Impact of Accelerated Pavement Testing (APT) on Pavement Engineering

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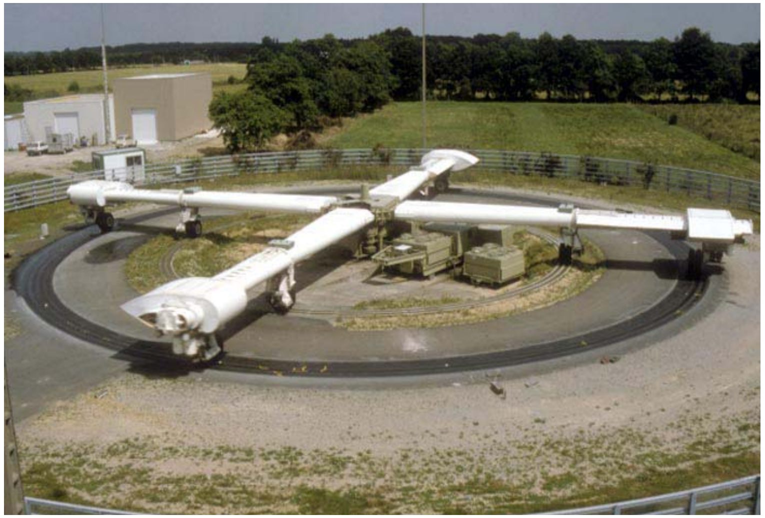
Introduction

LCPC activities on pavement design and modeling

- Contribution to the development and evaluation of French pavement design methodology
- Development of models for :
  - Low trafic 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
  - Airfield pavements ; impact of multi peak loading
- Design of innovative pavement structures

Presentation of LCPC APT facilities

Fatigue test track – large circular test track (pavement length 120 m)



“FABAC” Machines : mobile machines – simulation of full wheel loading on small length (2m)

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)
- Simulation 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, public or private companies, European research program

Use of APT for pavement engineering

Performance models – Two main different approaches, almost disconnected today ?

- Extensive survey campaigns of road networks (ex: at national scale) & global statistical approach
    - Tool: statistical analysis of broad data base, including equivalent pavement structures at different ages and supporting different traffic
    - Efficient way to derive “evolution laws” for PMS (maintenance & reinforcement planification) on standard pavement techniques

- Local mechanistic approach on test sections, looking more deeply to the nature of pavement materials and structures and to their behaviors
    - Tools: Real loading test, APT, laboratory testing, constitutive laws, structural models
    - More “introspective” approach ; specially recommended for innovation testing (materials, structures)

Advantages and limits of APT

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
- Good quantitative knowledge of the resilient behavior of the structures and damaging mechanisms

Limits

- Not representative of real traffic & climatic variations
- No long term ageing of materials
- Obtained results more comparative than intrinsic

Important rule for APT success

- Build a pavement dedicated to the distress to be studied and try not to mix pavement distresses
- Examples :
  - permanent deformation of bituminous layers
    ➔ use hydraulically bound base and sub base
  - fatigue of bituminous materials
    ➔ avoid using surface layer that could hide bottom to top cracks
  - ….

Examples of APT experiments and their impacts

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
- Determination of shift factor to be applied to High Modulus Mixtures (French EME)
- 3 full scale experiments on the LCPC test track (between 1990 and 1994)

Third “fatigue” experiment

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

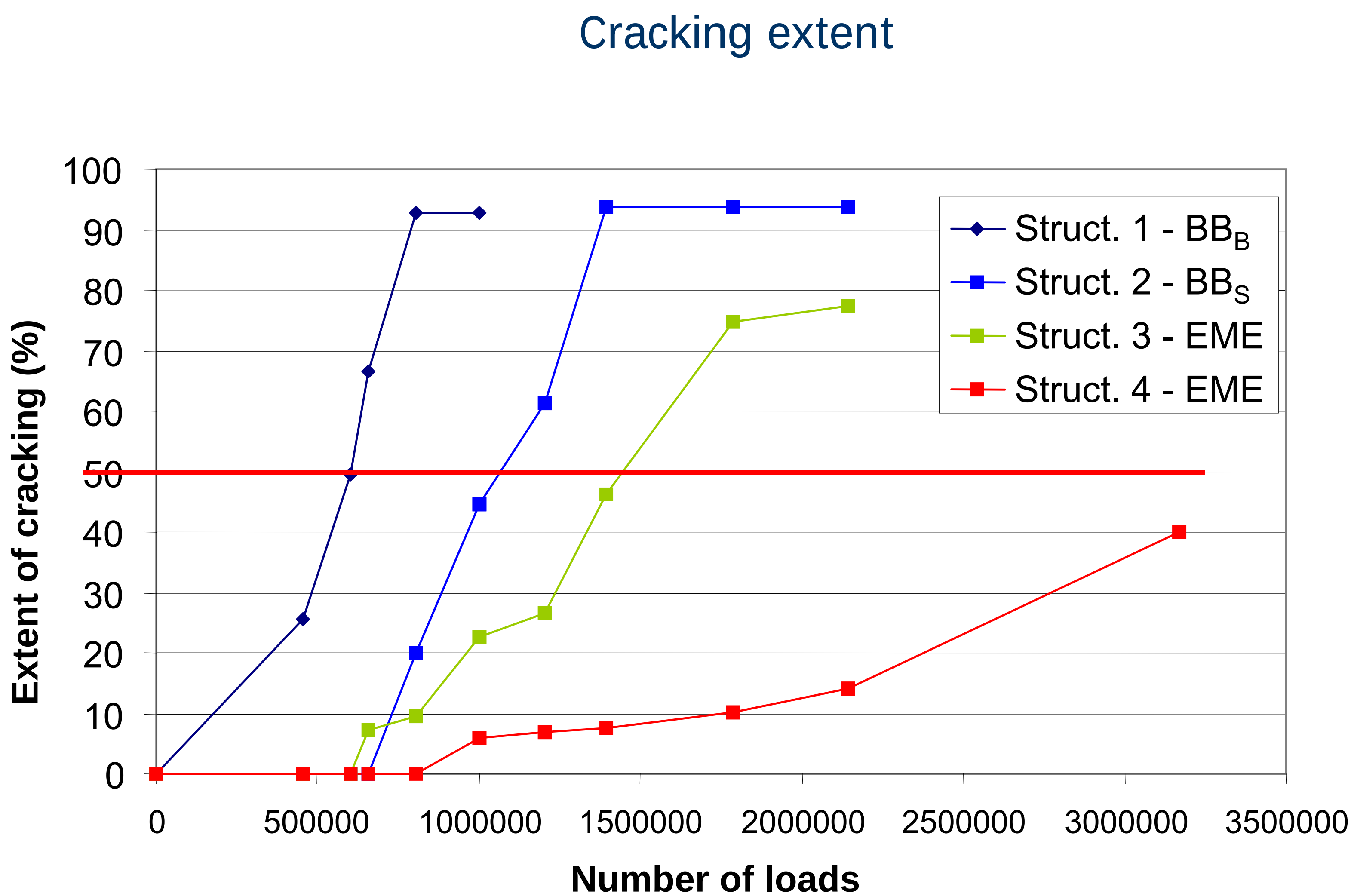
3 bituminous materials:

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

In situ performance of the 4 structures



Laboratory fatigue tests

5 different test procedures

Procedure	θ (°C)	f (Hz)	Type of loading
Controlled displacement test			
1	10	25	ε — 3 levels of 8 samples
3	20	40	ε — 3 levels of 8 samples or 12 samples
5	20	40	ε — 1:10 — 3 levels of 8 samples or 6 samples
Controlled force test			
6	20	40	σ — 3 levels of 8 samples or 12 samples
10	20	40	σ — 1:10 — 3 levels of 8 samples or 6 samples

Fatigue design method

Criterion on maximum tensile strain :

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

$\varepsilon_6(\theta,f)$: Strain leading to failure for 10^6 cycles, depending on temperature θ and frequency f

NE : number of standard axle loads

b : slope of the fatigue line

k : shift factor, 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: $$NE = 10^6 \cdot \left(\frac{\varepsilon_t}{k \cdot \varepsilon_6(\theta, f)}\right)^{1/b}$$

Comparison of design predictions and field performance

Calculation of shift factor k

(k = 1 → exact prediction of pavement life)

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

Fatigue test procedure	S1 BB_B	S2 BB_S	S3 EME 8 cm	S4 EME 10cm
3 – strain control Continuous	1,58	1,28	1,14	1,20
5 – strain control, with rest periods	**1,04**	**1,03**	0,8	0,8
6 – stress control, continuous	3,21	2,57		
10 – stress control, with rest periods	1,73	1,49	**1,10**	**1,08**

Conclusions – "fatigue experiments"

- Large differences in fatigue life predictions from different fatigue test procedures,
- Fatigue tests with rest periods seem more representative of in situ behaviour
- For the high modulus material (EME), the stress controlled fatigue test seems more representative of in situ behaviour.

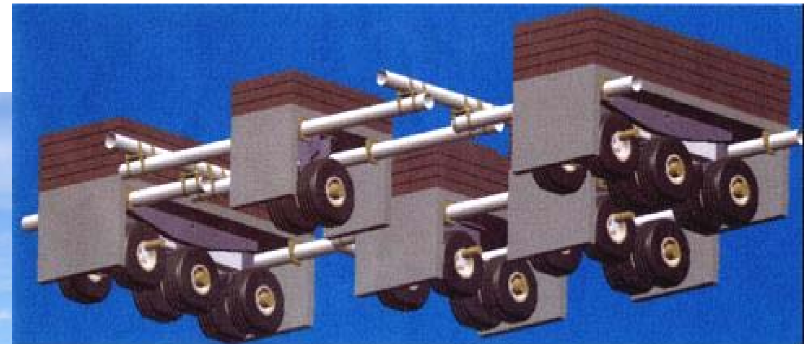
  ➔ more research needed on intrinsic characterisation of fatigue in laboratory

- Correction between in situ and lab behaviour dependent on the type of material (BB/EME)

