Study of the Fatigue of Asphalt Mixes Using the Circular Test Track of the Laboratoire Central des Ponts et Chaussées in Nantes, France

CHANTAL DE LA ROCHE, HUGUES ODÉON, JEAN-PIERRE SIMONCELLI, AND ALEXANDRA SPERNOL

The conventional French fatigue test has yielded significantly different results for two asphalt materials with the same grade of pure asphalt. A research program was begun to study the influence of the asphalt nature on the fatigue behavior of asphalt materials. The program included full-scale experimentation on the circular test track of the Laboratoire Central des Ponts et Chaussées, laboratory tests, and mechanical analysis. Four asphalt mixes with pure asphalt were tested on the experimental pavement: two asphalt concretes with asphalts 50/70 of A and B origin, a high-modulus asphalt mix (bitumen 10/20), and a classical asphalt road base (bitumen A). The asphalt materials were fatigue tested in the laboratory according to several procedures: two-point bending fatigue tests on trapezoidal samples, with controlled strain, with and without rest periods, and with controlled stress, without rest periods; and three-point bending fatigue tests on parallelepiped-like samples, with controlled stress, with and without rest periods. The ranking of the materials according to their laboratory fatigue behavior depends strongly on the test procedure. The mechanical analysis carried out on the basis of the laboratory test results and the behaviors observed on the test track indicate that the controlled stress fatigue tests lead to results closer to the test track behavior and that the shift factor to be applied to the high-modulus asphalt mix should be 1. All these results have to be confirmed by a repetition of this experiment still in progress.

Differences in results found between two asphalt mixes made with pure asphalt of the same grade in the usual laboratory fatigue test, that of French Standard NF P 98-261-1 (controlled strain two-point bending on trapezoidal specimen, with no rest periods), led to a study of the pertinence of this fatigue test with respect to the influence of the type of asphalt. The absence of rest periods and the dissipative heating that can be observed in the course of the test are two phenomena not found with actual traffic that might tend to shorten the life and affect differently the various types of asphalt.

Accordingly, a research program was set up to

- Compare the classification obtained from fatigue tests (conventional or with rest periods, with controlled stress or strain) with the ranking obtained on an experimental pavement tested on the circular fatigue test track of the Laboratoire Central des Ponts et Chaussées (LCPC);
- Identify the most pertinent laboratory test for the type of structure concerned; and
- Compare the life predictions for asphalt structures according to the French pavement design method with the results obtained on the test track.

In addition, the design of high-modulus asphalt pavement structures was compared with the classical asphalt road base design.

This research program was conceived in the context of the technical cooperation between the USAP (toll motorways companies) and the LCPC, which financed the experiment on the test track. The Shell Company was associated with the laboratory experiments at the start of this project and performed impulse fatigue tests at the Shell-KSLA laboratory (Amsterdam).

EXPERIMENT ON LCPC'S CIRCULAR FATIGUE TEST TRACK

The experiment presented here lasted from October 1990 to July 1991, during which 2,730,000 loadings were applied, leading to significant damage to the various pavement sectors tested (*1*).

