - the so-called EME2 is the reference material for Perpetual Pavement

- 1970’s: development of PMB’s
  - for economic reasons, their use is limited to wearing courses

✓ The world of cement concretes

- Theories of Caquot (1937), Faury (1944), Dreux (1970), Baron (1982) on aggregate packing and cement concretes with “minimal porosity”
  - ‘birth’ of High-Performance Cement Concretes (HPC)

- Is it possible to transpose such approaches in the field of asphalts?
What Influences the Results?

Gradation
- continuously-graded, gap-graded

Shape
- flat & elongated, cubical, round

Surface Texture (micro-texture)
- smooth, rough

Type & Amount of Compactive Effort
- static pressure, impact or shearing

Layer Thickness
Background on aggregate packing

The most prevalent "ideal" **continuous** gradation is based on the following empirical equation:

\[
P = 100\left(\frac{d}{D}\right)^b
\]

where

- **P**: percentage of aggregate, by weight, passing a particular sieve
- **d**: size of openings in the particular sieve, in millimeters
- **D**: maximum size of aggregate particles in the gradation, in millimeters
- **b**: coefficient. **Nijboer** (1948) & **Yoder** (1959) found that the maximum density of any continuously-graded compacted mix is obtained when **b** equals **0.45 or 0.5**
Background on aggregate packing

\[ P = 100(d/D)^{0.45} \] is the ‘reference line’ in the US

Supposed to be the “Maximum Density Line” for any continuous gradation
Background on aggregate packing

Interparticle interaction on the void index [Caquot 1937]

"wall effect"

Additional void interstices due to the wall effect

"loosening effect"

Minimization of the number of coarse aggregates contacts

Loss of contact between coarse particles

Solid D

Solid d

void
Background on aggregate packing

Baron’s approach for cement concretes [1982]
Evolution of void index (e) according to the coarse agg. proportion (p)

- Mix with high fines content
  \( p < p_x \)
  \( e = F(1-p) + Dp \)

- Mix with medium fines content
  \( p_x < p < p_T \)
  \( e = Ep \)

- Mix with low fines content
  \( p > p_T \)
  \( e = (C+1)p - 1 \)

Optimal proportion of coarse particles

\( p_x \)
\( p_T \)
Background on aggregate packing

Shift in aggregate porosity Vs average particle dimension

[Furnas 1928, Powers 1968, Olard & Perraton 2010]

- Shift in aggregate porosity Vs average particle dimension
  - $d_{\text{Fine}}$ too close to $d_{\text{Coarse}}$ ⇒ Interparticle interaction
  - $d_{\text{Fine}} << d_{\text{Coarse}}$ ⇒ Next to no interparticle interaction

Linear Effect

Nonlinear effect

Void index evolution without any wall effect
- $e = F(1-p)$

Void index evolution without any interference effect
- $e = (C + 1)p - 1$
Materials

- 4 Bitumens:
  - 35/50 & 35/50+2.5%SBS X-linked
  - semi-blown ‘35/50B’ & 35/50B+2.5%SBS X-linked

- Diorite aggregates:
  - 10/14mm, 0/4mm, 0/2mm (4/10mm gap) \( \frac{d_{\text{Fine}}}{d_{\text{Coarse}}} = \frac{2}{12} = 0.16 \)
  - limestone filler

- Binder content: 4.0%
Proposed way of optimizing aggregate packing

Use of Gyratory Compactor (20 gyrations)
Proposed way of aggregate packing optimization

Stage 1

0/4mm fraction is ‘dominant’

10/14mm fraction is ‘dominant’

GSC data (20 gyrations)

Calculated P_x and P_t

y = 1.7575x - 1

y = -0.4491x + 0.542

p_x = 60%

p_T = 80%

100% 10/14

100% 0/4
Proposed way of aggregate packing optimization

Stage 1

Stage 2

Void index (e)

0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0%
20%
40%
60%
80%
100%

GSC data (20 gyrations)
calculated Pₓ and Pₜ

y = 1.7575x - 1

y = 1.554x - 1

y = -0.3767x + 0.4948

y = 0.3922x

GSC data (20 gyrations)
calculated Pₓ and Pₜ

100% 0/4
100% 0/2
80% 10/14
80% 10/14
+20% 0/4

F

C
Proposed way of aggregate packing optimization

Stage 3

Graph showing the relationship between void index (e) and percentage (p) with two linear equations:

1. \( y = -0.5065x + 0.5576 \)
2. \( y = 1.4804x - 1 \)

Points F and C are highlighted, with F representing 100% filler and C representing 64% 10/14, 16% 0/4, and 20% 0/2.
Proposed way of aggregate packing optimization

- Like the ‘Matriochkas’ technique, the previous optimal quaternary granular blend (10/14 - 0/4 - 0/2 – filler) was obtained from the following iterative 3-step procedure:

  + Step 1: optimization of the 10/14 – 0/4 blend
  + Step 2: optimal content of 0/2 in the blend obtained at Step 1
  + Step 3: optimal content of filler in the blend obtained at Step 2

- Generalization to a (n-1)-step procedure when n granular fractions are considered
‘Optimal’ gradation curves: 10/14-0/4-0/2-filler

- Reference GB2 0/14
- HPA 0/14 (4/10 gap-graded) with 10% added filler
- HPA 0/14 (4/10 gap-graded) with 5% added filler
- HPA 0/14 (4/10 gap-graded) with 5% added filler + 10%RAP
- SMA Envelope

Slightly higher filler content
4/10mm discontinuity
‘Optimal’ gradation curves: 10/14-0/4-0/2-filler

- reference GB2 0/14
- HPA 0/14 (4/10 gap-graded)
- HPA 0/14 (4/10 gap-graded) + 10% RAP
- Maximum density line (for continuous gradations)
Laboratory evaluation of asphalt mixes

- Compacting ability [NF EN 12697-31]: **Gyratory compactor**

- Moisture resistance [NF EN 12697-12]: **Duriez test**

- Rutting resistance at 60°C [NF EN 12697-22]: **Wheel tracking test**

- **Complex modulus test** at 15°C-10Hz [NF EN 12697-26]

- **Fatigue test** at 10°C-25Hz [NF EN 12697-24]
### Results (1/4)

<table>
<thead>
<tr>
<th>Formula</th>
<th>GC 100 gyrations</th>
<th>Duriez Test</th>
<th>Rut Depth $3 \times 10^4$ cycles (mm)</th>
<th>E 15C-10Hz (MPa)</th>
<th>$\varepsilon_{60}$ 10C-25Hz ($10^{-6}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GB2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35/50</td>
<td>9.7</td>
<td>19.7</td>
<td>10.1</td>
<td>4.1</td>
<td>14,200 at 4.1%air</td>
</tr>
<tr>
<td>35/50 +2.5%SBS 5.7</td>
<td>15.7</td>
<td>12.3</td>
<td>2.4</td>
<td>15,600 at 3.2%air</td>
<td>115</td>
</tr>
<tr>
<td>GB5®</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35/50</td>
<td>5.9</td>
<td>15.9</td>
<td>11.8</td>
<td>5.1</td>
<td>16,500 at 2.7%air</td>
</tr>
<tr>
<td>35/45B</td>
<td>5.8</td>
<td>15.8</td>
<td>12.7</td>
<td>2.5</td>
<td>13,100 at 2.9%air</td>
</tr>
<tr>
<td>35/45B +2.5%SBS 5.7</td>
<td>15.7</td>
<td>13.1</td>
<td>3.0</td>
<td>13,700 at 2.5%air</td>
<td>130</td>
</tr>
</tbody>
</table>

GB5® High-Performance Asphalts — Buleen, November 20, 2012
✓ Use of ‘optimal’ GB5® skip gradings lead to significant improvements in:
  ✓ Compactability
  ✓ Compressive strength
  ✓ Stiffness modulus

✓ Use of 4.0% of semi-blown and/or polymer modified bitumen leads to improved rutting resistance & fatigue resistance
Results (3/4): $E^*$ Master Curve @ 15°C

Influence of the proposed gap-gradation

$E_0 \approx 100\text{MPa}$

$E_0 \approx 280\text{MPa}$

! Increase in the static modulus BY A FACTOR 3 !
Results (4/4): Cole-Cole Diagram

influence of the proposed gap-gradation

![Cole-Cole Diagram](image)

