Use of accelerated pavement tests (APT) for development and evaluation of performance models

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LCPC
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Introduction

LCPC activities on pavement design and modelling:

- Contribution to development and evaluation of French pavement design method

- Development of models for

  Low traffic pavements: Non linear behaviour of soils and unbound granular materials, prediction of rutting

  Bituminous pavements: visco-elastic behaviour, fatigue, visco-plastic behaviour (rutting)

  Rigid pavements: study and modelling of reflective cracking
Introduction

Development of models is in close relation with accelerated pavement testing activities (APT).

LCPC APT equipments:
- Fatigue test track – large circular test track (pavement length 120 m)
- “FABAC” Machines: mobile machines – simulation of full wheel loading on small length (2 m)
LCPC Fatigue test track

Circular outdoor facility, built in 1984
Track width up to 6 m - length 122 m (radius 19.5m)
Radius of rotation: adjustable from 15 m to 20 m
Maximum speed 13.5 rpm (100 km/h at radius 19.5 m)
Transverse wandering of real traffic can be reproduced
Various types of loads from 8-ton single-axle to 30-ton multiple-axle (only a half-axle per arm)
3 test sites - one including a water table control system (pumping station)

Experiments performed in partnership with Road authorities or private companies
APT versus Performance Models

Advantages

• Well controlled pavement construction and experimentation conditions (load, traffic, temperature, …)
• Internal instrumentation and detailed monitoring of pavements
• Response in relatively short time owing to the acceleration of traffic
• Possibility to make comparative tests

Limits

• Not representative of real traffic & climatic variations
• Missing the ageing of materials
• AT LCPC : difficulty to pursue long term “research programs” due to cost and compatibility with “external demand” from private partners
Examples of evaluation of models using APT

- Experiment for the evaluation of fatigue behaviour
- Development and evaluation of a model for the prediction of rutting of unbound pavement layers SAMARIS project
- ALT experiment on airfield pavements
Experiment on fatigue behaviour
Objectives of the experiments

• Comparison of fatigue behaviour of different bituminous materials, with different binders
  - in the laboratory, using different fatigue tests
  - in pavements

• Evaluation of the French fatigue design approach for bituminous pavements

3 full scale experiments on the LCPC test track
Third “fatigue” experiment

4 structures: 8 or 10 cm thick bituminous layer
40 cm thick granular base
clayey subgrade: $E = 30$ to 40 MPa

3 bituminous materials:
- $BB_B$: Bituminous concrete with 50/70 grade bitumen (reference)
- $BB_S$: Bituminous concrete with 50/70 polymer modified bitumen
- $EME$: high modulus bituminous mix, with 10/20 grade bitumen

2 structures – 8 and 10 cm thick

Loading conditions:
- 65 kN dual wheel load, 72 km/h
- 3.2 million loads applied
<table>
<thead>
<tr>
<th>Structure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1 (BBB)</td>
<td>8 BB 0/14 à 5,4% de bitume 50/70</td>
</tr>
<tr>
<td>S2 (BBs)</td>
<td>8 BB 0/14 à 5,4% de bitume 50/70 + SBS</td>
</tr>
<tr>
<td>S3 (EME)</td>
<td>8 BB 0/14 à 6,2% de bitume 10/20</td>
</tr>
<tr>
<td>S4 (EME)</td>
<td>10 BB 0/14 à 6,2% de bitume 10/20</td>
</tr>
</tbody>
</table>

**Structure I**

Tracé fin : Fissuration à l'état final à 1000000 de passages.
En gras : Première fissuration à 452000 passages.

**Structure II**

Tracé fin : Fissuration à l'état final à 2145000 passages.
En gras : Première fissuration à 806000 passages.

**Structure III**

Tracé fin : Fissuration à l'état final à 2145000 passages.
En gras : Première fissuration à 656000 passages.