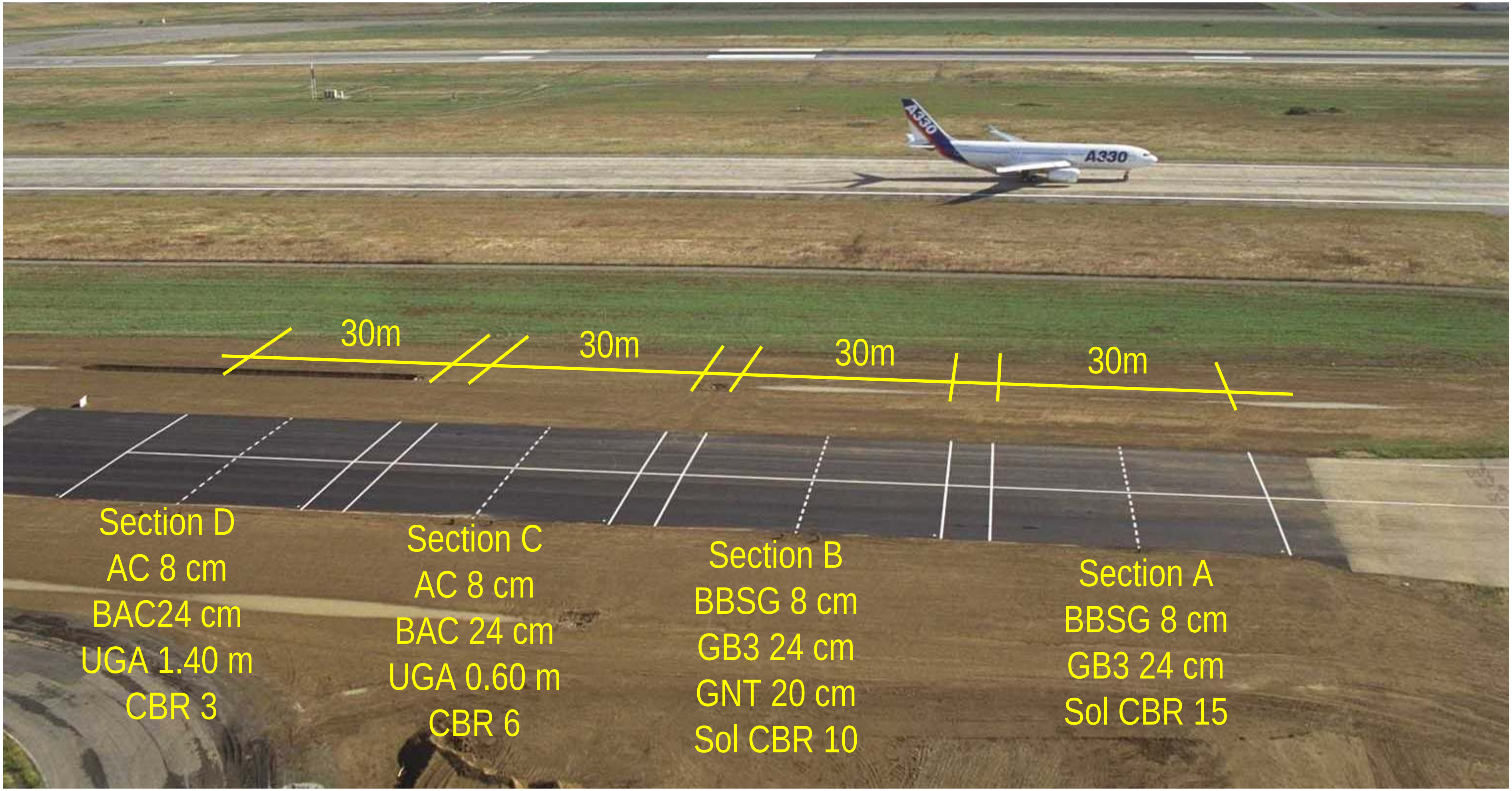
  ➔ Shift factor for EME = 1,0

[De la Roche et al, TRB 94, ISAP 98] [Rivière et al, ISAP 98

Airbus Pavement Experimental Program



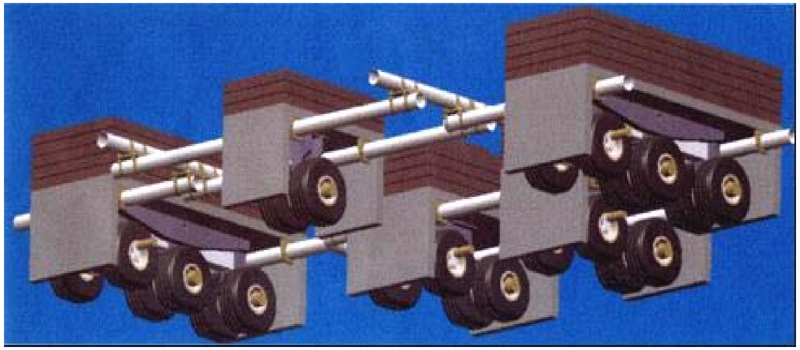
Airbus experimental program on flexible pavements – 1998-2003



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

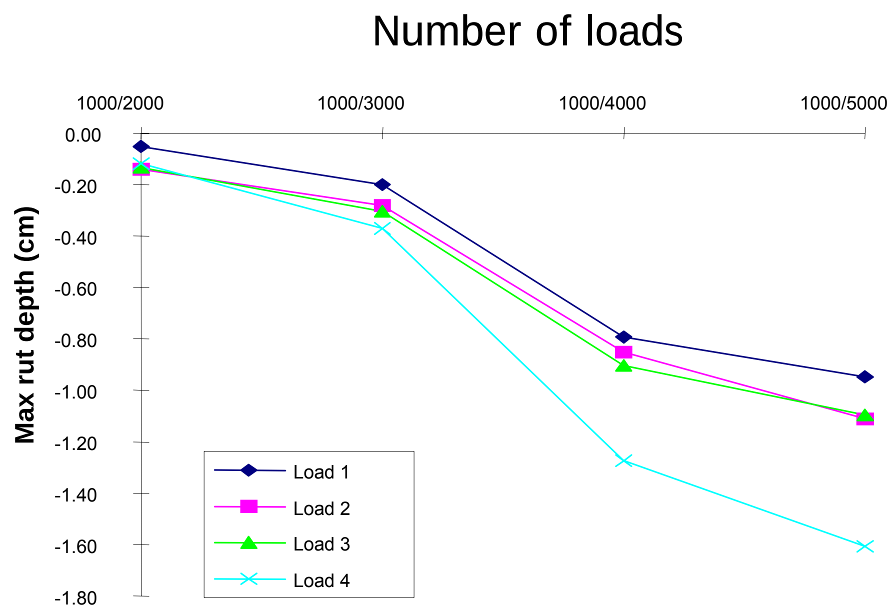
Evaluation of the possibility of applying the French road pavement design method to flexible airfield pavements

Observed pavement performance

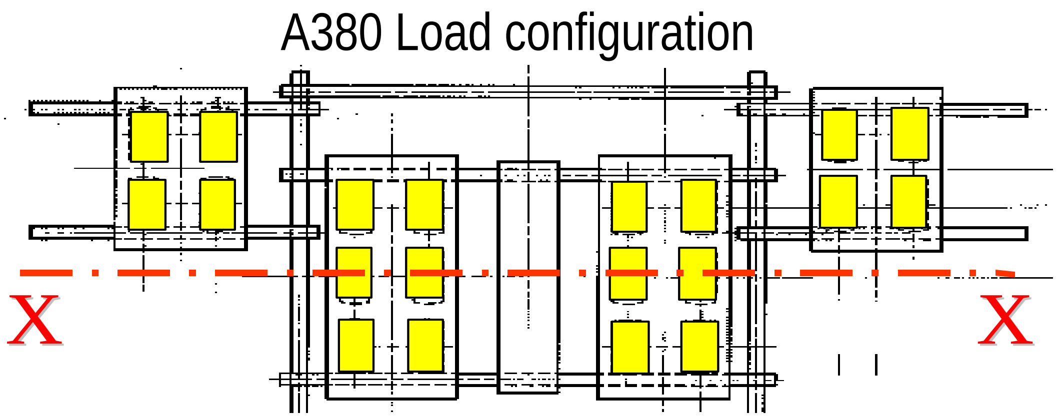
Main mode of distress of the flexible pavements = **rutting**

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

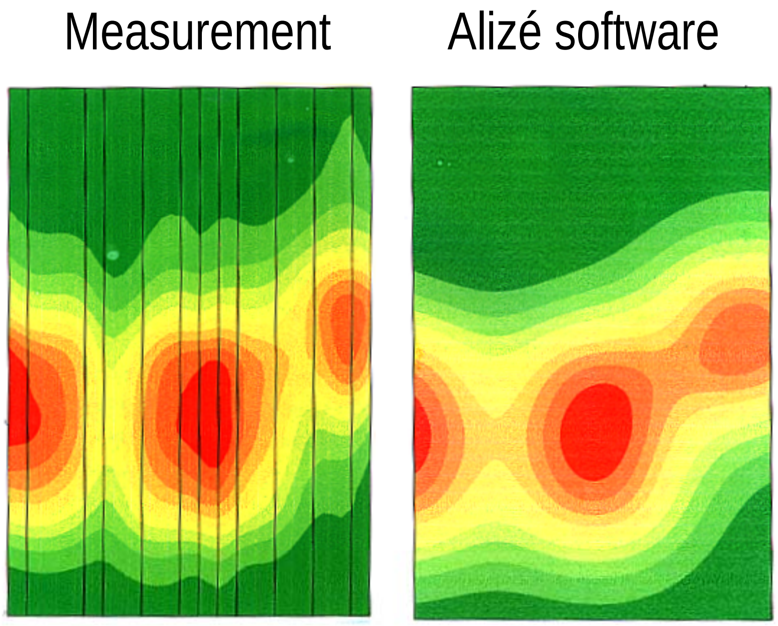
Evolution of rutting Section C – CBR 6

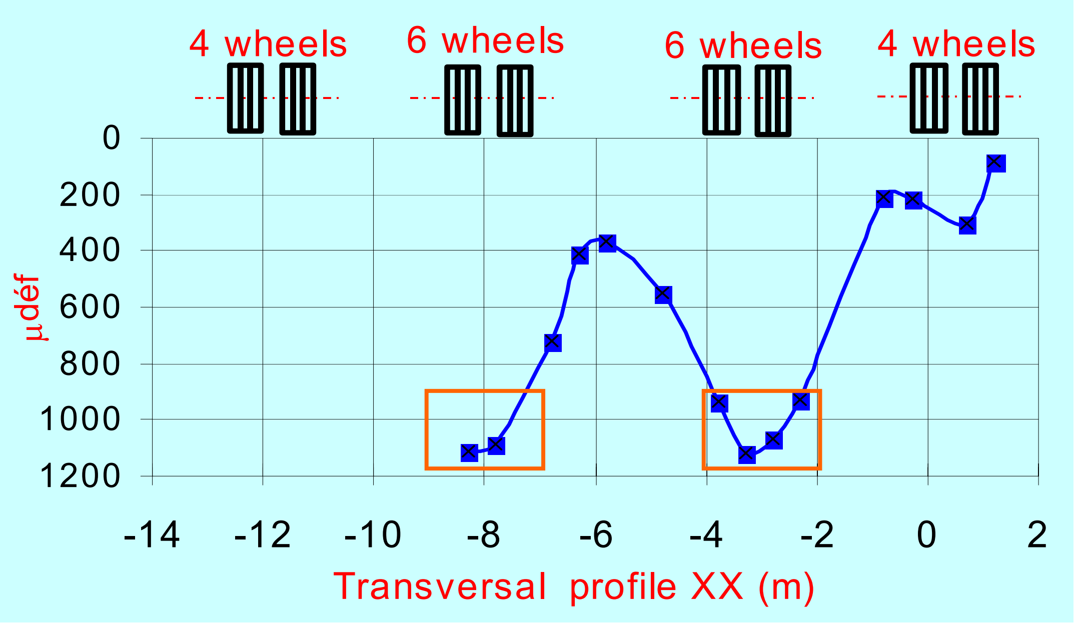


Linear elastic calculations (ALIZE Software)