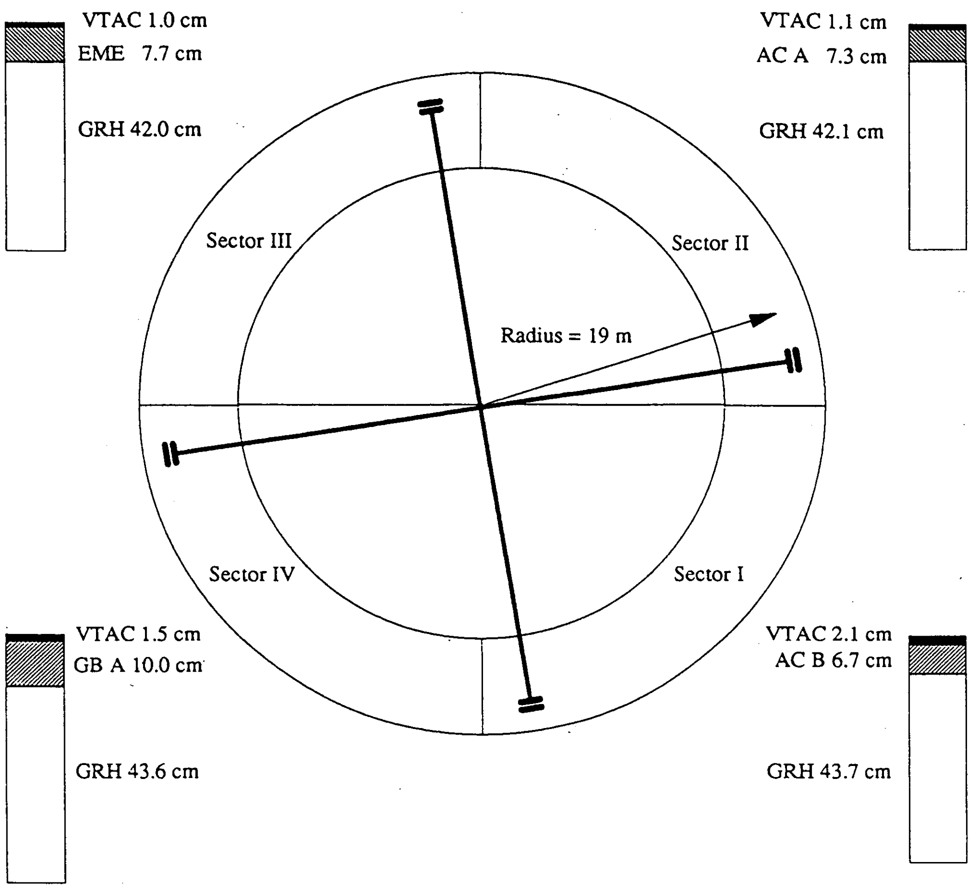
Experimental Conditions

Four 0/14 mm asphalt mix formulas were tested on four sectors arranged as shown in Figure 1:

- Sector I—an asphalt concrete made with 50/70 asphalt from Source B (AC B);
- Sector II—an asphalt concrete made with 50/70 asphalt from Source A (AC A);
- Sector III—a high-modulus asphalt mix (made with hard 10/20 asphalt) (EME); and
- Sector IV—a classical asphalt road base made with 50/70 asphalt from Source A (GB A).

These layers, built on a well-graded untreated granular material (GRH), were designed to yield, according to the usual design method, a service life on the order of 2 million cycles while com-

C. de La Roche and H. Odéon, Laboratoire Central des Ponts et Chaussées, Centre de Nantes, BP 19, 44340 Bouguenais, France. J.-P. Simoncelli, Société des Pétroles Shell, Direction Bitumes, 89 Boulevard Franklin Roosevelt, 92564 Rueil Malmaison Cedex, France. A. Spernol, Scétauroute-USAP, 23 Avenue du Centre, 78286 Saint-Quentin en Yvelines, France.



Sector	I	II	III	IV
Asphaltic binder	B 60/70	A 60/70	10/20	A 60/70
Content (%)	5.4	5.4	6.2	4.6

Grading curve of granular material used in the asphaltic mixes

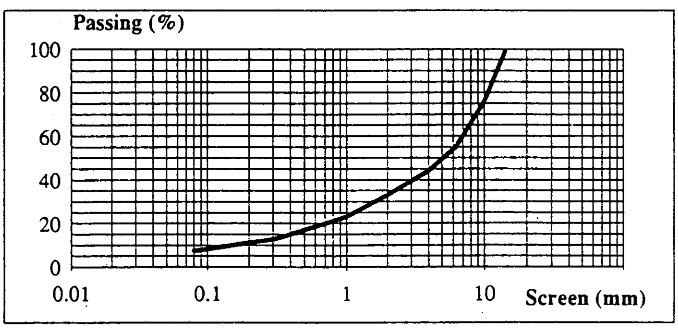


FIGURE 1 Experimental structures.

plying with the usual thicknesses of placement of these materials. The thickness of the asphalt road base was determined by the usual design method to yield the same calculated life as the high-modulus asphalt mix. All of the structures were covered with a wearing course of very thin asphalt concrete (VTAC) (20 to 25 mm theoretical thickness). The topographical surveys revealed thicknesses of asphalt materials (Figure 1) that were, on the average, less than the theoretical values (8 cm for AC B, AC A, and EME and 12 cm for GB A). The "foundation soil" was a clayey 0/10 sand, 2.80 m thick, on clayey silt.

The experiment was performed with the following configuration of the circular test track: load, 65 kN per dual wheel (half French legal axle) with transverse sweep over 1.60 m; speed, 10 rpm (70 kph linear at the mean radius of 19 m); and tires, Dunlop SP 321 inflated to 0.8 MPa.

During construction, the structures were equipped with strain gauges, pressure sensors, and thermocouples. There were also measurements of quasi-static deflection and of radius of curvature, surveys of the longitudinal and transverse profiles, and cracking surveys.

Course of Experiment and Main Results

This experiment was performed during two periods: one "cold" (90 percent of loadings between 0°C and 15°C), which included 1,165,000 loadings and resulted in the appearance of the first cracks in Sectors I and II; and one "warm" (80 percent of loadings between 15°C and 20°C), which included 1,565,000 additional loadings until significant cracking developed in all four sectors.

Initialization of Measurements (Zero Point)

The data presented in Table 1 correspond to the measurements made at the start of the experiment, before damage to the structures. The measured deflections are rather homogeneous, and the observed variations seem to depend only on the variations of thickness of the asphalt layers. On the whole, the deflection values are high, which indicates a low soil bearing capacity. The values of the radii of curvature are consistent with the measured deflections and thicknesses. The strains at the base of the asphalt layers of Sectors I and II are of the same order of magnitude. The same is true of Sectors III and IV.

Results at End of Cold Period

Increases in deflections are comparable and moderate for Sectors I and III. Deflections increase a little more in Sector II and less in Sector IV (Figure 2).

