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The LCPC's ALT facility contribution to pavement cracking knowledge

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ABSTRACT: The full scale observation of damage and failure mechanisms of pavements due to traffic is quite essential for the improvement of road materials and construction methods, as well as for the development and the validation of modelling tools and pavement design methods. An alternative to the survey of real roads over long periods consists in performing accelerated pavement tests (APT). LCPC has today more than 20 years of experience in APT applied to study of pavement deterioration and cracking. Since 2006, in relation with an LCPC research program to update the French pavement design method, a detailed analysis of existing data of LCPC APT tests is being carried out. The objective of this work is to improve the understanding and modelling of the development of rutting and fatigue in different types of pavements. This paper presents the first conclusions of this synthesis, in relation to fatigue cracking, for the purpose of the RILEM Technical Committee - Cracking in Asphalt Pavements (TC-CAP).

1 INTRODUCTION

To improve the understanding and modelling of fatigue mechanisms and crack localization and propagation phenomena in bituminous pavements, it is necessary to rely on observations of real pavement behaviour. Data on pavement performance can be obtained from road data bases. This data can be used to derive laws of evolution of distresses, depending on the type of structures, traffic and successive maintenance operations (Kobisch 2000, Brillet et al. 2006). However, it is necessary to complement this statistical approach with mechanical data, including accurate information on materials, description of applied loads and instrumentation of the pavements. The feedback from real pavements is also considerably delayed, because of the long service life of these structures (20 to 30 years on the French national network).

The interest of accelerated loading tests is to allow the development and the observation of deterioration mechanisms of full scale pavements, in a much shorter time than on the real road network. In addition, these tests are performed in controlled conditions, and on instrumented pavements, and thus provide more complete data.

At LCPC, in Nantes, two accelerated pavement testing facilities are in operation: A large scale accelerated testing facility, the LCPC fatigue test track (Autret et al. 1987, 1988, www.lcpc.fr), and a small scale linear accelerated testing facility, the FABAC machine (Balay et al. 1998, Perez et al. 2007, Chabot et al. 2008, www.lcpc.fr).

Within the framework of numerous partnerships with the French road authority, motorway companies, pavement contractors or bitumen producers, LCPC has performed a great number of fatigue experiments with its large outdoor ALT facility, since its commissioning in 1984. Approximately 60 new pavement structures, and 15 pavement reinforcements, have been tested. This installation allows to test pavements up to their failure, and to follow the evolution of pavement distress (rutting, cracking) with traffic loading. Depending on the types of materials

and pavement structures, different rates of evolution and types of cracking are observed: longitudinal or transversal cracks, bottom up or top down cracking.

This paper describes cracking mechanisms observed on 16 pavement structures tested on the LCPC large ALT facility, which are all low traffic pavements, with less than 12 cm of bituminous materials, and a granular base. A detailed study of the damage of those structures has been made by means of trenches and cores. Comparisons of the observed behaviour with predictions obtained with the French pavement design method (LCPC, SETRA 1994), based on multi-layer linear elastic analysis, are also discussed. The results are presented in two parts, concerning respectively:

- Pavements with a very thin bituminous wearing course (less than 6 cm), presented in part 4;
- Pavements with a thicker wearing course (between 6 and 12 cm), presented in part 5.

2 THE LCPC FATIGUE TEST TRACK

The LCPC accelerated pavement testing facility, in Nantes, is an outdoor circular carousel, with a diameter of 40 meters (see Figure 1). The installation comprises a central 750 kW motor unit and four arms carrying the wheel loads, which can reach a maximum speed of 100 km/h. The experimental pavement has a mean radius of 17,5 m and a width of 6 m, and thus a total length of approximately 110 m. The position of the load can be adjusted at a different radius on each arm, for instance to test simultaneously the effect of different load configurations. During loading, a lateral wandering of the loads can be applied (Autret & Gramsammer 1990).

The arms can be equipped with various load configurations: single or dual wheel, single, tandem or triple axles. A large range of loads can be applied: between 45 and 80 kN on a single half axle, up to 135 kN with multiple axles. A very low stiffness suspension system allows to continue to run on pavements presenting severe deteriorations.

The test facilities comprise three circular tracks where the pavements are built, one of them equipped with a waterproof concrete pit, allowing to control the water table level in the subgrade by means of pumps. The loading system can be moved from one ring to another within approximately one week. The pavement structures are built using normal road-building equipment and in general, 4 different structures are tested simultaneously in each experiment, including in general a reference structure with well known behaviour.