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





Results of linear elastic calculations

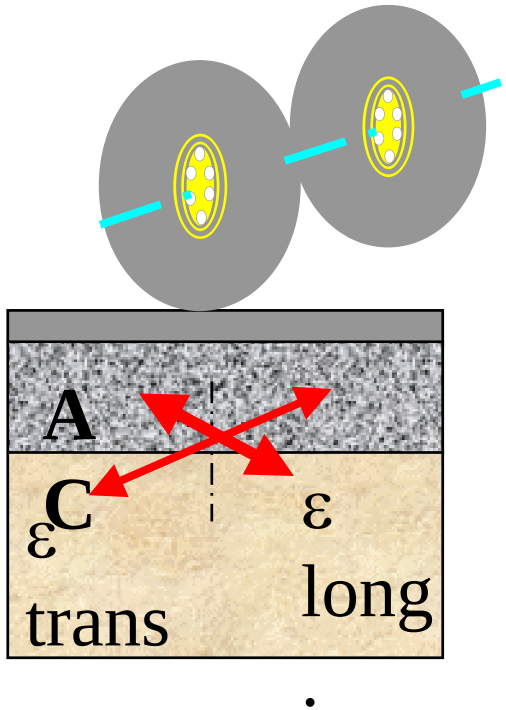
Good prediction of vertical strains in granular layers and subgrade

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

- Maximum values poorly simulated
- Discordance in directions of maximum tensile strains ε_t:

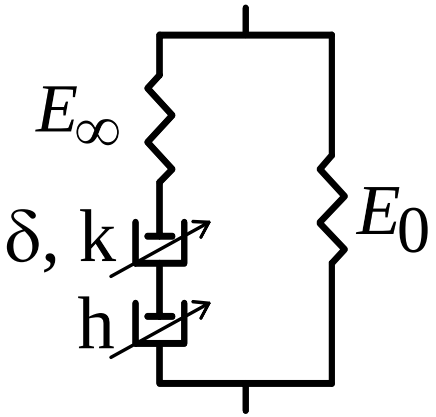
Measurements : ε_t transversal > ε_t longitudinal

Calculations : ε_t longitudinal > ε_t transversal



⇒ **Attempt to take into account viscoelastic behaviour**

Visco-elastic model for bituminous materials



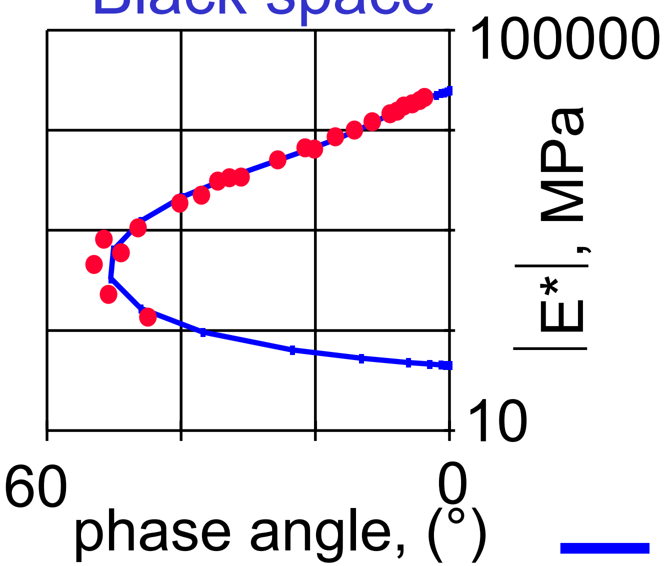
HUET - SAYEGH MODEL (1965)

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

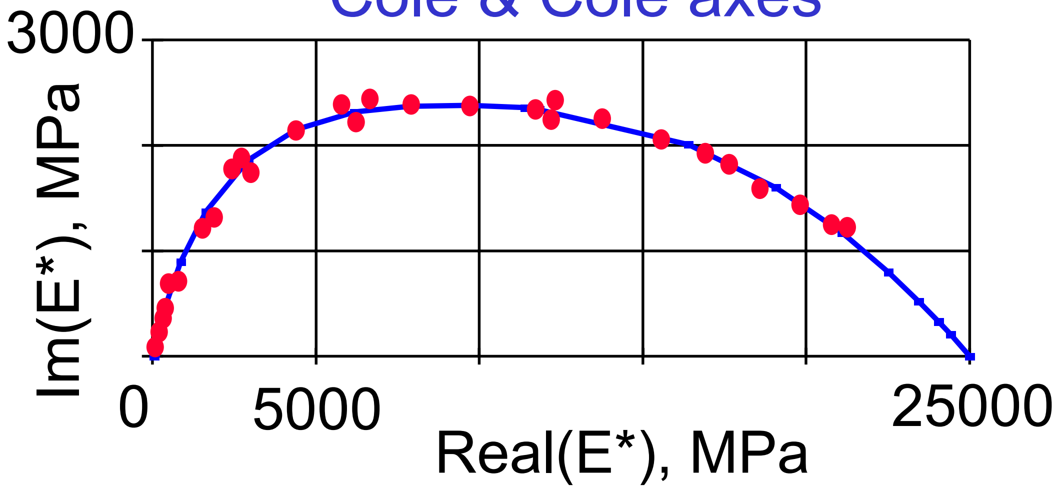
$E_\infty = 25000\ MPa$; $E_0 = 45\ MPa$;

$\delta = 2{,}7$; $k = 0{,}27$; $h = 0{,}7$

Black space



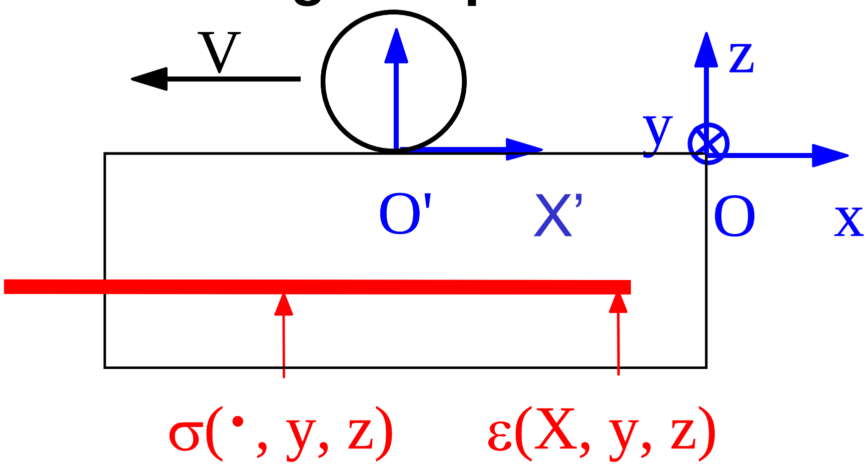
Cole & Cole axes



Huet-Sayegh's model ● measurements

Finite element model : module CVCR of CESAR-LCPC

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

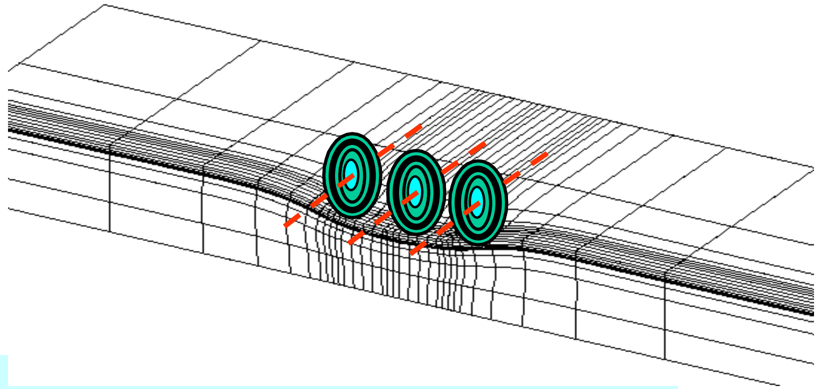
Models available in CVCR :

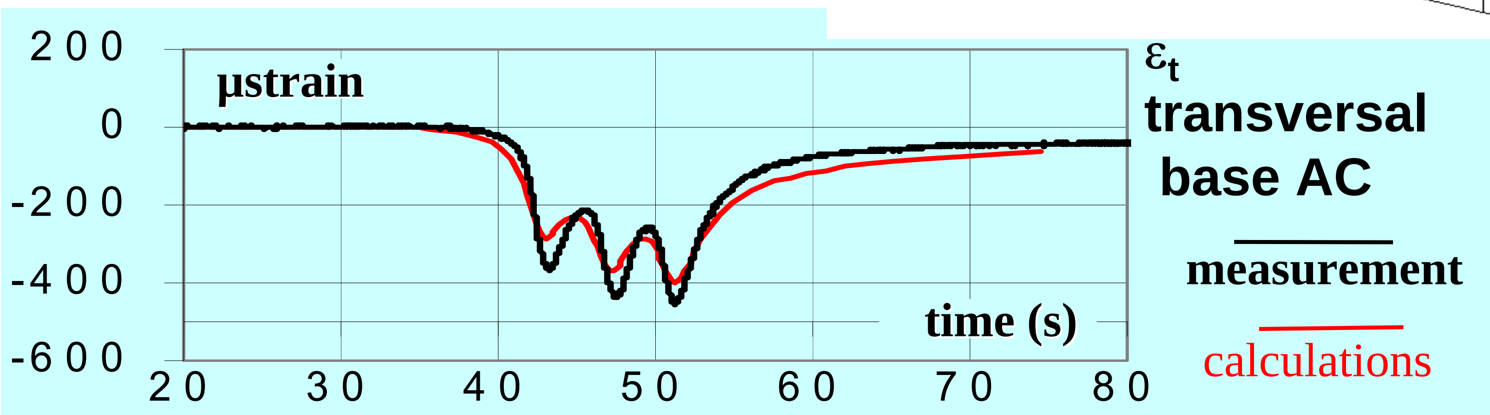
Linear and non linear elasticity (Boyce model, k-θ model)

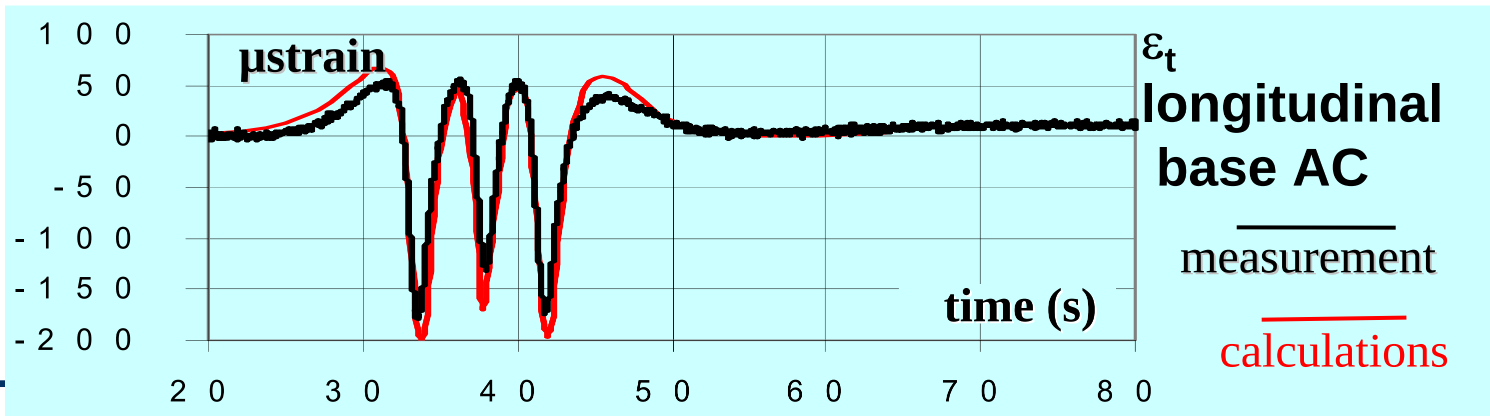
Huet-Sayegh visco-elastic model

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 ≈ 400 μstrain, lower number of cycles (10^4))

Rutting :

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

Use of APT for pavement structure innovation

Grave-Mousse test at LCPC's APT facility

Grave-Mousse ®

- new material for treated road bases developed by EJL Contractor (now EUROVIA) since about 10 years.