The first cracks are observed at the surface of the pavements after 1,165,000 loadings (end of cold period), following heavy rains. Core drillings confirmed that they were in fact structural cracks through the bound layers. The presence of VTAC probably masked the appearance of the first cracks in the pavement base. The extent of cracking measured at the end of the cold period is indicated in Figure 3.

Whereas the extent of cracking is locally large on Sectors I and II at the end of this first period of traffic, the cracks are fine and the pavements cannot be regarded as destroyed. For Sector III, the cracks appeared in a zone of underthickness and are therefore not significant. As for Sector IV, no crack was recorded. Consequently, it was decided to continue the experiment without maintenance a few months later (warm period).

Results at End of Warm Period

A reduction of the deflections was noted between the last measurements of the previous period and the first measurements of the new period; it may have resulted from a change in the moisture condition of the foundation soil. With the traffic and the increase of cracking, the deflections increased regularly on Sectors I and II. On Sector III the deflection measurements increased substantially with the total traffic, whereas Sector IV measurements increased very little (Figure 2).

Cracking evolved in a way that varied from one structure to another during the warm period. Whereas it developed similarly in Sectors I and II, it appears that the onset of cracking in Sector III occurred later during the cold period, and a comparable subsequent development was observed. On the other hand, the cracking of Sector IV appeared late during the warm period but then developed faster than on the other sectors (Figure 3).

At the end of the experiment, Sector I (AC B) exhibited the most damage and had a high density of cracks. Sector II (AC A) had a lower average cracking density with a large area that was preserved (this zone corresponds to a slight local overthickness of the layer of asphalt concrete). Sector III (EME) has areas of dense cracking along with a few longitudinal cracks. Other areas have transverse cracking only. The extent of cracking at the end of the experiment was close to those of Sectors I and II. The extent of cracking of Sector IV (GB A) reached only 47 percent at the end of the experiment.

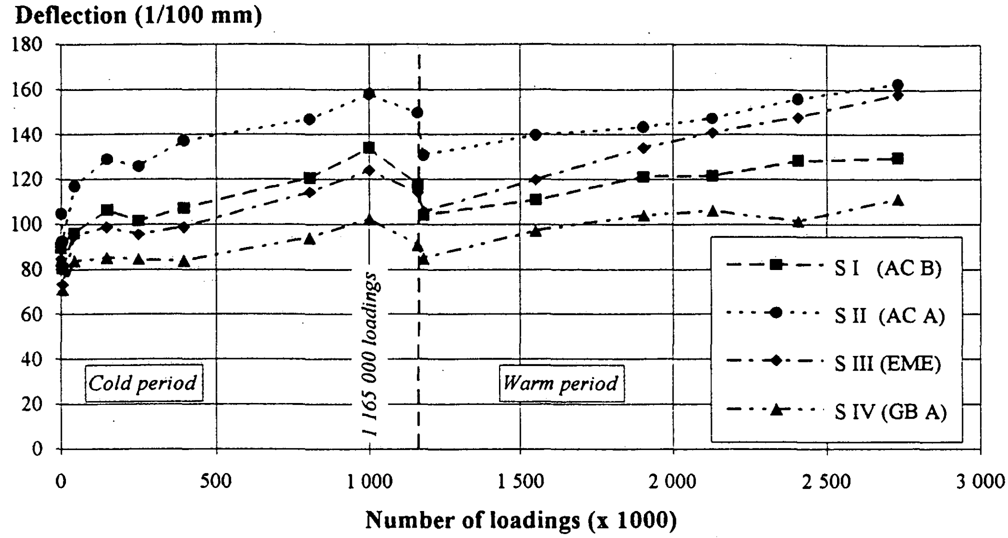
Since none of the sectors was totally destroyed at the end of the experiment, the strengths of the various structures were compared at the same percentage extent of cracking—50 percent (which is the final value reached on Sector IV). The number of axle loads for 50 percent cracking, denoted N 50, is 1,250,000

TABLE 1 Measurements on Test Track at Zero Point

Sectors Materials	I AC B	II AC A	III EME	IV GB A
Mean deflection (0.01 mm)	96	111	91	90
Measurement temperature 26°C				
Mean radius of curvature (m)	111	91	161	158
Measurement temperature 21°C				
Order of magnitude of the strains at the base of the asphaltic layers (μstrains)				
Longitudinal strains	134 *(3)*	122 *(4)*	87 *(1)*	95 *(4)*
Transverse strains	131 *(1)*	120 *(1)*	42 *(1)*	111 *(1)*
Measurement temperature in °C	19.5	19	19	17.5

(*) The italicized figure in parentheses is the number of gauges on which the mean was determined to calculate the order of magnitude of the strains.

(**) The longitudinal and transverse strains (base of asphaltic layer) were measured with speed of 10 rpm and load of 6.5 T; one of the wheels of the pair directly above the gauges, at the zero point.



	Number of loadings	Sector I AC B	Sector II AC A	Sector III EME	Sector IV GB A
Deflections	40,000	96	117	95	84
1/100 mm	1,165,000	118	150	114	91
(20°C)	2,700,000	129	163	158	111

FIGURE 2 Deflections referred to 20°C.

loadings for Sector I, 1,750,000 loadings for Sectors II and III, and 2,750,000 loadings for Sector IV.