Figure 1. View of the LCPC fatigue test track.

3 PAVEMENT INSTRUMENTATION AND MONITORING

The experiments presented in this paper have all been performed with a dual wheel 65 kN load, (standard French equivalent axle load, shown in Figure 2), and a loading speed of 70 km/h. Generally, bituminous layers are instrumented during construction with thermocouples and strain gage sensors, measuring longitudinal and transversal (horizontal) tensile strains at the bot-

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tom of the layers. Vertical strains in unbound layers and subgrade, and also vertical displacements of the pavement surface are measured using displacement transducers. In situ tests and distress measurements are also performed after different levels of traffic, including measurements of deflections, transversal profile and visual survey of surface cracking.

In this study, it is proposed to examine mainly the extent of cracking, defined as the percentage of the length of the pavement section showing visible cracking. (see Figure 2). A transversal crack is assumed to have a length of 50 cm.

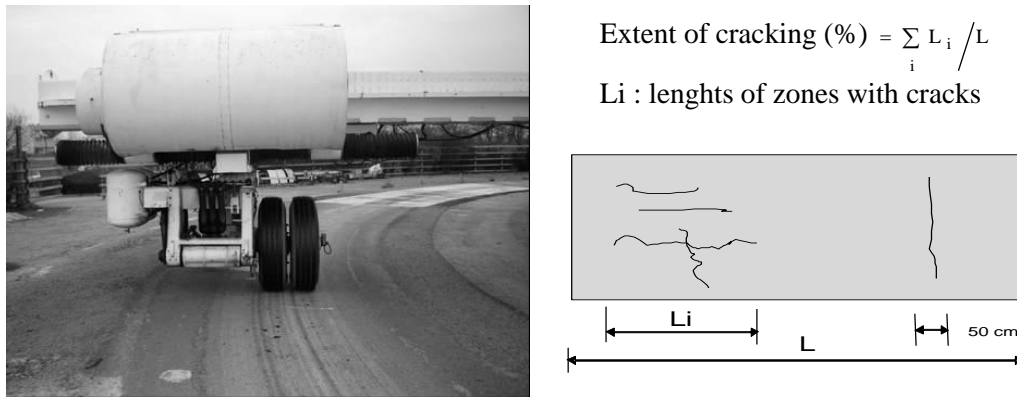


Figure 2. Dual wheel 65 kN load applied in the experiments and assessment of the extent of cracking.

Typical examples of measurements of longitudinal and transversal strain variations at bottom of bituminous layers, in pavements with a bituminous wearing course and a granular base are shown in Figure 3.

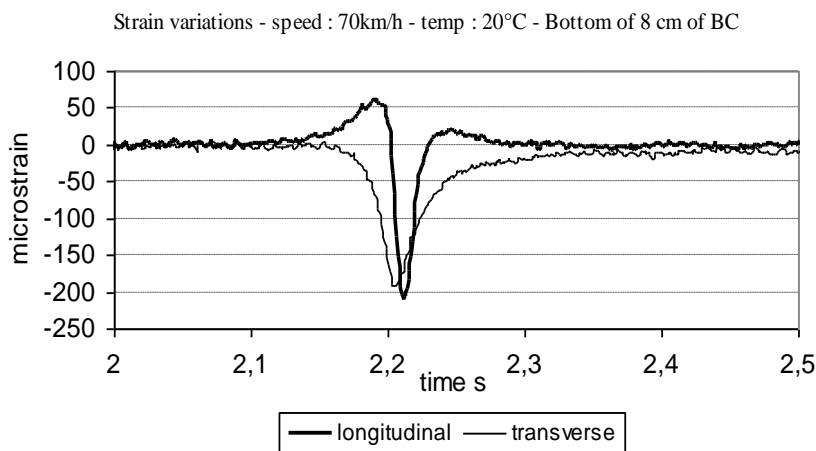


Figure 3. Typical measurements of longitudinal and transversal strains at the bottom of a thin bituminous surface layer (compressive strains positive).