**Structure IV**

Zone particulière de fin de chantier
Tracé fin : Fissuration à l'état final à 3160000 passages.
En gras : Première fissuration à 1000000 de passages.
In situ performance of the 4 structures

Extent of cracking

Number of loads

Extent of cracking (%)
## Laboratory fatigue tests

### 5 different test procedures

<table>
<thead>
<tr>
<th>Procedure</th>
<th>$\theta$ (°C)</th>
<th>$f$ (Hz)</th>
<th>Type of loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controlled displacement test</td>
<td>1</td>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>Controlled force test</td>
<td>6</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>20</td>
<td>40</td>
</tr>
</tbody>
</table>
Fatigue design method

Criterion on maximum tensile strain:

\[ \varepsilon_{tad} = \varepsilon_6(\theta, f) \cdot \left(\frac{NE}{10^6}\right)^b \cdot k \]

\[ \varepsilon_6(\theta, f) : \text{Strain leading to failure for } 10^6 \text{ cycles, depending on temperature } \theta \text{ and frequency } f \]

\[ NE : \text{number of standard axle loads} \]

\[ b : \text{parameter} \]

\[ k : \text{various coefficients of correction, taking into account the risk of failure, the bearing capacity of the soil, the difference between the model and observed pavement behaviour} \]

**Predicted pavement life:**

\[ NE = 10^6 \cdot \left( \frac{\varepsilon_t}{k \cdot \varepsilon_6(\theta, f)} \right)^{1/b} \]
Results of laboratory fatigue tests

Values of failure strain $\varepsilon_6$ or failure stress $\sigma_6$

<table>
<thead>
<tr>
<th>Fatigue test procedure</th>
<th>$BB_B$</th>
<th>$BB_s$</th>
<th>EME</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 – strain control</td>
<td>147</td>
<td>237</td>
<td>133</td>
</tr>
<tr>
<td>Continuous – $\varepsilon_6$ ($\mu$strain)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 – strain control, with rest periods - $\varepsilon_6$ ($\mu$strain)</td>
<td>227</td>
<td>292</td>
<td>187</td>
</tr>
<tr>
<td>6 – stress control, continuous - $\sigma_6$ (MPa)</td>
<td>0.62</td>
<td>0.82</td>
<td></td>
</tr>
<tr>
<td>10 – stress control, with rest periods - $\sigma_6$ (MPa)</td>
<td>1.18</td>
<td>1.41</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Improved fatigue resistance of the polymer modified bitumen material

Improved fatigue life with rest periods

Different relative behaviour of the EME in stress or strain controlled tests
Comparison of design predictions and field performance

Calculation of correction coefficient $k$
($k = 1 \rightarrow$ exact prediction of pavement life)

\[
NE = 10^6 \cdot \left( \frac{\varepsilon_t}{k \cdot \varepsilon_6(\theta, f)} \right)^{1/b}
\]

<table>
<thead>
<tr>
<th>Fatigue test procedure</th>
<th>S1 $BB_B$</th>
<th>S2 $BB_s$</th>
<th>S3 EME 8 cm</th>
<th>S4 EME 10 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 – strain control</td>
<td>1,58</td>
<td>1,28</td>
<td>1,14</td>
<td>1,20</td>
</tr>
<tr>
<td>Continuous</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 – strain control,</td>
<td>1,04</td>
<td>1,03</td>
<td>0,8</td>
<td>0,8</td>
</tr>
<tr>
<td>with rest periods</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 – stress control,</td>
<td>3,21</td>
<td>2,57</td>
<td></td>
<td></td>
</tr>
<tr>
<td>continuous</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 – stress control,</td>
<td>1,73</td>
<td>1,49</td>
<td>1,10</td>
<td>1,08</td>
</tr>
<tr>
<td>with rest periods</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Conclusions – “fatigue experiment”

- Large differences in fatigue life predictions from different fatigue test procedures
- Fatigue tests with rest periods seem more representative of in situ behaviour
- Correction between in situ and lab behaviour dependent on the type of material (BB/EME)
- For the high modulus material (EME), the stress controlled fatigue test seems more representative of in situ behaviour.
Model for the prediction of rutting in unbound pavement layers

Developed in European project SAMARIS (2002-2006)
• SAMARIS : European project of the 5th PCRD
  • 2002-March 2006
  • Pavement and Structure Streams
• Task 5 : Development of a performance-based approach for the prediction of rutting of unbound pavement materials
  • Selection of permanent deformation models for unbound granular materials
  • Development of a structural method of calculation of rutting of unbound pavement layers
  • Comparison with results of ALT full scale pavement experiment
Laboratory study of permanent deformations

Test method: cyclic triaxial test
Advantages: realistic simulation of « stress paths » due to traffic loading

Test equipment

![Test equipment](image)