Conclusions Concerning Behavior on Circular Test Track

The following main conclusions can be drawn from these full-scale tests:

- With the actual thicknesses, on foundation soils having the same bearing capacity, it takes approximately 1.5 times as many loadings to obtain the same extent of damage on Sector II (AC A) as on Sector I (AC B). This difference must be considered in light of the differences in the thicknesses of the AC and of the VTAC on these two sectors.
- The comparison of GB A, 10 cm thick, and EME, 7.5 cm thick, on a foundation liable to deformation (not the usual conditions of use of such a material) clearly favors GB A.
- Cracking appears to start in EME substantially later than in both conventional asphalt mixes at similar thicknesses of placement, but the evolution of this cracking, once started, appears faster.

LABORATORY TESTS

Tests on Binders

The original binders were sampled when the pavements of the circular test track were built and the recovered binders were extracted from slabs cut from the test track. They underwent conventional tests (Table 2) and complex modulus tests [Figure 4 (top)], which indicate the following (*2*):

- All binders are within the specifications. Asphalt B shows a large evolution after RTFOT.
- Generally, Asphalt A exhibits more thermal and kinetic sensitivity than Asphalt B; its Black's curve (logarithm of modulus of complex modulus versus phase angle) evolves faster, and its isothermals are steeper. It is also less structured.
- Asphalt B and the hard asphalt have very different rigidities and thermal sensitivities but similar kinetic sensitivities.

On the whole, the results of the recovered binders give the same trends.

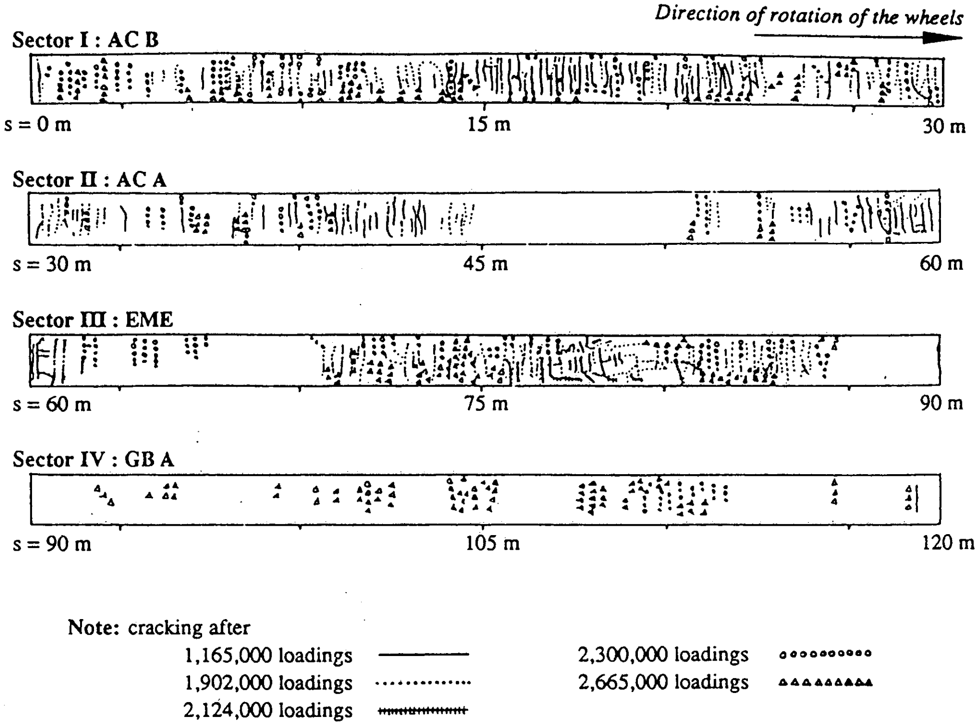
Tests on Asphalt Mixes

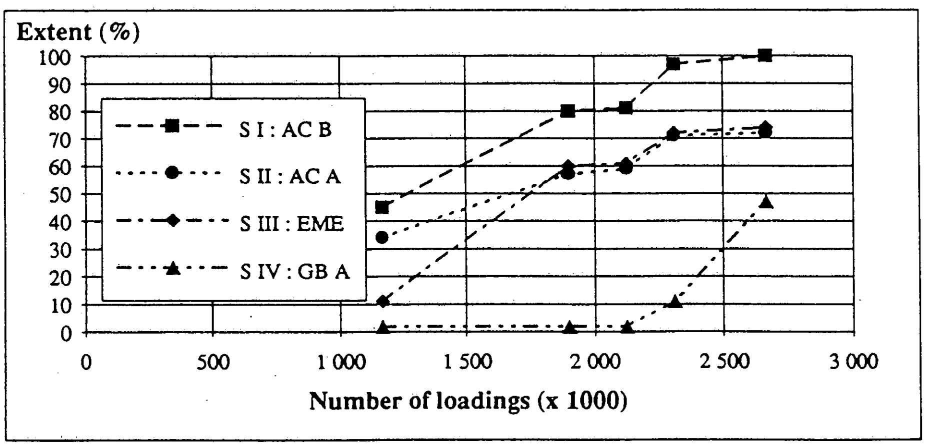
All tests performed on the four asphalt mixes presented here were performed on specimens cut from slabs of materials sampled in place. These slabs were taken in the untraveled areas of the circular test track, before rotation.