- Increase in the glassy modulus BY 20%!
  - $E_\infty \approx 38000 \text{MPa}$
  - $E_\infty \approx 46000 \text{MPa}$
Comparative Pavement Design
*(in France: realized at 15°C & 10Hz)*

<table>
<thead>
<tr>
<th></th>
<th>Traditional Solution</th>
<th>Innovative GB5® Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EME2</strong></td>
<td>EME2 Binder content=5,7%</td>
<td>GB5 35/45B Binder content= 4%</td>
</tr>
<tr>
<td><strong>Overlay</strong></td>
<td>4cm BBM</td>
<td>4cm BBM</td>
</tr>
<tr>
<td><strong>Base course</strong></td>
<td>16cm EME2</td>
<td>14cm GB5</td>
</tr>
<tr>
<td><strong>Difference in base layer thickness</strong></td>
<td>- 2cm (- 10%)</td>
<td>- 4cm (- 20%)</td>
</tr>
<tr>
<td><strong>Difference in aggregate quantity</strong></td>
<td>Reference</td>
<td>- 10%</td>
</tr>
<tr>
<td><strong>Difference in bitumen quantity</strong></td>
<td>- 28%</td>
<td>- 39%</td>
</tr>
<tr>
<td><strong>Difference in materials cost/m²</strong></td>
<td>-23%</td>
<td>-27%</td>
</tr>
</tbody>
</table>

The proposed mix design makes SBS affordable in base courses!
2010: some GB5® trials
2011: GB5® roadworks on A43 & A41N highways with PMB Biprene® & HiPMB Orthoprene®
GB5® 0/14 (4/10 gap)
‘Budillon-Rabatel’ aggregate + 15% RAP + 3.5% PMB (‘Biprene® 41’)
\[ E^*(15^\circ C-10Hz) = 17,500\text{MPa} \] & \[ \varepsilon_6 = 133 \times 10^{-6} \]
GB5® 0/14 (4/10 gap)
‘Budillon-Rabatel’ aggregate + 15% RAP + 3.5% HiPMB (‘Orthoprene®’)
E*(15°C-10Hz)=11,000MPa & Fatigue(10°C-25Hz) εf=205 10^-6

4.4% air on the field
2011: GB5® roadworks on A43 & A41N highways
31,000T with PMB Biprene® & HiPMB Orthoprene®
2011: GB5® roadworks on A43 & A41N highways
31,000T with PMB Biprene® & HiPMB Orthoprene®

continuous
0/14mm gradation

0/14mm gradation
(4/10mm gap-graded)
2012: In-situ follow-up of GB5® & EME2 on A41N highway
2012: GB5® roadwork on HONFLEUR Harbor (7,000T)

2 trial sections with low-emission & low-energy asphalt LEA®:
- LEA® 90°C
- LEA® 130°C
Conclusions

- Transposition of aggregate packing methods first developed in the field of high-performance cement concretes

- Our experimental method for aggregate packing optimization is based on GSC at 20 gyrations. Depending on the number of used granular fractions \( n \), the optimization is done after \( n-1 \) steps.

- The ‘optimal’ GB5® gap gradings lead to:
  
  + excellent compactability
  + enhanced compressive strength and stiffness modulus

- The use of about 4% of semi-blown and/or polymer modified bitumens leads to a fatigue resistance enhanced by 40% at least
Conclusions

- Optimized gradation leads to high density (95%) with low bitumen content (4% to 4.5%) ⇒ interesting economic outlook

- Improved compressive strength & stiffness modulus ⇒ no need of hard bitumen grades

- Patented alternative to ‘EME’ with softer grades as usual (Pen>30) and lower binder content for high quality base & binder layers

- 40 aggregate natures combined with different gradations have been tested in Eiffage lab (Hot- or Warm- or Cold-Mix Asphalts)

- 250,000 tons of GB5® mixes with PMB’s already paved in France since this mix design makes the PMB affordable in base courses
Perspectives for 2013

- Generalization, in France, of GB5® mixes with PMB’s as a cost-effective alternative for long-life base courses

- Implementation of the GB5® mix design in other countries (validity with other materials, climates...).

- Further work:
  - role of aggregate angularity & surface texture
  - 2D Imaging Analysis

(Hammoum, Bertaud, Bonnet, 2002 et 2003)
Make SBS affordable in base courses, optimize aggregates first! (think global)

Thank you for your attention!