4 PAVEMENTS WITH LESS THAN 6 CM THICK BITUMINOUS WEARING COURSES

4.1 Experimental results

Eight pavements of this type have been analysed. Table 1 gives the main characteristics of the pavement structures, and of the bituminous materials. The levels of deflection of each pavement, under the standard 65 kN dual wheel load, at the start of the experiments, are also indicated. The bituminous mixes used in all these experiments are mixes specified in France for low traffic pavements, presenting high bitumen contents (between 6 and 6.45 % of grade 50/70 bi-

tumen); their standard elastic moduli (at 15 °C and 10 Hz) vary from 4000 MPa to 5000 MPa. The experiments S2, S3 and S4 have been analysed by Odéon et al. (1994).

Table 1. Main characteristics of the pavement structures with 5 cm thick wearing courses.

Experiment name	Layer Thickness (cm)		Soil Modulus (MPa)	AC composition (in %)					Deflection 0,01mm
	BC	UGM		%bit	6/10	2/6	0/2	fines	
S1 Ex B0	5.0	45	60	6.45	43	15	41	1	100-140
S2 TP Sor	5.0	40	60	6.05	28	30	42	-	65-75
S3 TP Pom	5.0	40	60	6.05	28	30	42	-	90-110
S4 TP Poe	5.0	55	60	6.05	28	30	42	-	80-105
S5 DR1 p1	5.0	20	110	6.20	38	24	36	2	70-85
S6 DR1 p2	5.0	35	80	6.20	38	24	36	2	70-80
S7 DR2 p1	5.0	20	110	6.20	38	24	36	2	85-95
S8 DR2 p2	5.0	35	80	6.20	38	24	36	2	85-95

On these structures, the first distress observed was rutting, and cracks started to develop only when the rut depth exceeded 12 to 15 mm. Investigations performed at the end of the experiments indicated that the rutting was mainly due to permanent deformations of the unbound granular layers and not only of the subgrade, contrary to what is assumed in the French pavement design method, where the only design criterion for rutting is the maximum vertical elastic strain ϵ_z at the top of the subgrade.

For these very thin pavements, the measurements indicate that maximum tensile strains at the bottom of the bituminous layers are generally transversal, and located under the centre of each wheel. They are generally 1.2 to 1.5 times higher than longitudinal strains. This probably explains why the cracks observed in these experiments were mainly longitudinal (assuming bottom-up cracking), except on structures S5, S6 and S8. Figure 4 shows a typical example of the crack patterns observed on these structures.

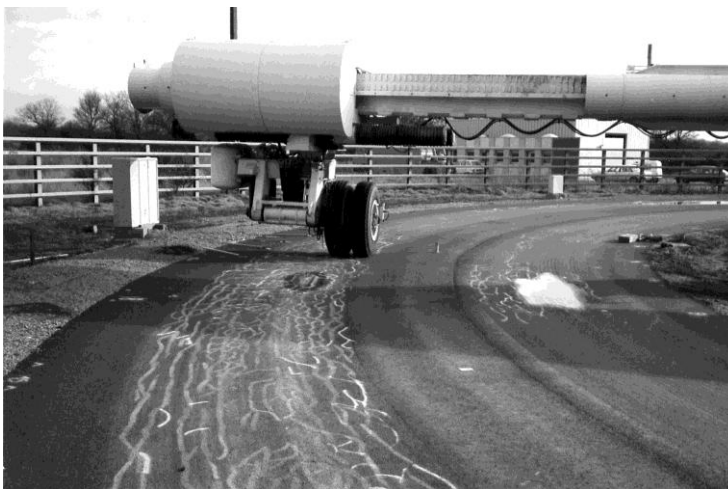


Figure 4. Illustration of cracks observed on structure S1 at the end of the experiment.

On structures S5 and S6, cores taken after observation of the first cracks indicated that the cracks were superficial, and stopped a few millimetres below the surface. These first transversal cracks were short (20 to 40 cm) and very thin, and led to a production of fines due to attrition. Visco-elastic calculations performed on similar pavement structures (Heck et al. 1998, Duhamel et al. 2005) have shown that visco-elastic behaviour can generate significant tensile stresses at the top of the thin bituminous layer, near the wheel, and this could be one possible explanation of the top down cracking.