Measurements of Complex Modulus

Complex modulus tests (*3*) on trapezoidal specimens, in accordance with French standard NFP 98-260-2, were performed by the Bordeaux LRPC. The corresponding Black's curves (logarithm of modulus of the complex modulus versus phase angle) are given in Figure 4 (bottom). Modulus measurements were also made in all the other laboratories at the beginning of the fatigue test, either on trapezoidal specimens in two-point bending or in three-point bending on beams (Table 3).

The results obtained by each of the laboratories are consistent, taking into account the temperature and frequency influences. This





Sector	I	II	III	IV
Cracking (%) after				
1,165,000 loadings	45	34	11	0
2,665,000 loadings	100	72	74	47

FIGURE 3 Cracking.

is an important first conclusion given the multiplicity of apparatuses and methods used.

Fatigue Tests

The conditions of the fatigue tests are given in Table 4.

Controlled Strain Fatigue Tests

The four asphalt mixes were tested in continuous fatigue with controlled strain by Procedures 1, 2, and 3. The results are given in terms of ϵ_6 and the slope of the fatigue line in Table 3. ϵ_6 is the strain corresponding to conventional failure (i.e., reduction of the force at the top by half) of the specimen at 1 million loadings. The fatigue line is obtained by a regression of the form

$$\ln (\text{number of cycles}) = a - \text{slope} \times \ln \epsilon$$

on the individual results.

These results confirm that with respect to the two-point bending fatigue test on trapezoidal specimens in the continuous mode, Asphalts A and B lead to very different values of ϵ_6 between AC B

TABLE 2 Characteristics of Binders—Original, After RTFOT, and Extracted

Bitumen	50/70 B			50/70 A			10/20		
Tests results	Pen	RB	PfI	Pen	RB	PfI	Pen	RB	PfI
Original binder	61	51	-0.5	65	48	-1.1	16	69.5	0.3
After RTFOT	37	59	0.1	42	53	-0.9	13	75	0.8
Extracted binder	44	56	-0.1	39	53.5	-0.9	13	75	0.8

Note: *Pen:* *Penetration at 25°C (mm x 0.1)*
RB: *Ring and Ball Temperature (°C)*
PfI: *Pfeiffer penetration index*

and AC A (*4*). The results from the different laboratories, in terms of ϵ_6, rank the asphalt mixes as follows, for all test procedures: AC B ≈ EME > AC A ≈ GB A. The results by Procedures 1 and 2 show that AC B is a little more sensitive to temperature than AC A in terms of fatigue performance. Similarly, EME is more sensitive to temperature than GB A.

Controlled Stress Fatigue Tests

Controlled stress fatigue tests were performed by Procedure 4 for the four materials and by Procedures 6 and 7 for AC A, AC B, and EME only. This makes it possible to compare the stresses σ_6 and the slopes of the fatigue lines (Table 3). σ_6 is the stress corresponding to conventional failure (doubling of the displacement at the top) of the specimen at 1 million loadings. The fatigue line is obtained by a regression of the form

$$\ln (\text{number of cycles}) = a - \text{slope} \times \ln \sigma$$

on the individual results.

The results obtained rank the asphalt mixes as follows: EME >> GB A ≈ AC B > AC A in the continuous mode and EME >> AC A ≈ AC B in the discontinuous mode.

The values of σ_6 determined by Procedure 6 (three-point bending) are higher than those measured by Procedure 4 (two-point bending).

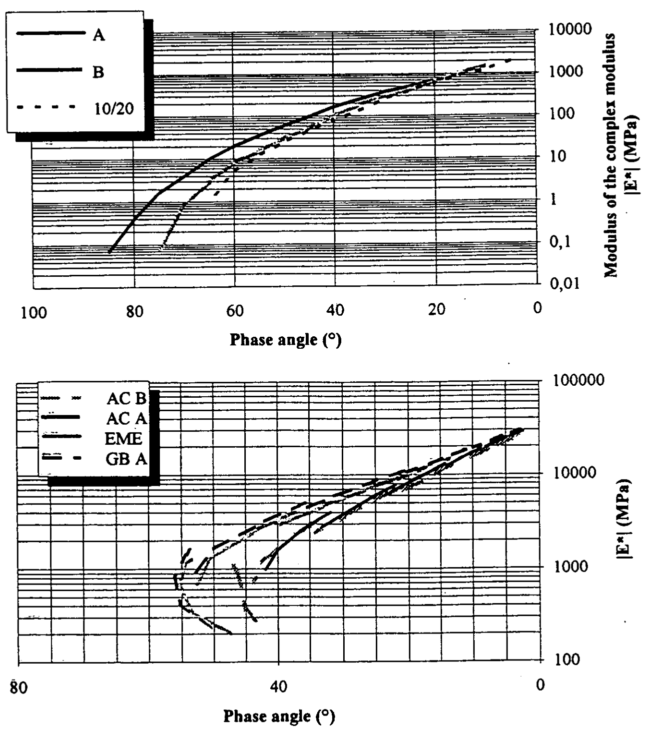


FIGURE 4 Complex modulus curves in the Black space: *top*, Black curves of the original binders; *bottom*, Black curves of the asphalt mixes.

