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 Pretoria
EIFFAGE is a European leader in construction works and concessions.

EIFFAGE Travaux Publics is the group’s roads and railways branch.

Road material production line:
- Aggregate production: 18 millions tons.
- Asphalt production: 12 millions tons.
- Binder production: 200 000 tons of emulsions, fluxed bitumens & PMBs.

GB5® technology transfer from EIFFAGE to MUCH ASPHALT (KwaZulu-Natal)
I won’t speak (a lot) about RUGBY...
Outline

- Background on EME2 mix design
- Theoretical background on aggregate packing
- Use of Gyratory Compactor for aggregate packing optimization
- Innovative combination of gap gradings & PMB’s
- Testing of the so-called GB5® mixes, results & achievements
- Perspectives
French standard NFP98140
(1992, Updated 1999)

Typical characteristics:
- Binder content ≈ 6% by mass of aggregate
- Hard binder: Pen 10-30
- Low air voids content (<6%)

Specs of EME2:

\[ E^* > 14000 \text{ MPa } (15^\circ \text{C} \text{ & } 10 \text{ Hz}) \]
on cylindrical or trapezoidal samples

\[ \varepsilon_6 > 130 \times 10^{-6} \text{ } \mu \text{s } (10^\circ \text{C} \text{ & } 25 \text{ Hz}) \]
on trapezoidal samples (2PBT)
**Background on EME2 pavement design**

*Kc* is a **calibration coef** determined by modeling the *in-situ* behavior of test sections (**Transfer function and risk assessment technique**)

\[
\varepsilon_{t,ad} = \varepsilon (NE, \theta_{eq}, f) k_r k_c k_s
\]

<table>
<thead>
<tr>
<th>Material</th>
<th>Kc</th>
<th>≈ 30% bonus vs EME</th>
<th>≈ in-situ brittle behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>road base asphalt concrete, GB</td>
<td>1.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>bituminous concrete, BB</td>
<td>1.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>high modulus asphalt concrete, EME</td>
<td>1</td>
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<td></td>
</tr>
</tbody>
</table>

Accelerated Load Testing (ALT) facility at IFSTTAR Nantes (France)
A good **compaction is a top priority for a good durability**: 
- if density is > 97%: there is a real **risk of rutting**
- if density is < 94%, the performances (E*15°C and $\varepsilon_6$) are **below specs**

If the manufacturing temperature is >190°C, it brings about accelerated aging
Background on EME2: “yes, it may rut!”

- No risk of rutting @ 1 Hz [Wheel tracker EN 12697-22]
- Risk of rutting with buses running on rubber tires and guided by a single central rail
- Risk of rutting under heavy static pressure on harbor platforms
EME2 0/20 mix design with high RAP content

How would we recycle the RA from EME2 given that we are starting from stiff binder?
✓ In France, EME2 appeared in late 1980’s. It was developed during the 1990’s.

✓ First High-Rate Recycling roadworks (with Astec Double Barrel Plant) were done in France by EIFFAGE in the very onset of 1990’s.

✓ We are currently recycling at 50% some old EME2 that were initially designed with 50% RA … (!)

✓ What is the influence of multi-recycling?

Objectives of the proposed approach

✓ 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 HiMA to decrease the base course thickness
  - use of hard bitumens (Pen@25°C<30dmm)
  - increase in binder content (up to 6%)
  - 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
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. \textit{Nijboer} (1948) & \textit{Yoder} (1959) found that the maximum density of any continuously-graded compacted mix is obtained when \( b \) equals \textbf{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.
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
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**
  \[ p > p_T \]
  \[ e = (C+1) - 1 \]

**Optimal proportion of coarse particles**
Background on aggregate packing

Shift in aggregate porosity Vs average particle dimension

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

**Diameter Ratio**

- $d_{\text{Fine}}$ too close to $d_{\text{Coarse}}$ ⇒ Interparticle interaction
- $d_{\text{Fine}} << d_{\text{Coarse}}$ ⇒ Next to no interparticle interaction
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)

- Attrition
- Segregation
- Abrasion
Proposed way of aggregate packing optimization

Stage 1

0/4 mm fraction is ‘dominant’

10/14 mm fraction is ‘dominant’

\[ y = 0.5035x \]

\[ y = -0.4491x + 0.542 \]

\[ y = 1.7575x - 1 \]
Proposed way of aggregate packing optimization

Stage 1

- GSC data (20 gyrations)
- Calculated Pₓ and Pₜ

Stage 2

- GSC data (20 gyrations)
- Calculated Pₓ and Pₜ

Equations:

- Stage 1: $y = 1.7575x - 1$
- Stage 2: $y = -0.3767x + 0.4948$

Points:

- F: 100% 0/4
- C: 100% 10/14
- 80% 10/14 + 20% 0/4

Graph showing void index (e) vs. p(%) with different stages and calculations.
Proposed way of aggregate packing optimization

Stage 3

Void index (e) vs. p(%) graph with data points and equations:
- $y = -0.5065x + 0.5576$ for high filler content
- $y = 1.4804x - 1$ for calculated $P_x$ and $P_t$

Plot points and lines for optimization analysis.