Table 2 describes the experimental conditions, and the distresses observed on the 8 pavement structures. The evolution of cracking with the number of loads is shown in Figure 5. Although the pavement structures are similar, two types of evolution can be seen: On structures S1 to S4,

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and also S7, the first cracks appear early (between 50 000 and 200000 cycles), and cracking develops rapidly to failure (more than 90 % cracking after 100 000 to 500 000 cycles). On structures S5, S6 and S8, development of cracking is much slower (50 % cracking is attained after 750 000 to 1 million loads). Two main factors probably explain these differences:

- The bearing capacity of the soil: In experiments S1 to S4, the soil (clayey sand) had an elastic modulus of about 60 MPa after construction. In comparison, in experiments S5 to S8, a stiffer soil with levels of modulus varying between 80 and 110 MPa was used. This is in accordance with the French design method, where a penalization factor is applied to low bearing capacity soils.
- The climatic conditions. Structures S1 to S4 were tested in autumn or winter, with mild temperatures and heavy rainfall, leading to high moisture contents in the unbound layers. Structures S5 and S6 were tested during summer with high temperatures and practically no rainfall. Structures S7 and S8 were tested in Summer and autumn, with a high water table level in the soil. Dry and hot conditions certainly contributed to the good performance and slow evolution of cracks on structures S5, S6. Structures S7 and S8, with high water table level, present a different behaviour. On structure S7, with a thin granular base (20 cm) cracking developed much earlier than on section S8, with a 35 cm thick granular base.

Table 2. Distresses observed on the pavements with 5 cm thick wearing courses.

Experiment	first cracks	Number of loads (millions) leading to		Rut depth at 10% cracking mm	Temperature in BC (°C)	Rainfall mm	Soil Modulus MPa
		10% cracking	50% cracking				
S1	Longitudinal	0.350	0.450	22	10-30°C	medium	60
S2	Longitudinal	0.180	0.300	12	5-20°C	abundant	60
S3	Longitudinal	0.100	0.110	12	5-20°C	abundant	60
S4	Longitudinal	0.060	0.080	12	5-20°C	abundant	60
S5	Transversal	0.500	0.950	20	20-55°C	dry	110
S6	Transversal	0.590	1.050	20	20-55°C	dry	110
S7	Longitudinal	0.050	0.200	15	0-45°C	medium	80
S8	Transversal	0.300	0.750	20	0-45°C	medium	80

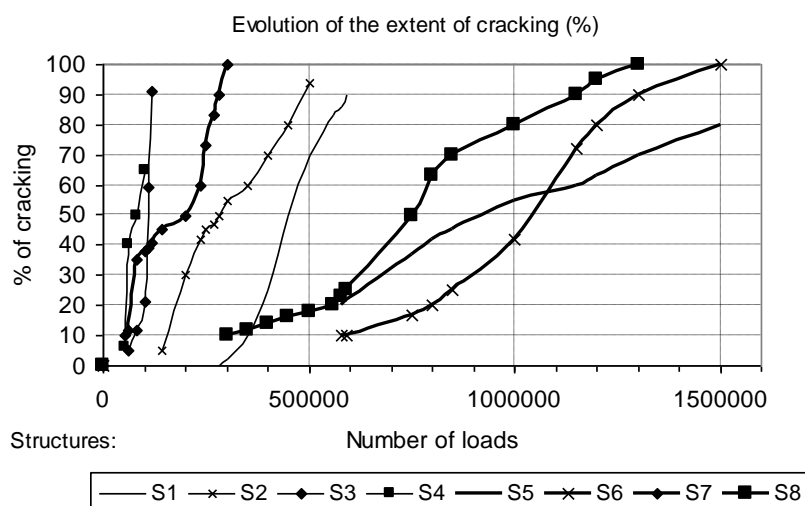


Figure 5. Evolution of the extent of cracking on the pavements with 5 cm thick wearing courses.

4.2 Predictions of pavement lives and conclusions

The observations on the low traffic pavements with less than 6 cm thick bituminous wearing course clearly show that the main distress mode of these pavements is rutting, mainly localized in the granular layers and subgrade. In the French design method, based on a multi-layer linear

elastic model, the design criterion used for these pavements with a thin surface layer is only a rutting criterion. No bituminous layer fatigue criterion is used, and this is coherent with the observed behaviour. The rutting criterion is expressed by:

$$\varepsilon_z \leq 16000 (\text{NE})^{-0.222} \quad (1)$$

with: ε_z : the maximum vertical strain at the top of the subgrade
 NE the number of equivalent standard axle loads (130 kN axle).

In these pavements with a thin surface layer, cracking was observed only after a significant level of rutting, and then contributed to the degradation of the pavement, in particular by facilitating infiltration of water. This good resistance to cracking is probably due to the use of specific bituminous mixes, specified in France for low traffic pavements, which a high bitumen content, and this confirms the interest of these materials.