Continuous and Discontinuous Fatigue

To quantify the influence of the rest period on fatigue behavior, tests with and without rest periods were performed in two ways: by Procedure 5, for which trapezoidal specimens were loaded at the top in strain (two-point bending) and by Procedures 6 and 7, for which rectangular specimens are loaded in stress at midpoint (three-point bending).

The controlled strain tests were performed in continuous and discontinuous fatigue for only one level of strain of the specimen, 200 μstrains. This strain level was considered representative of the strains obtained on the circular fatigue test track at the base of the layer of asphalt mix. This analysis leads to the following ratios of life durations (continuous/discontinuous): 4 for AC B, 2 for AC A, 3 for EME, and 1 for GBA.

The results of the continuous and discontinuous controlled stress tests were analyzed in terms of initial stress: for a stress level of 2 MPa, the corresponding lives in the continuous and discontinuous modes are deduced from the fatigue line of the test. This leads to the following ratios of life durations (continuous/discontinuous): 7 for AC B, 8 for ACA, and 2 for EME.

For the two asphalt concretes, it is found that the incidence of the rest periods differs between the controlled stress test (AC A and AC B benefit from the rest periods in the same way whichever analysis is performed) and the controlled strain test (AC B then performs better). However, the discontinuous tests were performed according to different procedures: the controlled strain test is a test with bursts of loading (8 sec or 320 loading cycles, 80 sec of rest), whereas the controlled stress test is in pulses (one loading cycle; five cycles of rest).

EME gives ratios of numbers of cycles that are of the same order as those of the asphalt concretes in the tests with bursts of

TABLE 3 Results of Laboratory Tests on Asphalt Mixes

Sectors / Materials		I AC B	II AC A	III EME	IV GB A
MODULI OF THE ASPHALT MATERIALS					
Moduli of the complex modulus measured in LRPC Bordeaux					
10°C, 10 Hz		10,280	12,374	15,024	13,486
20 °C, 10 Hz		5,110	5,876	9,788	7,097
10 °C, 30 Hz		12,425	14,991	17,037	15,831
20 °C, 30 Hz		6,892	8,102	11,750	9,342
Moduli measured in the laboratory at the beginning of the fatigue tests					
LCPC (10°C, 25 Hz - 2 point)		12,000	14,200	16,600	15,000
LPC Ang (10°C, 25 Hz - 2 point)		12,500	16,000	18,300	17,500
LCPC (20°C, 25 Hz - 2 point)		6,900	8,000	11,000	9,600
Shell (20°C, 40 Hz - 3-point)		6,900	9,300	11,400	-
FATIGUE TESTS RESULTS*					
Controlled strain fatigue tests					
Procedure 1	ε_6 (μstrain)	140 ± 10	90 ± 5	140 ± 6	88 ± 11
10°C, 25 Hz in air	slope	6.3	5.2	5.3	4.3
Procedure 2	ε_6 (μstrain)	169 ± 11	104 ± 8	159 ± 13	91 ± 9
20°C, 25 Hz in air	slope	6.0	5.2	5.7	4.1
Procedure 3	ε_6 (μstrain)	143 ± 10	92 ± 6	136 ± 6	91 ± 6
10°C, 25 Hz in water	slope	3.7	4.5	5.9	5.7
Controlled stress fatigue tests					
Procedure 4	σ_6 (MPa)	0.67 ± 0.06	0.52 ± 0.11	1.38 ± 0.06	0.67 ± 0.04
20°C, 25 Hz continuous	slope	5.5	4.4	6.2	7.0
Procedure 6	σ_6 (MPa)	1.19 ± 0.18	1.13 ± 0.05	1.91 ± 0.11	-
20°C, 40 Hz continuous	slope	6.1	6.2	5.9	-
Procedure 7	σ_6 (MPa)	1.68 **	1.70 **	2.20 **	-
20°C, 40 Hz discontin.	slope	6.9	9.0	3.4	-

* *The results of the fatigue tests are given in terms of values of ε_6 and σ_6, with the associated 95% confidence interval and of the slope of the fatigue line.*

** *95% confidence interval not calculated because total number of values less than 5.*

-material not tested

loading (controlled strain) but performs much more poorly than these same asphalt concretes in the pulsed tests (controlled stress).

GB A seems not to be improved by the introduction of a rest period, but this remark applies only to the test with bursts of loading (controlled strain).