Points:
- $P_x$
- $P_t$
- $P=86.5\%$

Composition:
- 64% 10/14
- +16% 0/4
- +20% 0/2
- 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)

**Fixed binder content=4.0%**

<table>
<thead>
<tr>
<th><strong>Formula</strong></th>
<th><strong>GC 100 gyrations</strong></th>
<th><strong>Duriez Test</strong></th>
<th><strong>Rut Depth 3 $10^4$ cycles (mm)</strong></th>
<th><strong>E 15C-10Hz (MPa)</strong></th>
<th><strong>$\varepsilon_6$ 10C-25Hz ($10^{-6}$)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>GB2</td>
<td><strong>Binder nature</strong></td>
<td>%Air VMA R Moist. Res. (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GB2</td>
<td>35/50</td>
<td>9.7 19.7 10.1 93</td>
<td>4.1</td>
<td>14,200 at 4.1%air</td>
<td>86</td>
</tr>
<tr>
<td>GB2</td>
<td>35/50 +2.5%SBS</td>
<td>5.9 15.9 11.8 83</td>
<td>5.1</td>
<td>16,500 at 2.7%air</td>
<td>89</td>
</tr>
<tr>
<td>gap graded</td>
<td>GB5®</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GB5®</td>
<td>35/50</td>
<td>5.7 15.7 12.3 93</td>
<td>2.4</td>
<td>15,600 at 3.2%air</td>
<td>115</td>
</tr>
<tr>
<td>GB5®</td>
<td>35/45B</td>
<td>5.8 15.8 12.7 92</td>
<td>2.5</td>
<td>13,100 at 2.9%air</td>
<td>115</td>
</tr>
<tr>
<td>GB5®</td>
<td>35/45B +2.5%SBS</td>
<td>5.7 15.7 13.1 91</td>
<td>3.0</td>
<td>13,700 at 2.5%air</td>
<td>130</td>
</tr>
</tbody>
</table>
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

Increase in the static modulus BY A FACTOR 3!

$E_0 \approx 280 \text{MPa}$

$E_0 \approx 100 \text{MPa}$
Results (4/4): Cole-Cole Diagram

influence of the proposed gap-gradation

GB2 0/14_Reference
GB5 0/14_4/10 gap-graded

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></td>
<td>EME2</td>
<td>GB5 35/45B</td>
</tr>
<tr>
<td>Overlay</td>
<td>4cm BBM</td>
<td>4cm BBM</td>
</tr>
<tr>
<td>Base course</td>
<td>16cm EME2</td>
<td>14cm GB5</td>
</tr>
<tr>
<td>Difference in base layer thickness</td>
<td>-2cm (-10%)</td>
<td>-4cm (-20%)</td>
</tr>
<tr>
<td>Difference in aggregate quantity</td>
<td>Reference</td>
<td>-10%</td>
</tr>
<tr>
<td>Difference in bitumen quantity</td>
<td>-28%</td>
<td>-39%</td>
</tr>
<tr>
<td>Difference in materials cost/m²</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
31,000T with PMB Biprene® & HiPMB Orthoprene®

GB5® High-Performance Asphalts — CSIR Pretoria, November 7, 2013
GB5® 0/14 (4/10 gap)
‘Budillon-Rabatel’ aggregate + 15% RAP + 3.5% PMB (‘Biprene® 41’)
$E^* (15^\circ C - 10Hz) = 17,500\, MPa$ & $\text{Fatigue}(10^\circ C - 25Hz) \varepsilon_6 = 133 \times 10^{-6}$

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

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) ε₆=205 10⁻⁶

4.4% air on the field
2011: GB5® roadworks on A43 & A41N highways
31,000T with PMB Biprene® & HiPMB Orthoprene®
2012: In-situ follow-up of GB5® & EME2 on A41N highway
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 (<94-98%) with **low bitumen content (3.9% to 5.0%)** ⇒ 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

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

- **465,000 tons** of GB5® mixes with PMB’s already paved in France since this mix design makes the PMB affordable in base courses
Many other implementations...

HONFLEUR Harbor – 2012

Airfields

Railways

Bridge decks
Perspectives

- 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 with IFSTTAR (French Ministry of Roads) and the Universities of Lyon and Egletons (France):
  + role of aggregate angularity & surface texture
  + 2D Imaging Analysis & 3D μ-tomography
Perspectives: Adaptation of Level 4 Testing

\! Pay attention \!

\( \varepsilon_6 \) is test configuration-dependent but 2PB results \( \approx \) 4PB results (?)

  (11 fatigue tests within the Rilem TC182)
Make SBS affordable in base courses, optimize aggregates first! (think global)

Thank you for your attention!

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