To evaluate the French design method, design calculations have been performed, with the rutting criterion, for the 8 experimental pavements. For each pavement, two calculations have been performed. The first one was performed with standard values of elastic moduli of the unbound granular layers and subgrade, defined from empirical criteria (standard design procedure). The second calculation was performed with values of elastic moduli back-calculated from in situ measurements (FWD or deflection tests). The results of the design predictions (number of axle loads NE to failure) are presented in Table 3. In general, better predictions are obtained with the back-calculated layer moduli. These last predictions are reasonable for all structures except S4, with ratios between the experimental and predicted design life varying between 1.1 and 3.3. The only exception is structure S4, where the real life is largely over-predicted. This structure differs by its very thick granular base (55 cm). With such a thick granular layer, the subgrade strain ε_z becomes low, and the subgrade strain criterion is not any more applicable. Clearly, for structure S4, another design criterion is required (rutting criterion for the granular layer).

Table 3. Comparison of predicted and observed lives of the experimental pavements (number of 130 kN axle loads NE).

	S 1	S 2	S 3	S 4	S 5	S 6	S 7	S 8
Standard design NE	14600	902 000	492 000	2610000	28400	224 000	28400	224 000
Design with back calculated moduli NE	118 000	388 000	61 000	1180000	150 000	450 000	160 000	520 000
Experimental NE	36 000	340 000	115 000	95 000	430 000	800 000	80 000	900 000

To improve the rutting predictions, further research is carried out at LCPC to develop a finite element model, for calculation of permanent deformations in these low traffic pavements (Finite element program ORNI, Hornych et al, 2007).

5 PAVEMENTS WITH 6 TO 12 CM THICK BITUMINOUS WEARING COURSES

5.1 *Experimental results*

Eight pavement structures with more than 6 cm thick bituminous layers have been analysed. The main characteristics of the pavement structures and materials are given in Table 4. In these experiments, different bituminous mixes have been tested:

- Classical bituminous concretes (BBSG) in structures S9 to S12, with elastic moduli at 15 °C and 10 Hz varying between 6000 and 7000 MPa.
- Road base bituminous materials (GB) in structures S19 and S20 with elastic moduli at 15 °C and 10 Hz varying between 9000 and 12000 MPa. On structure S19 this material was covered by a 2 cm very thin bituminous concrete layer; no wearing course was used on S20.
- High modulus bituminous mixes (EME) in structures S22 and S23, with elastic moduli at 15 °C and 10 Hz varying between 12000 and 13000 MPa.

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For all these structures, the main mode of distress is cracking of the bituminous layers. When the extent of cracking attains 10 %, the rut depth remains low, varying generally between 3 and 7 mm. Moreover, the type of bituminous mix influences the mode of cracking observed.

Table 4. Main characteristics of the pavement structures with 6 to 12 cm thick wearing courses.

Experiment name	Layer Thickness (cm)		Soil Modulus (MPa)	Bitumen		AC composition (in %)				Deflection	
	BC	UGM		%bit	10/14	6/10	2/6	0/2	fines	0,01mm	
S9 Enr ph1 str1	7.0	40	50/70	5.40	29	16	22	32	1	90-100	
S10 Enr ph1 str2	7.5	40	50/70	5.40	29	16	22	32	1	110-120	
S11 Enr ph2 str1	9.0	40	50/70	5.40	29	16	22	32	1	100-120	
S12 Enr ph2 str2	7.5	40	50/70	5.40	29	16	22	32	1	130-140	
S19 Enr ph1 str4	11.0	40	50/70	4.60	29	16	22	32	1	70-90	
S20 Enr ph 2 str3	11.0	40	50/70	4.60	29	16	22	32	1	90-110	
S22 Enr ph 1 str3	8.0	40	10/20	6.20	29	16	22	31	2	70-80	
S23 Enr ph 2 str4	6.0	40	10/20	6.20	29	16	22	31	2	100-120	

Table 5 describes the experimental conditions, and the distresses observed on the pavement structures with 6 to 12 cm thick bituminous layers. The evolution of cracking on these structures is summarised in Figure 7. For structures S9 to S12, with a standard bituminous concrete, the first cracks were in all cases transversal (an example is shown in Figure 6), and there was evidence that some of them initiated at the top of the layer, and propagated downwards. For these structures, measurements indicated that the longitudinal and transversal tensile strains, at the bottom of the bituminous layer were of the same level. Cores taken on structures S9 and S10, after the observation of the first cracks, indicated that these cracks were superficial, and went only a few millimetres below the surface. Later, the cracks propagated through the whole bituminous layer. The first cracks appeared for levels of rut depth of about 4 to 7 mm.