Conclusions Concerning the Laboratory Tests

The four asphalt mixes were tested under different conditions and by different laboratories. The results lead to the following conclusions:

- The modulus values measured by the different laboratories are consistent.
- The results of the fatigue tests and the corresponding classification of the asphalt mixes depend on the test conditions.

For both asphalt mixes with 50/70 asphalt, the following conclusions are drawn:

- ϵ_6 of AC B is substantially greater than ϵ_6 of AC A with controlled strain.
- σ_6 of AC B is slightly greater than σ_6 of AC A with controlled stress without rest periods.
- σ_6 of AC B is equal to σ_6 of AC A with controlled stress with rest periods.
- The life ratios between the continuous and discontinuous tests are close for AC A and AC B in the pulsed tests (with controlled stress) and favor AC B in the tests with bursts of loading (with controlled strain).

For EME and GB A, the following observations are made:

- The fatigue performance level of EME is substantially greater than that of GB A.
- The fatigue characteristics of GB A are not improved by the introduction of rest periods in a controlled strain test with bursts of loadings.

TABLE 4 Conditions of Fatigue Test

Procedure	Laboratory	θ (°C)	f (Hz)	Loading
1	LCPC	10	25	ε; 3 levels of strain, 8 specimens per level
2	LCPC	20	25	ε; 3 levels of strain, 8 specimens per level
3	LPC Angers	20 (in water)	25	ε; 3 levels of strain, 8 specimens per level
4	LPC Bordeaux	20	40	ε; 3 levels of strain, 8 specimens per level
5	LPC Bordeaux	20	40	ε; and 8:80 (1); 1 level of strain (200 mstrain), 8 specimens
6	KSLA	20	40	σ; 6 to 8 specimens (stress sweep)
7	KSLA	20	40	σ; 1:5 (2); 2 to 4 specimens (stress sweep)

Note : (1) 8 s or 320 loading cycles, 80 s without loading
(2) one loading cycle, then 5 without loading

• EME has a life ratio between the continuous and discontinuous tests that is of the same order of magnitude as those of the two asphalt mixes in the controlled strain tests with bursts of loading and much smaller than those of the two asphalt mixes in the controlled stress pulsed tests.

MODELING OF THE BEHAVIOR OF THE STRUCTURES

The French design method for road pavement structures is a rational method (*5*). The strains (and stresses) engendered in the structure by a 65-kN pair are first determined, using the Alizé software, on the basis of the multilayer static linear elastic model of Burmister. On the basis of the initial characteristics of the structure, allowable strains (and stresses) are then calculated for each of the layers for a specified probability of failure, according to the fatigue behavior of the material (with reference to the controlled strain fatigue test—Procedure 1), the traffic, and the bearing capacity of the foundation soil. The structure will perform correctly if the calculated strain and stress values are less than or equal to the allowable values.

A shift factor corrects for the differences between the strain values derived from the model and those deduced from observation of the behavior of actual pavements. A shift factor value is assigned to each family of materials.

Determination of Structure of Calculation Model

The foundation soil is represented with two layers: the substratum, treated as a half-space having a Young's modulus of 400 MPa, and a 2.8-m-thick clayey sand layer. Deflection measurements made at the surface of this layer allowed backcalculation of a mean modulus of 35 MPa for this material.

The moduli of the two layers of GRH (200 MPa and 250 MPa) are backcalculated from quasi-static deflection measurements made by Benkelman beam and measurements of the radius of curvature made at the beginning of the experiment at the surface of the VTAC.

The fit obtained is not as good for the deflection measurements on Structures III and IV: the calculated values are, respectively, 24 and 19 percent greater than the measured values. Since identical characteristics were selected for the foundation soil of the four sectors, the fit is not equally good everywhere. This is due to the difference in stiffness of the four structures and to the nonlinear character of the foundation soil, which was not represented here.

Mechanical Analysis

First of all, it is interesting to compare the strain values derived from the calculation with those measured in the bound layers for identical temperature and frequency conditions (15°C, 10 Hz).

The description of these structures is completed by considering the dynamic modulus values of the asphalt materials measured in the laboratory. The pavements, which exhibit variations of thickness, are divided into zones of uniform thickness on which the extent of cracking is recalculated.

Analysis of Strains on Passage of an Axle

Table 5 gives three series of values (referred to 15°C and 10 Hz):

1. The strain values, based on strain gauge measurements (these values are derived from filtered signals, corrected for temperature and frequency);
2. The strain values computed with the Alizé software in which the half axle load is represented as a double circular area (contact pressure 0.662 MPa, loading radius 125 m); and
3. The strain values from a finite-element calculation on a three-dimensional static elastic model (César-LCPC software), to evaluate the influence of the load geometry. In this model, the half axle load is represented by two 0.18- × 0.33-m rectangular areas at a uniform pressure of 0.542 MPa, which is closer to the imprint recorded for the wheels of the pair.