- bitumen-foam treated aggregates, used for new pavement as for overlay construction

- New pavement structure and innovative concept using Grave-Mousse in the middle part of a three-layer structure ➔ design model to be defined and validated

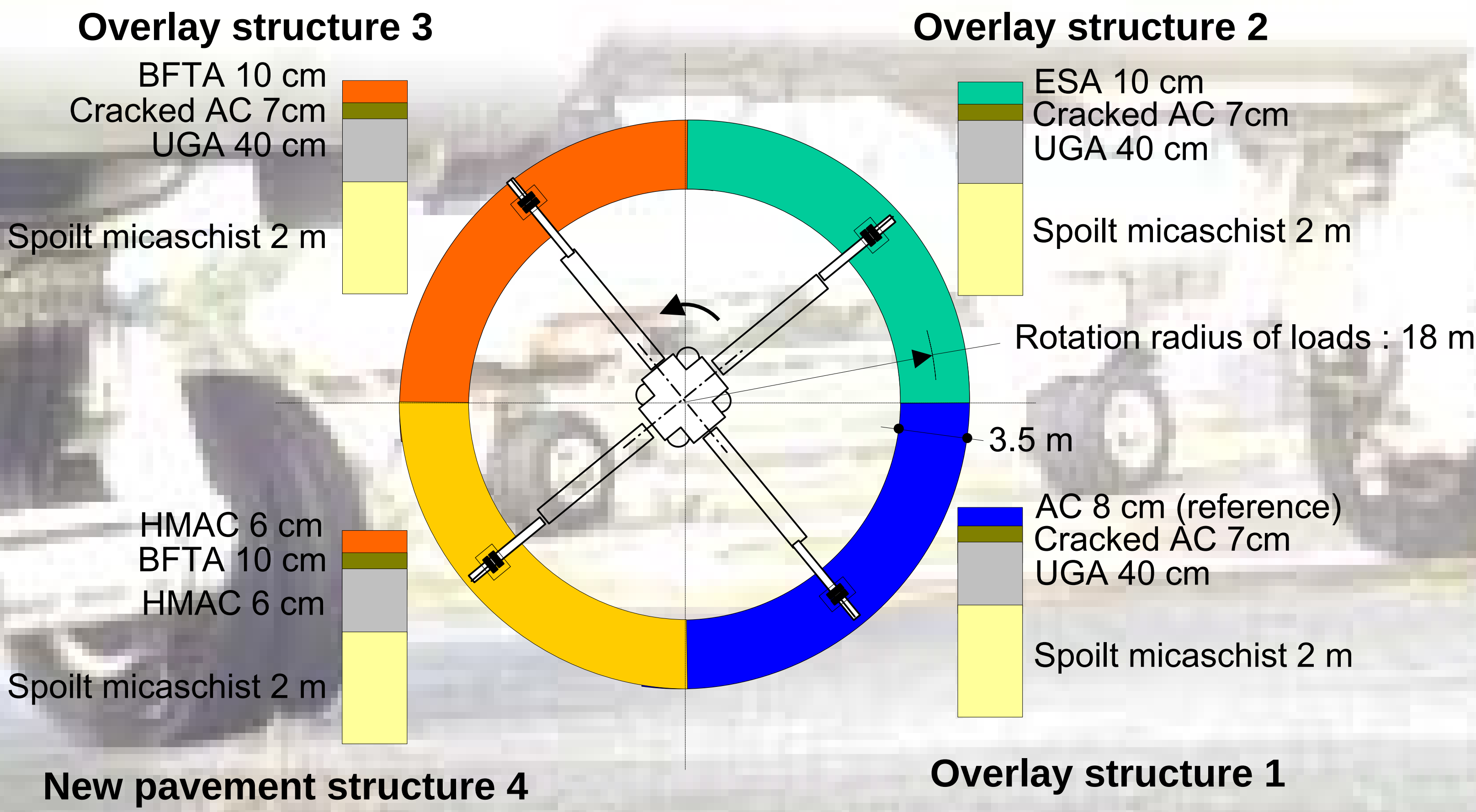
- In overlay, functioning and endurance of this new material under heavy traffic to be checked.

Grave-Mousse test at LCPC's APT facility

Experiment with LCPC's APT facility :

- Partners : Private contractor EJL
- Fatigue test performed from July 1995 to March 1996
- 3 overlays and 1 new pavement, 28 m long x 3.5 m width
- 2.87 millions single axle load from 45 kN to 85 kN /twinned wheels, equivalent to 4.3 millions of the French standard load (130 kN/single axle) ie about 15 years of service on average trafic national network
- Load speed:
  - 44 km/h until 70 000 loadings (consolidation stage)
  - 68 km/h for all the other loadings.

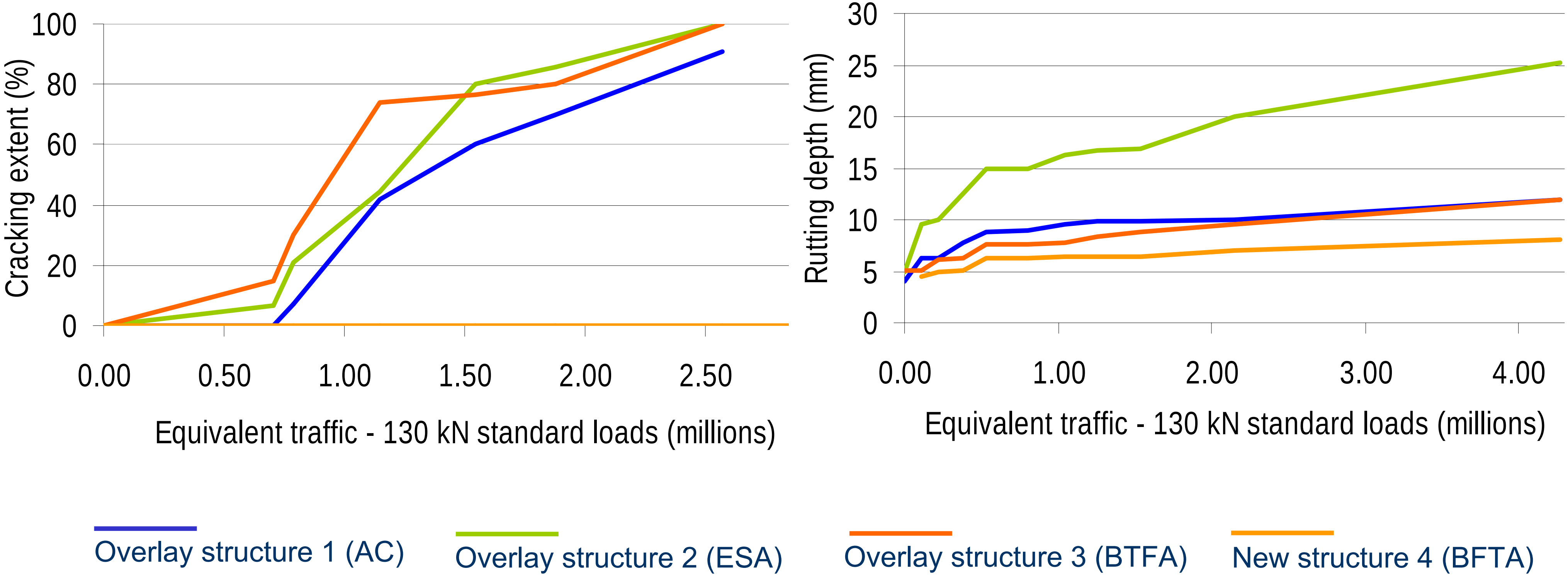
The 4 structures tested



AC : asphat concrete
ESA : emulsion stabilised aggregates
UGA : untreated graded aggregates

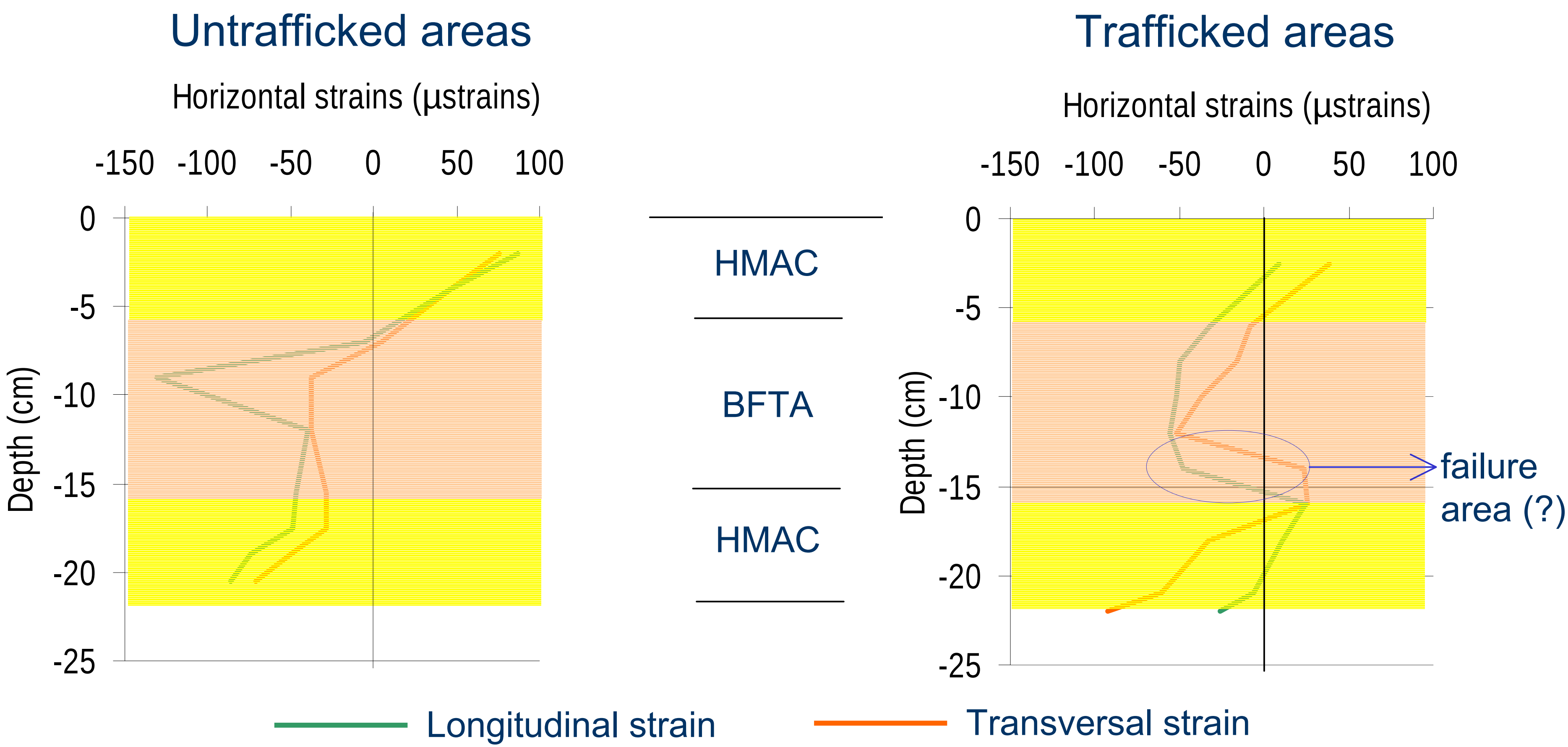
BFTA : bitumen-foam treated aggregates
HMAC : high modulus asphalt concrete