Figure 6. Transversal cracking observed on structure 9.

For structures S19 and S20 (road base bituminous material, with a relatively low bitumen content), cracks were also transversal. They started to appear for levels of rut depth of 3 to 5 mm, and rapidly crossed the whole layer.

Structures S22 and S23 were built with high modulus bituminous mixes. Usually, these materials are used for base course, and are covered with a wearing course, but on the test track, they were tested without wearing course. In these stiff materials, the cracks (again mainly transversal) appeared for low levels of rutting (2 to 4 mm) and developed rapidly.

Structures S9, S10, S19 and S22 present a long life (between 1.3 and 2.6 million loads to reach 50 % of cracking), see Figure 7 . Structures S11, S12, S20 and S23 present a much shorter life (0.3 to 1 million loads), despite the fact that they were built to have the same characteristics (S11 was identical to S9, etc.). However, the structures S11, S12 and S20 were built on a layer of crushed gravel which had been extracted and recompacted, and which had a low density. In addition, structure 23, with high modulus bituminous mix, had a thinner bituminous layer (6cm instead of 8cm).

Table 5. Distresses observed on the pavement structures with 6 to 12 cm thick wearing courses.

Exp	first cracks	Number of loads (millions) leading to		Rutting at 10% cracking mm	Temperature AC in °C	Rainfall mm
		10% cracking	50% cracking			
S9	Transverse	1.000	1.300	7	5-40°C	medium
S10	Transverse	1.000	1.700	7	5-40°C	medium
S11	Transverse	0.250	1.000	4	5-30°C	medium
S12	Transverse	0.250	0.300	5	5-30°C	medium
S19	Transverse	2.300	2.700	5	5-40°C	medium
S20	Transverse	0.250	0.400	3	5-30°C	medium
S22	Transverse	1.200	1.750	3	5-40°C	medium
S23	Transverse	0.200	0.300	3	5-30°C	medium

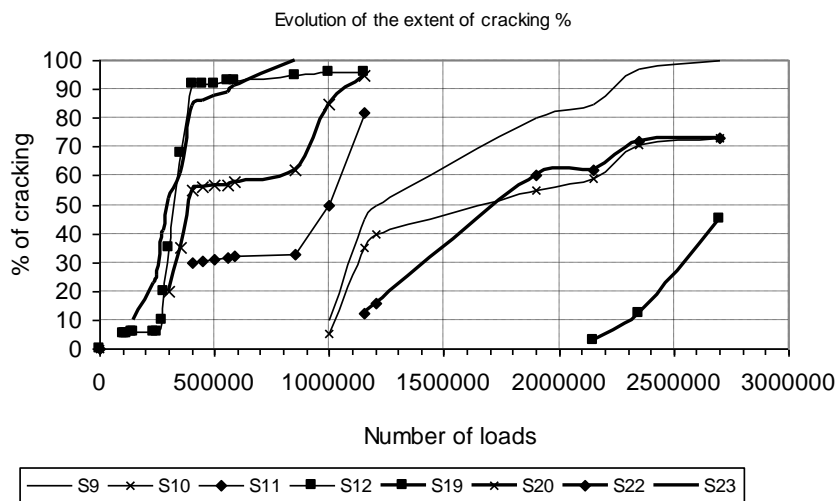


Figure 7. Evolution of the extent of cracking on the pavements with 6 to 12 cm thick wearing courses.

5.2 Predictions of pavement lives and conclusions

For these pavements, design calculations were performed, in order to predict the pavement life, and make comparisons with the observed behaviour. For these bituminous pavements, two design criteria are applied, in the French pavement design method: the rutting criterion limiting the maximum vertical strain at the top of the subgrade (equation 1), and a fatigue criterion limiting the maximum tensile strain ϵ_t at the bottom of the bituminous layer. However, the relevant design criterion is generally the fatigue criterion, expressed as follows:

$$\epsilon_t = \epsilon_6 \cdot N_e^b \quad (2)$$

with: ϵ_6 the strain leading to a fatigue life of 10^6 cycles, determined at 10 °C and 25 Hz,
 b : the slope of the fatigue line,
 N_e the number of equivalent standard axle loads (130 kN dual wheel axle loads),

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$E(10^{\circ}\text{C})$: the modulus of the bituminous material at 10°C and 10 Hz,

$E(\theta)$: the modulus of the bituminous material at the design temperature θ and 10 Hz,

k_r , k_s and k_c are coefficients related respectively with the risk of failure, the penalization for low bearing capacity soils and the calibration of the model (comparison between predictions of the model and behaviour observed on real pavements).