Test procedures

\[
p = \frac{(\sigma_1 + 2\sigma_3)}{3} \quad q = (\sigma_1 - \sigma_3)
\]

Graph showing:
- \(q/p\) values: 1, 1.5, 2, 2.5
- Stress vs. permanent axial strain
- Number of cycles vs. permanent axial strain
Selected permanent deformation models

2 modelling approaches:

- **Routine level**: utilizable for design
  
  Empirical permanent deformation model

  \[ \varepsilon^p_1(N) = f(N).g(p_{\text{max}}, q_{\text{max}}) \quad \text{Gidel (2001)} \]

- **Advanced level**: for research or analysis
  
  Elasto-plastic model with isotropic and kinematic hardening
  
  Chazallon (2000)
Example of calibration of empirical permanent deformation model

\[ \varepsilon_1^P (N) = \varepsilon_1^P 0 \left[ 1 - N^{-B} \right] \left[ \frac{L}{P_a} \right]^n \frac{1}{(m + \frac{s}{P_{max}} - \frac{q_{max}}{P_{max}})} \]

Gidel (2001)

Maraichère UGM

Cyclic Triaxial Tests at \( w = 5 \% \)
Structural modelling approach

Main hypothesis: For one cycle \( \delta \varepsilon^p \ll \varepsilon^e \)

→ Separate modelling of resilient behaviour and permanent deformations

Three steps:

1. 3D Finite Element calculation of the stress fields in the pavement structure using the resilient behaviour (non linear elastic, visco-elastic models)

2. Use of the stress fields and stress path to calculate permanent strains at the different points of the pavement in the vertical transversal plane

3. Calculation of the displacement field (rutting)
   - FEM method (program ORNI): 3D structural calculation.
   - Simplified method: integration of \( \varepsilon_{1p} \) in the vertical direction
Modelling of a full scale experiment

Experiment performed in 2003 on the LCPC fatigue test track

5 low traffic pavement structures (each 25 m long)
Full scale loading conditions: 65 kN dual wheel load, 72 km/h
1.5 million loads applied
Low water table level (-2.6 m)
Modelling of structure 4

Structure 4

UGM

Soil

6.5 cm

50 cm

2.24 m

Evolution of rutting and cracking

Lateral load distribution

![Graph showing lateral load distribution with percentage of loads (%)]

Evolution of rutting and cracking

![Graph showing evolution of rutting and cracking with mean rut depth, min. rut depth, max. rut depth, and extent of cracking (%)]
Modelling hypotheses

Modelling of rutting of UGM layer and subgrade (empirical model)
Simulation of load wandering and variations of temperature with traffic

Temperature distribution used for calculations

![Graph showing temperature distribution](image-url)
Examples of rut depth calculations

- Bituminous concrete: linear elastic
- UGM: non-linear elastic
- Empirical permanent deformation model
- Soil: linear elastic $E = 100$ MPa, $n = 0.35$

Loading: 65 kN load (single or dual wheel)
1.5 million loads - Constant temperature

Pavement structure:
- 8 cm bituminous concrete
- 50 cm UGM
- 220 cm soil

3D mesh modelling of resilient behaviour

Stress paths in UGM layer

- $z = -0.18$ m
- $z = -0.43$ m

Graph:
- $p$ (kPa) vs $q$ (kPa)
- $z = -0.18$ m
- $z = -0.43$ m
Calculation: influence of lateral load wandering

Evolution of maximum rut depth

Rut profiles after 1.5 million loads (single wheel):

- Low influence of lateral wandering

No lateral wandering

Lateral wandering (11 positions)
Influence of wearing course temperature

Evolution of maximum rut depth for different temperatures:

Rut profiles for different Temperatures (8.5 to 42.5°C)

⇒ Large influence of temperature
Comparison of model with experiment

Rutting of UGM only

Rutting of UGM + soil
Conclusions – Modelling of rutting

• First results encouraging but difficulty to simulate real in situ conditions (temperature and moisture variations…)

• Models predict a too fast stabilisation of permanent deformations

Perspectives:
- more detailed evaluation of ORNI
- Improvement of the models for unbound materials
- Modelling of permanent deformations of bituminous materials
Application of ALT to PM for airfield pavements
Airbus experimental program on flexible pavements – 1998-2003