Cracking and rutting vs traffic



New structure 4: dammage mechanism

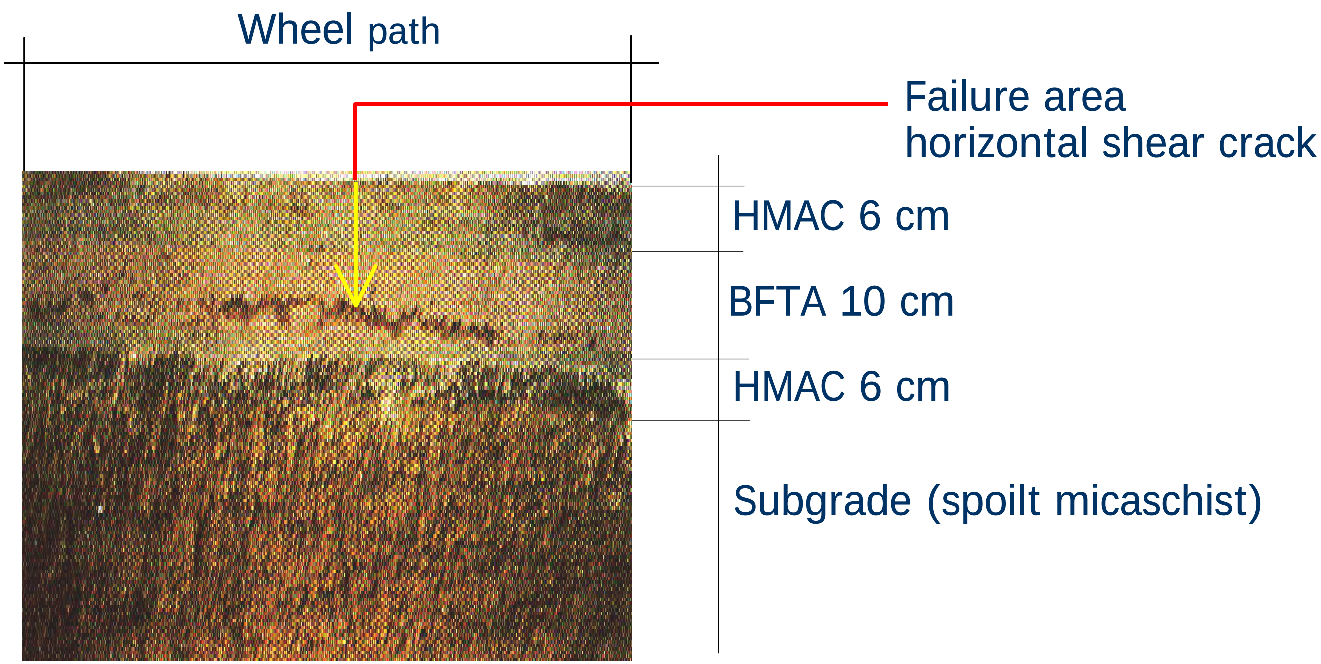
Typical horizontal strains profiles measured under the 65 kN standard load



(tensile strains are positive)

New structure 4: dammage mechanism

Trench in the new structure 4 at the end of the experiment



Numerical modeling: main results

Theoritical modeling:

- multilayer elastic model (Burmister). Young moduli are back-calculated from deflections, curvature radii and strains measured.

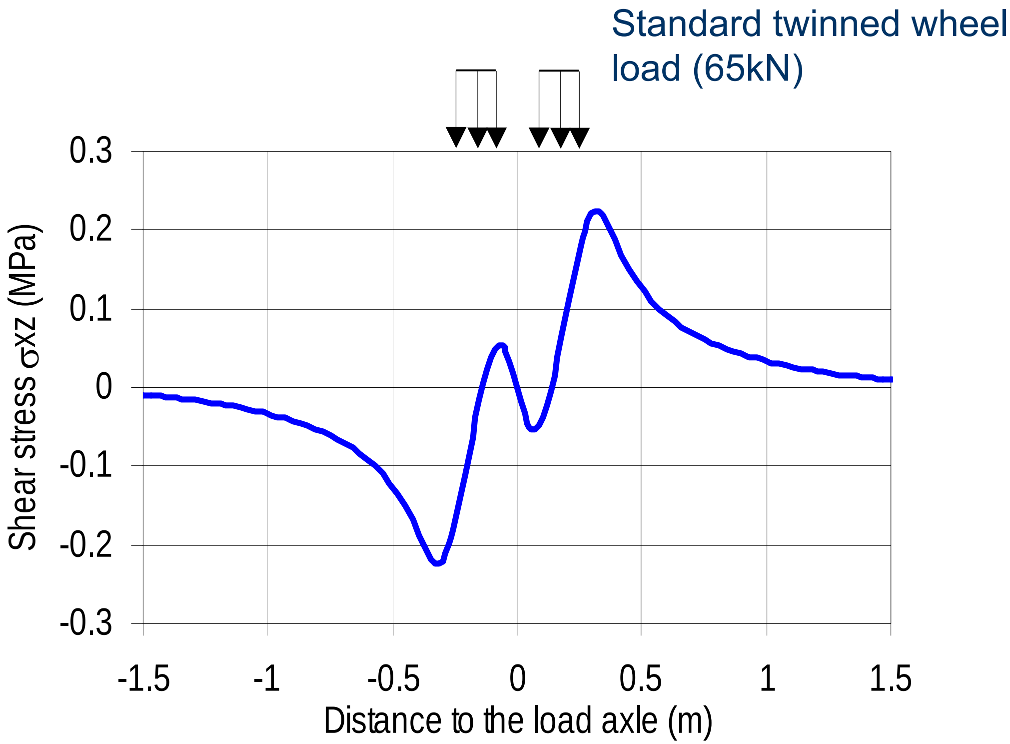
	Young modulus (15°C, 10Hz)
- reference AC :	10 000 Mpa
- BFTA :	4 000
- ESA :	2 500
- Cracked AC :	2 000

- Fatigue behavior evaluated from fatigue laboratory tests, and calibrated by ajustement with experimental results.
- Scattering of the fatigue parameters are taken into account, leading to a probabilist determination of the pavement dammage due to the traffic.
- The theoretical risk of failure is assimilated to the cracking extent.
- New structure 4 : shear failure plane is modelized by a low modulus thin layer (2 cm thick, at 2 cm above the BFTA/HMAC interface, Young modulus 750 MPa).

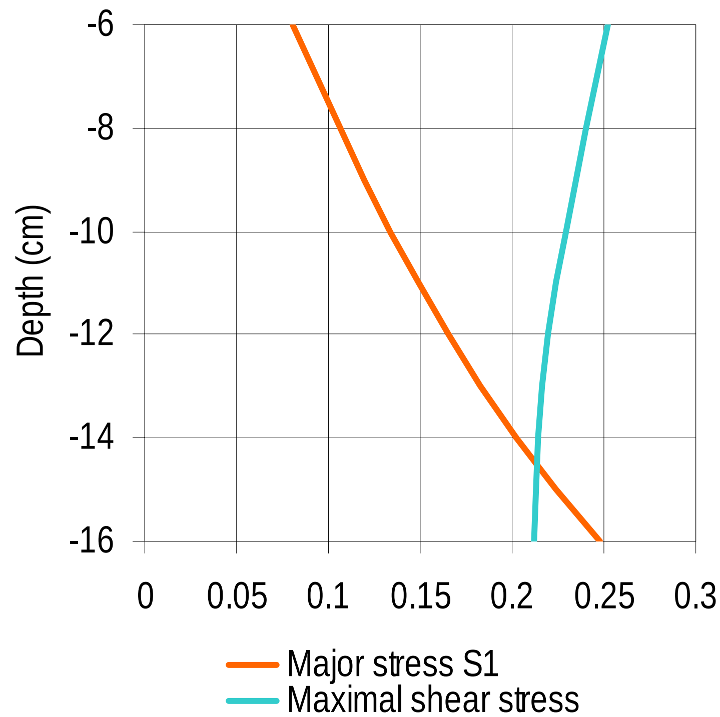
Numerical modeling: main results

New structure 4 : internal shear en tensile stresses

Shear stresses at the midle part of the BFTA layer



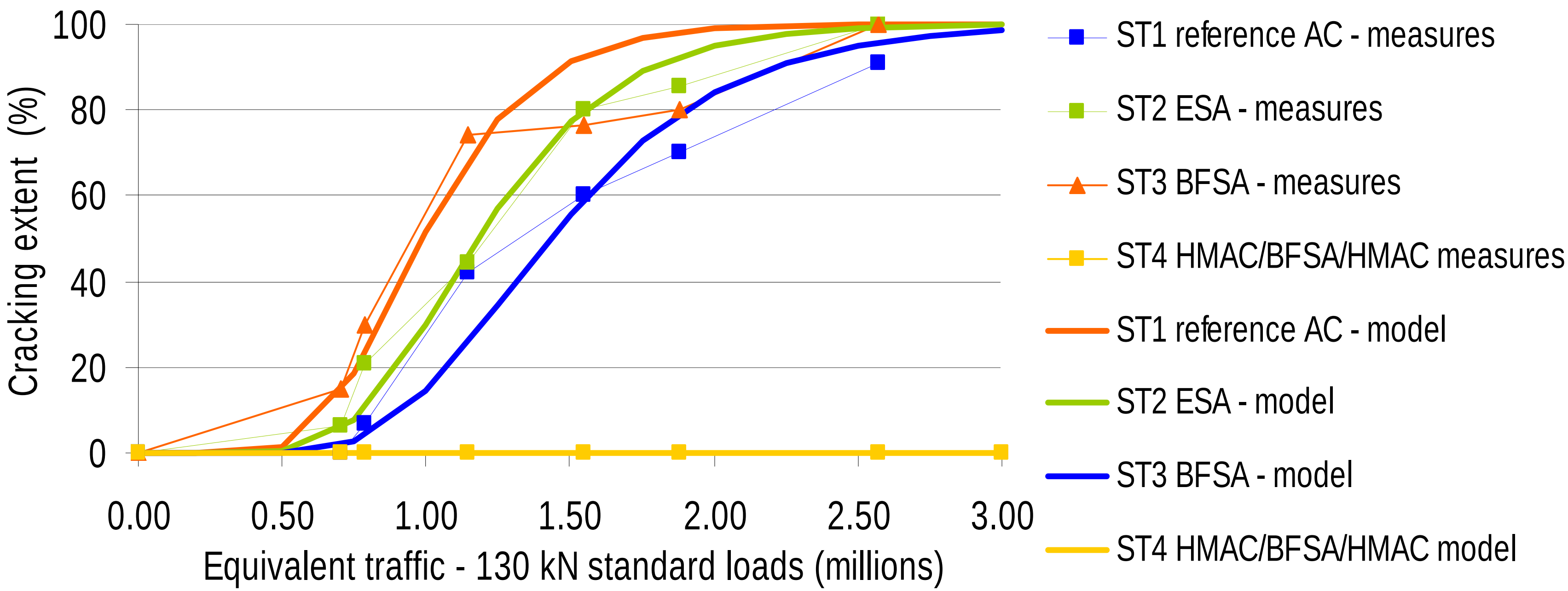
Vertical distribution of stresses in the BFTA



(tensile stresses are positive)

Numerical modeling: main results

Measured and calculated evolution of cracked area



General Conclusions

APT is a useful tool for :

- Identification of pavement deterioration mechanisms, and suitable models
- Validation of models
- Experimentation of innovative structural design
- Improvement of laboratory test procedures

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
- Viscoelastic behavior of bituminous pavements and development softwares based on analytical models such as Viscoroute-LCPC.