This fatigue design criterion was applied, for the 8 pavement structures, using fatigue parameters determined from two-point bending fatigue laboratory tests. Two calculations were performed for each pavement structure: in the first one, a constant temperature of 15°C (generally adopted for standard design) was used. In the second calculation, the temperature variations were considered, by cumulating the fatigue damage occurring at each temperature θ (by intervals of 5°C), using the Miner hypothesis for damage accumulation.

Comparisons of the design lives predicted with these two approaches with the experimental pavement lives (number of loads leading to an extent of cracking of 50 %, assumed equal to the design risk of failure) are given in Table 6. Clearly, for these pavements, the two design approaches lead to unrealistically low design lives. It must be stressed that all the pavements are tested in accelerated conditions, without normal seasonal variations, and material ageing, which could be favorable. But, nevertheless, the application of the fatigue criteria, based on laboratory tests, leads here to very poor predictions. This could mean that:

- For these relatively thin pavements, the conventional fatigue criterion (assuming bottom up cracking) does not describe correctly the failure mechanisms.
- The laboratory fatigue tests are not representative of the in situ behaviour. The bending test, without confinement, may be too severe compared with the in situ stress conditions, as well as the continuous high frequency loading (25 Hz). For instance, studies performed by de la Roche et al. (1994) have shown the strong influence of rest periods on fatigue behaviour.
- The fatigue criterion (based on parameters determined at 10°C , equation 2) is probably not sufficient to take into account the thermal susceptibility of the materials, and this is at present a subject under research at LCPC.
- It is probable that, due to the absence of ageing and seasonal variations, the accelerated tests lead to higher pavement lives than on real roads. This effect may be corrected by considering the relative performance in comparison with a reference pavement.

Table 6. Comparison of predicted and observed lives of the experimental pavements (degradation level 50 %).

	S 9	S 10	S 11	S 12	S 20	S 21	S 22	S 23
Standard design ($\theta = 15^{\circ}\text{C}$) NE	69 000	14 500	50 000	63 000	153 000	102 000	169 000	29 900
Design with variable temperature NE	68 000	6 400	11 700	8 700	30 700	7 400	328 000	11 600
Experimental NE	1 250 000	1 687 500	995 000	322 000	2 700 000	385 500	1 750 000	294 500

6 CONCLUSIONS

The paper presents a synthesis of pavement deterioration mechanisms observed in APT experiments, on the LCPC fatigue carousel, on low traffic pavement structures, with unbound granular bases. The experiments lead to similar deterioration mechanisms as on real pavements. The main deterioration mechanism depends on the thickness of the bituminous surfacing (less than 6 cm, or between 6 and 12 cm). For the pavements with very thin bituminous layers, the main deterioration mechanism is rutting due to permanent deformations of the unbound layers, and significant cracking appears only after 10 to 15 mm of rutting; this cracking is mainly longitudinal. For the pavements with thicker bituminous layers (6-12 cm), the main deterioration is cracking,

and rutting remains much more limited (3 to 7 mm). In this case, the cracking is mainly transversal, contrary to the longitudinal cracking generally observed on real pavements.

For the two types of structures, design calculations have been performed with the French design method. For the very thin pavements, reasonable predictions of the service life are obtained, despite the simplifications of the model (subgrade rutting criterion only). For the thicker pavements, where bituminous layer fatigue is the design criterion, however, the design method leads to a large under-estimation of the observed pavement life, showing the limits of the conventional fatigue criterion. These results show the necessity:

- to improve the modelling of fatigue damage in pavements. Research is presently carried out at LCPC on development of a damage model for bituminous materials in pavement structures (Bodin et al., 2004a, b) and on modelling of pavements with vertical discontinuities, to understand crack propagation phenomena (Chabot et al., 2007).
- to study the real representativity of accelerated tests, which do not take into account ageing of materials, climatic effects and variability of loads, regarding fatigue mechanisms.
- to develop specific sensors to survey development of cracking in pavements.

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