Section D
AC 8 cm
BAC24 cm
UGA 1.40 m
CBR 3

Section C
AC 8 cm
BAC 24 cm
UGA 0.60 m
CBR 6

Section B
BBSG 8 cm
GB3 24 cm
GNT 20 cm
Sol CBR 10

Section A
BBSG 8 cm
GB3 24 cm
Sol CBR 15
Objectives of the Airbus experimental program

Tests on 4 instrumented pavement structures with soils of different bearing capacity (CBR 3 to 15)

Simulation of loads of different aircrafts, using a load simulator

Objectives:

Study of the behaviour of flexible airfield pavements under heavy aircraft loading conditions

Evaluation of the possibility of applying the French road pavement design method to flexible airfield pavements
Observed pavement performance

Main mode of distress of the flexible pavements = **rutting**

No fatigue cracking - densification of the bituminous layers under heavy loading

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**Evolution of rutting Section C – CBR 6**

![Image of pavement with measurements and graph showing evolution of rutting with number of loads and max rut depth in cm.](image-url)
Linear elastic calculations (ALIZE Software)

A380 Load configuration

Prediction of vertical strains at top of subgrade (structure C)

Measurement

Alizé software

Transversal profile XX (m)

-14 -12 -10 -8 -6 -4 -2 0 2

0 200 400 600 800 1000 1200

μ defined for 4 wheels and 6 wheels.
Results of linear elastic calculations

Good prediction of vertical strains in granular layers and subgrade

Poor prediction of maximum tensile strains at bottom of bituminous layers:

- Maximum values poorly simulated
- Discordance in directions of maximum tensile strains $\varepsilon_t$:

  Measurements: $\varepsilon_t$ transversal $> \varepsilon_t$ longitudinal
  Calculations: $\varepsilon_t$ longitudinal $> \varepsilon_t$ transversal

⇒ Attempt to take into account viscoelastic behaviour
Visco-elastic model for bituminous materials

HUET - SAYEGH MODEL (1965)

\[ E^*(\omega, \theta) = E_0 + \frac{E_\infty - E_0}{1 + \delta(i\omega\tau(\theta))^{-k} + (i\omega\tau(\theta))^{-h}} \]

\[ E_\infty = 25000 \text{ MPa} \; ; \; E_0 = 45 \text{ MPa} \; ; \]
\[ \delta = 2.7 \; ; \; k = 0.27 \; ; \; h = 0.7 \]
Modelling of a pavement under moving wheel load (in 3D)

Hypotheses:
- Constant speed $V$
- Constant properties along $x$

Calculation in the referential of the moving load $(O', X', y, z)$

$X' = x + Vt$

Static mechanical problem - no time steps

Modification of the visco-elastic law: becomes a non-local law

**Models available in CVCR:**

- Linear and non linear elasticity (Boyce model, k-$\theta$ model)
- Huet-Sayegh visco-elastic model
Viscoelastic modelling of strains at bottom of bituminous layers

Load : 6 wheel bogie
240 kN per wheel
First conclusions of the Airbus experiment

Main mode of distress of the flexible pavements = rutting
No detectable fatigue of bituminous layers, despite high tensile strains

Modelling of resilient behaviour
- Reasonable prediction of vertical strains in subgrade with linear elastic calculations.
- Visco-elastic modelling necessary to predict correctly strains in bituminous layers

Modelling of fatigue
- Need to adapt the fatigue tests to aeronautical loading conditions
  (high strain levels \(\approx 400 \, \mu\text{strain}\), lower number of cycles \((10^4)\))

Rutting:
Need to develop suitable design criteria and specifications for resistance to rutting of materials (bituminous and unbound)
General Conclusions

APT is a useful tool for:
- Identification of pavement deterioration mechanisms, and suitable models
- Validation of models

But validation on real pavement sections is also necessary

Recent research at LCPC on design/performance models focuses in particular on:
- Prediction of rutting
- Design of airfield pavements or special pavements (ex: industrial platforms) subject to heavy, complex loads
Conclusions

• Most models are “semi-rational” and do not describe perfectly in situ behaviour

• Determination of representative model parameters is essential (see fatigue experiments)

• Application of models to design is not straightforward:
  
  Need to apply “correction” factors or “safety” factors, based on comparisons with real pavement performance

  Need to develop better statistical approaches to take into account variability of
  
  Pavement and material properties
  Climatic conditions
  Traffic