References – Research on pavement modelling

Bitumen Cracking modeling (Nguyen, 2006) (Chailleux, ICAP2006)

Damage modeling (Bodin, 2002) (Bodin et al., ASCE2004), ….

Visco-elastic structural model (Duhamel et al., BLCPC2005) (Chabot et al, ICAP2006), …

Cracking structural model (Tran, 2004) (Chabot et al., BLPC2005), ….

Visco-plastic modeling (Nguyen, 2006) (Nguyen et al., ICAP2006), …

Non linearity modeling for GNT and soil material (El Abd, 2006) (Hornych et al., RMPD2006 or 2007) …

Additionnal not presented

Model for the prediction of rutting in unbound pavement layers

Developed in European project SAMARIS (2002-2006)

SAMARIS

- **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

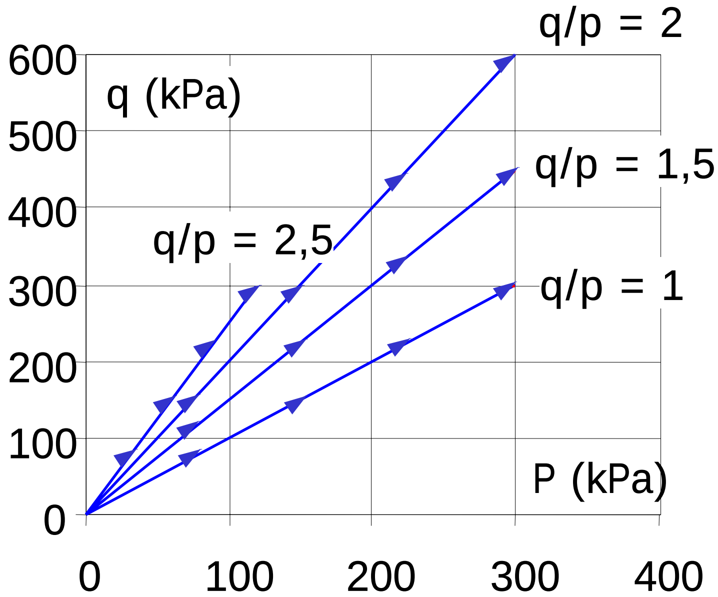
Laboratory study of permanent deformations

Test method : cyclic triaxial test

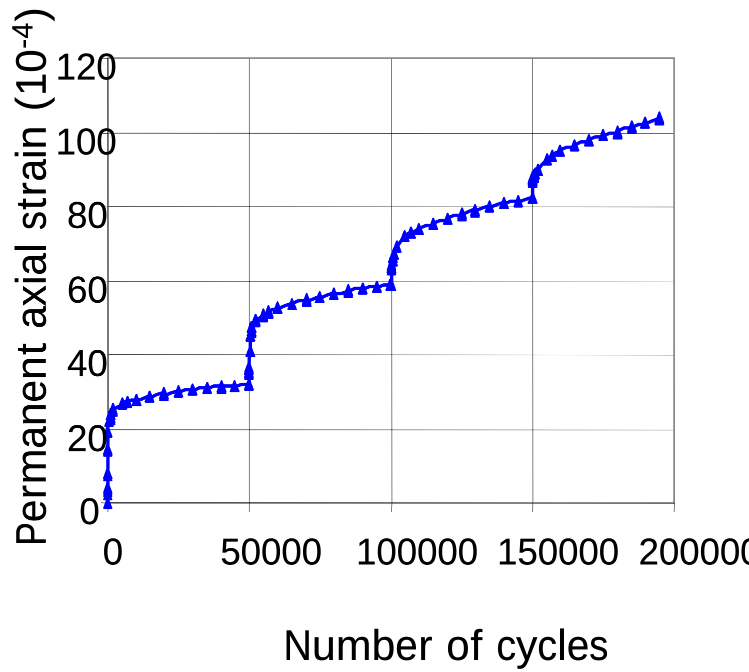
Advantages : realistic simulation of « stress paths » due to traffic loading

Test equipment

Test procedures



$p = (\sigma_1 + 2\sigma_3)/3 \quad q = (\sigma_1 - \sigma_3)$



Selected permanent deformation models

2 modelling approaches :

- **Routine level** : utilizable for design

  Empirical permanent deformation model

  $\varepsilon^{p}{}_{1}(N) = f(N).g(p_{max}, q_{max})$ Gidel (2001)

- **Advanced level** : for research or analysis

  Elasto-plastic model with isotropic and kinematic hardening

  Chazallon (2000)

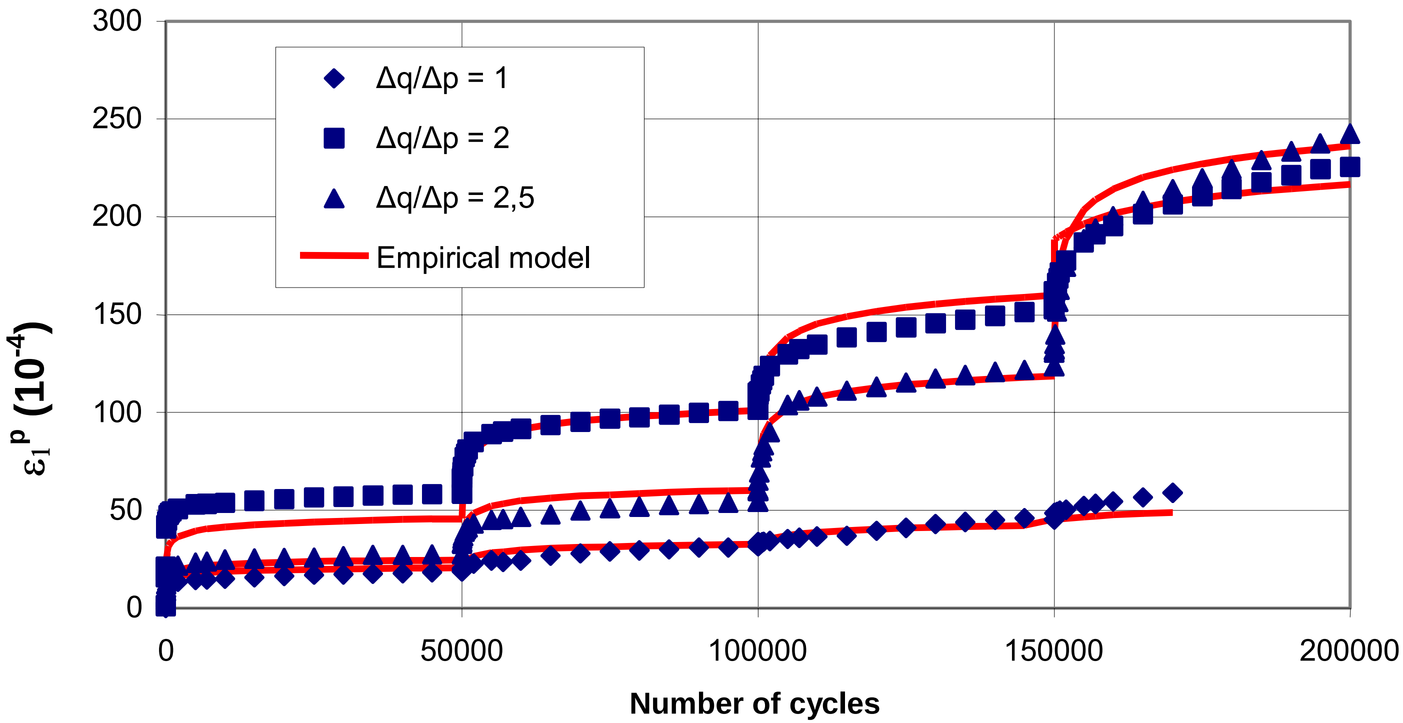
Example of calibration of empirical permanent deformation model

$$\varepsilon_1{}^p(N) = \varepsilon_1{}^p{}_0 . \left[1 - N^{-B}\right] . \left[\frac{L}{p_a}\right]^n . \frac{1}{(m + \frac{s}{p_{max}} - \frac{q_{max}}{p_{max}})}$$

Gidel (2001)

Maraichère UGM

Cyclic Triaxial Tests at
 w = 5 %



Structural modeling approach

Main hypothesis : For one cycle $\delta \underline{\underline{\varepsilon}}^{p} << \underline{\underline{\varepsilon}}^{e}$

→ 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 ε_1^{p} 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)

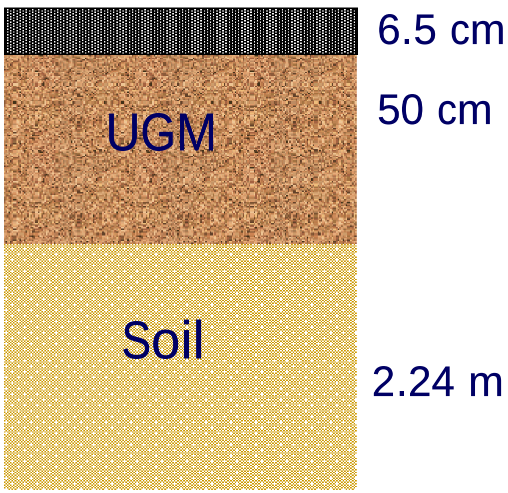
Full scale loading conditions : 65 kN dual wheel load, 72 km/h

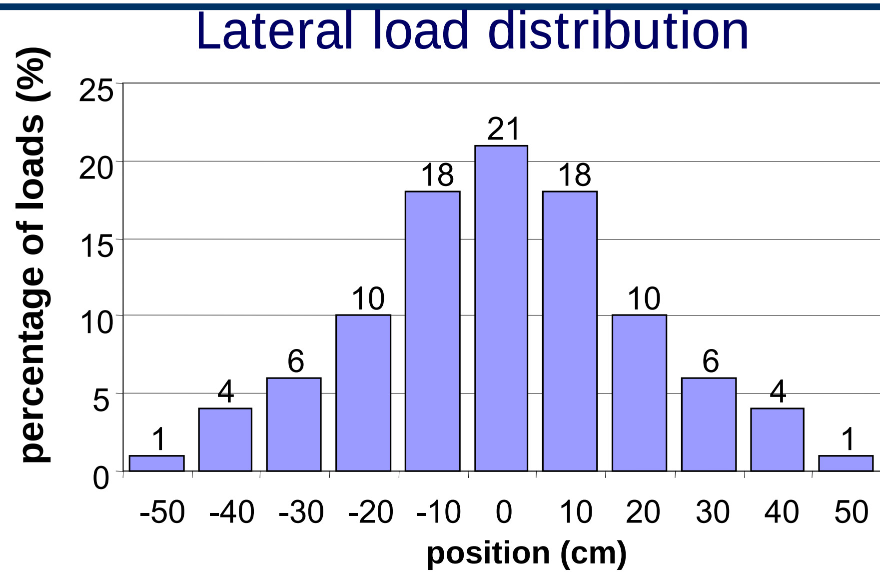
1.5 million loads applied

Low water table level (–2.6 m)

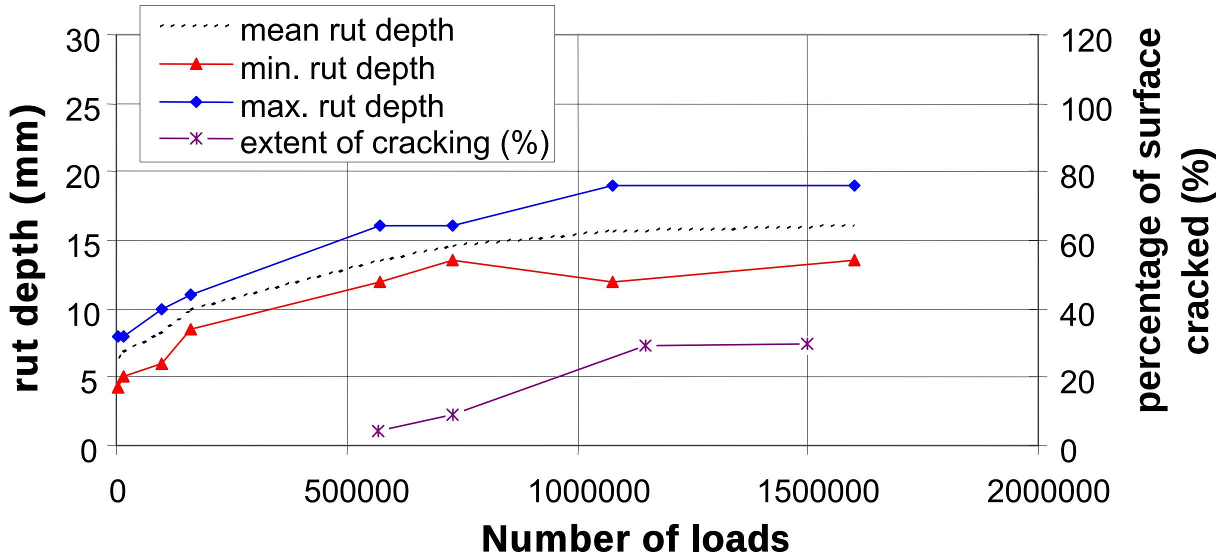
Modelling of structure 4

Structure 4





Evolution of rutting and cracking

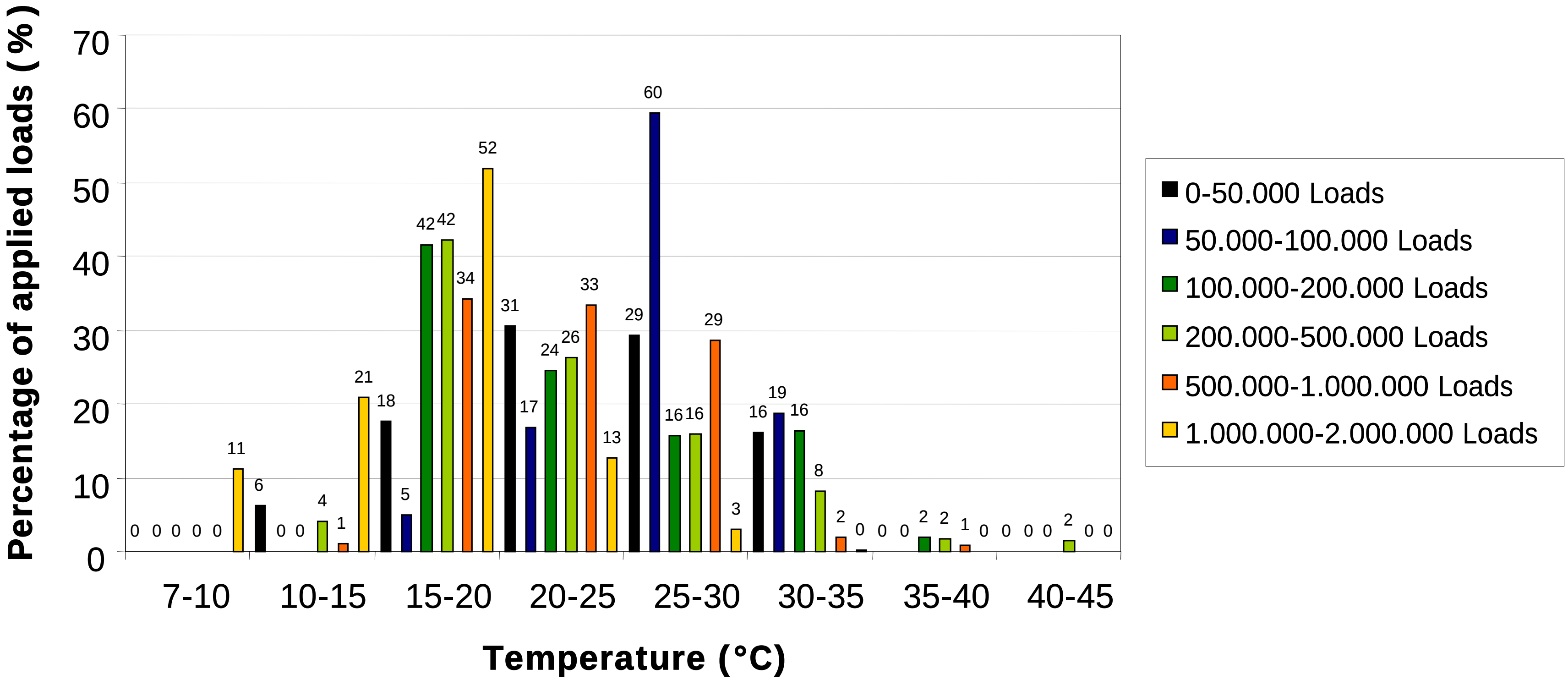


Modelling hypotheses

Modelling of rutting of UGM layer and subgrade (empirical model)

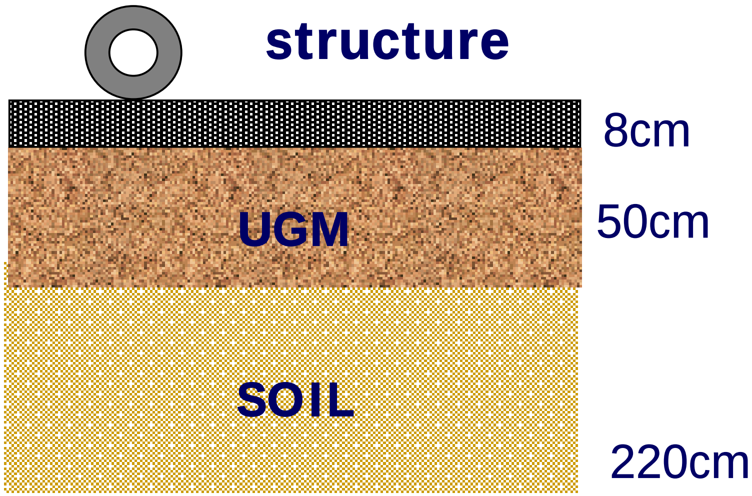
Simulation of load wandering and variations of temperature with traffic

Temperature distribution used for calculations



Examples of rut depth calculations

Pavement structure



Loading : 65 kN load (single or dual wheel)

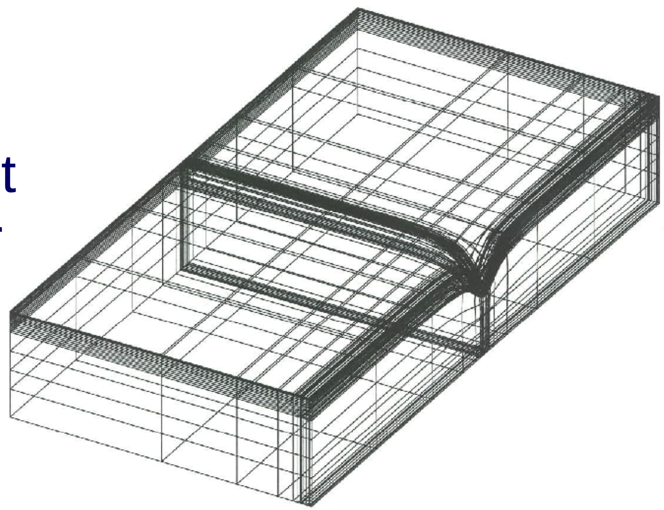
1.5 million loads - Constant temperature

- Bituminous concrete : linear elastic
- UGM : non linear elastic

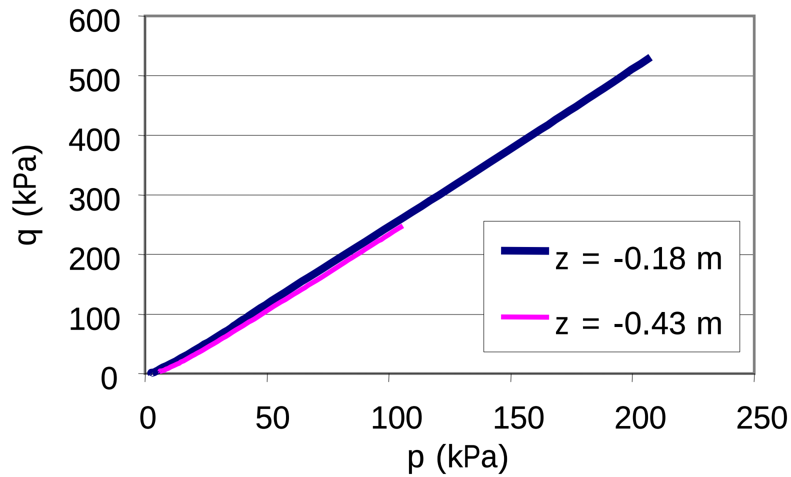
+ empirical permanent deformation model

- Soil : linear leastic E = 100 MPa, n = 0,35

3D mesh modelling of resilient behaviour

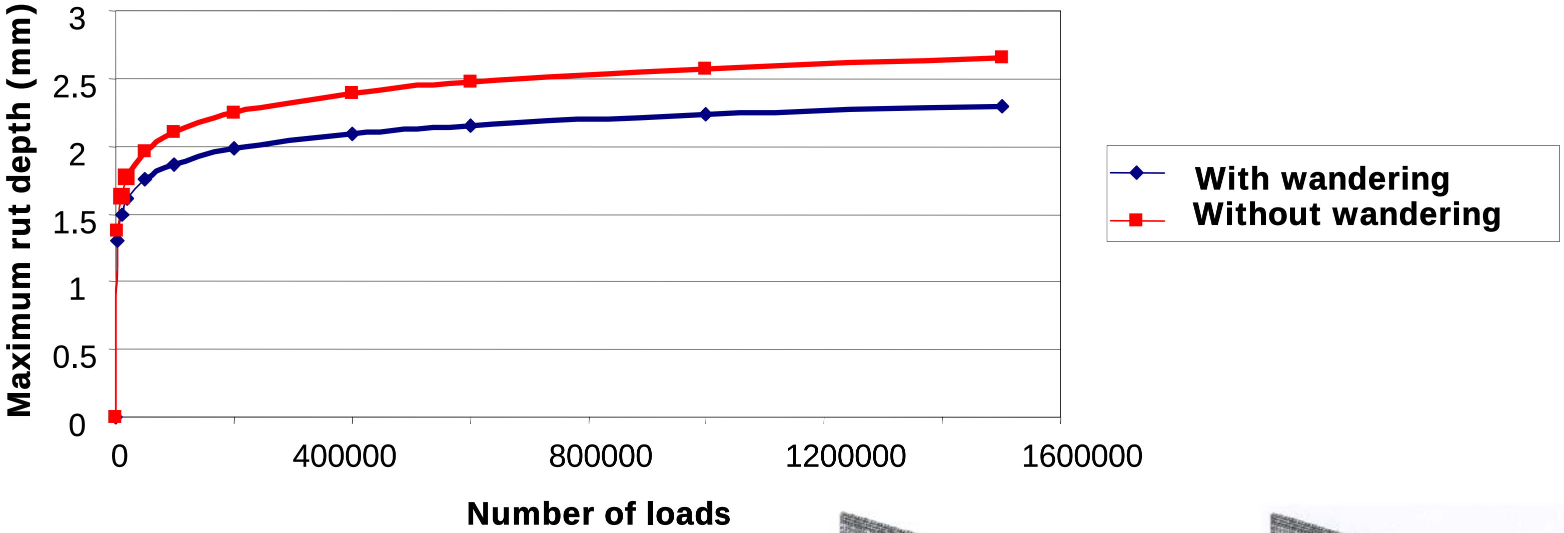


Stress paths in UGM layer



Calculation : influence of lateral load wandering

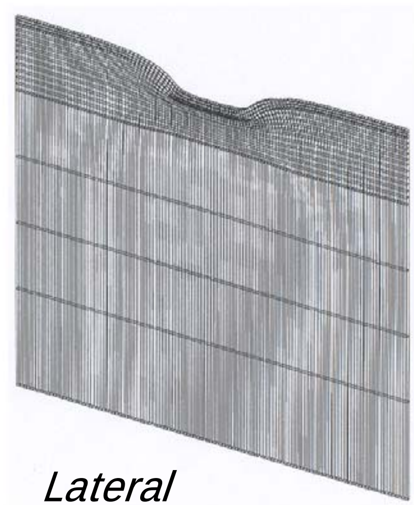
Evolution of maximum rut depth



Rut profiles after 1.5 million loads (single wheel) :

⇨ Low influence of lateral wandering

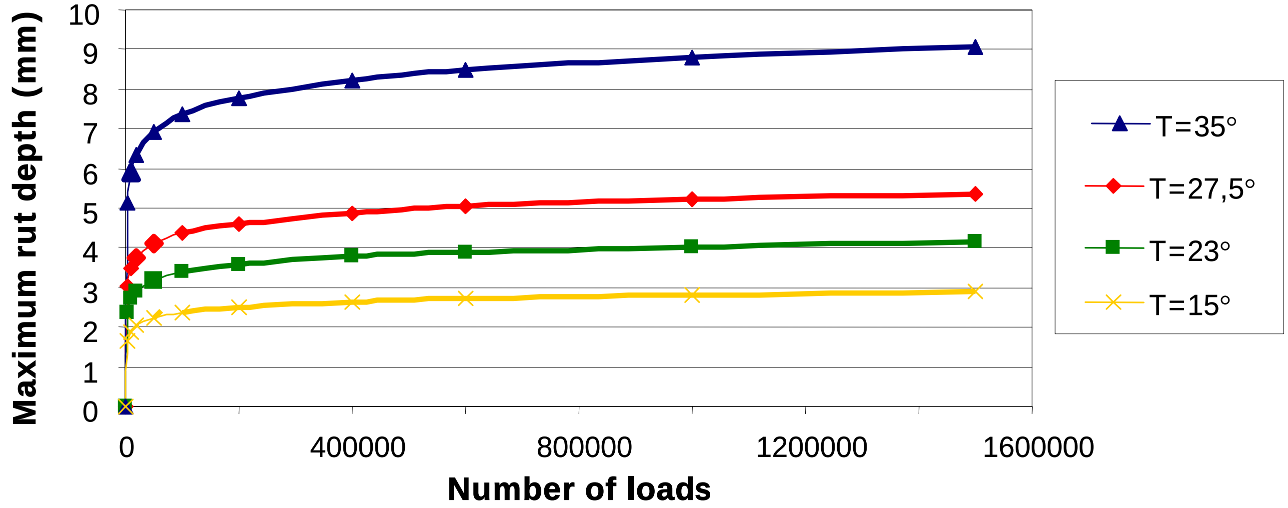
No lateral wandering



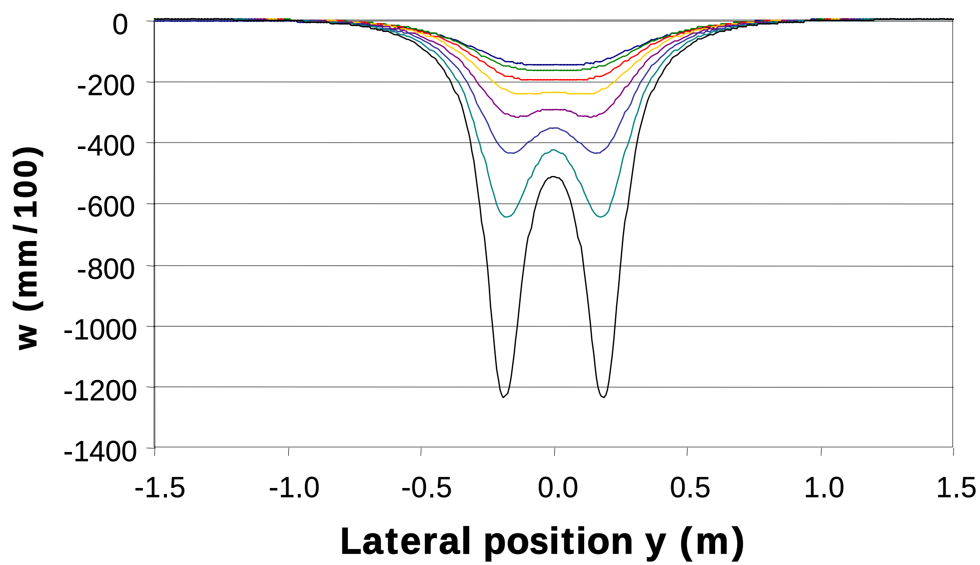
Lateral wandering (11 positions)

Influence of wearing course temperature

Evolution of maximum rut depth for different temperatures :



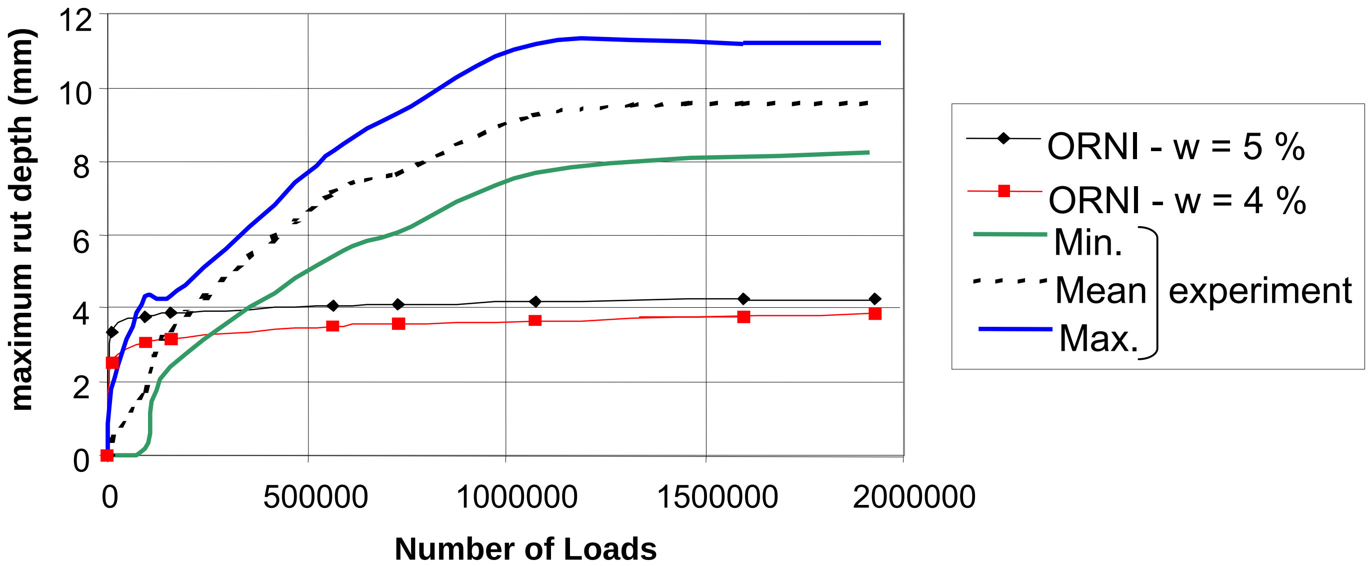
Rut profiles for different Temperatures (8.5 to 42.5°C)

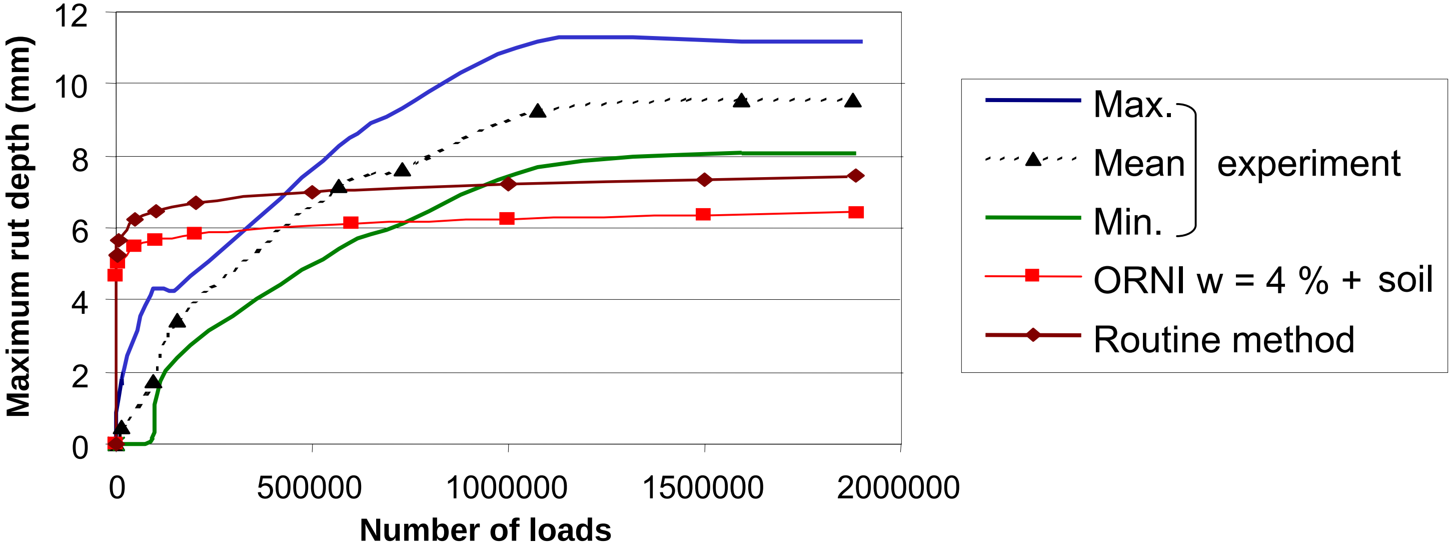


⇨ Large influence of temperature

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