Several conclusions can be drawn from these values:

1. The calculated strains in the asphalt material are systematically greater than the measured values.
2. At the base of the asphalt layers, the longitudinal strains are generally greater than the transverse strains. This finding is corroborated by the appearance of transverse cracks in the wheelpath on the structures of the circular test track.
3. The strain values obtained by the calculation with César-LCPC are generally closer to the measured values than those given by the Alizé model. It is therefore apparent that, on thin structures, the shape of the imprint has a decisive impact on the values of the maximum strains at the base of the bound layers.
4. Finally, large differences in the strains between the sections of different thicknesses of Sectors III and IV indicate the significant effect of thickness of the asphalt layer.

Life Prediction

From the strains calculated by the Alizé and César-LCPC software for 15°C and 10 Hz, it is possible to determine the allowable numbers of loading cycles for each structure using the fatigue characteristics determined by the usual test (Procedure 1) and the fatigue characteristics determined in controlled stress tests (Procedures 4, 6, and 7) and to compare them with those based on the observations on the circular test track.

Use of the Fatigue Characteristics of the Usual Fatigue Test

According to the design method, the number of cycles N for which fatigue failure of the asphalt material occurs with a probability of 50 percent is

$$N = 10^6 \left[\frac{\epsilon_{cal}}{k\epsilon_6(\theta)}\right]^{1/b}$$

where

ϵ_{cal} = calculated maximum tensile strain under a passage of an axle,
$\epsilon_6(\theta)$ = strain for which there is failure at 10^6 loadings in the bending fatigue test at a constant temperature of θ,
k = shift factor reflecting the difference between the calculation approach and observation of the behavior of actual pavements, and
$1/b$ = slope of the fatigue line of the material.

The usual fatigue test is performed at 10°C and 25 Hz (Procedure 1); the value of ϵ_6 is corrected in temperature to be referred to 15°C according to the following equation:

$$\epsilon_6(\theta)\sqrt{E(\theta)} = C^{ste}$$

The tensile strain value, derived from the calculations performed by Alizé and César-LCPC and used to determine the number of loading cycles, is the maximum of the longitudinal and transverse strains; it is generally the longitudinal strain. All of these characteristics are summarized in Table 5.

The number of cycles Nz at which the structure fails because of excessive permanent strain in the unbound layers (GRH and foundation soil) is determined by the criterion $\epsilon_z = 22{,}500 Nz^{-1/4.1}$. This criterion was not critical in this study. The analysis indicates that the pavements should fail first by fatigue of the asphalt layers, a result in agreement with the findings on the pavements of the circular test track.

To compare calculation results with the observations of pavement behavior on the circular test track, an assumption must be made. It will be assumed that 50 percent cracking observed on the circular test track is associated with the 50 percent risk of failure.

A search is then made for the coefficients k to be associated with each of the sectors so that the number of loadings leading

TABLE 5 Characteristics for Calculations of Modeling and Results

Materials	AC B	AC A	EME		GB A	
Sectors	I	II	III		IV	
			min	max	min	max
Distance along curve (m)	5 to 30	30 to 48 52 to 60	77 to 87	60 to 77 87 to 90	90 to 108	108 to 120
Thicknesses (m)						
Asph . mat.	0.081	0.080	0.073	0.089	0.101	0.128
GRH 1	0.218	0.210	0.207	0.211	0.225	0.204
GRH 2	0.218	0.210	0.207	0.211	0.225	0.204
Number of cycles on the circular test track for 50% cracking (x 1,000)	1,100	1,450	1,450	2,000	2,700	2,750
Measured strains (µstrain)						
ε long (base of AC)	136	92	107	75	78	79
ε trans (base of AC)	124	89	77	41	87	83
ε vert (top of GRH)	-	935	1419	-	-	829
ε vert (top of soil)	632	554	410	410	691	-
Characteristics for calculation						
E (15°C;10 Hz) MPa	7,700	9,125	12,400		10,300	
Procedure 1 ε_6 µstrain	140	90	140		88	
-1/b	6.3	5.2	5.3		4.3	
Procedure 4 σ_6 MPa	0.67	0.52	1.38		0.67	
-1/b	5.5	4.4	6.2		7.0	
Procedure 6 σ_6 MPa	1.19	1.13	1.91		-	
-1/b	6.1	6.2	5.9		-	
Procedure 7 σ_6 MPa	1.68	1.70	2.20		-	
-1/b	6.9	9.0	3.4		-	
Calculated maximum tensile values						
Strain ε Alizé µstrain	235	222	205	179	177	149
ε César µstrain	172	160	148	137	136	121
Stress σ Alizé MPa	2.18	2.46	3.10	2.72	2.22	1.88
σ César MPa	1.69	1.84	2.39	2.18	1.79	1.59
Back-calculated shift factor k						
Procedure 1 k Alizé	1.5	2.3	1.4	1.3	2.2	1.9
César	1.1	1.6	1.0	1.0	1.7	1.5
$k / k_{AC\ B}$ Alizé	1	1.5	0.93	0.87	1.47	1.27
César	1	1.45	0.91	0.91	1.54	1.36
Procedure 4 k Alizé	2.7	4.1	2.1	2.0	3.2	2.7
k César	2.1	3.1	1.6	1.6	2.6	2.3
Procedure 6 k Alizé	1.5	1.8	1.5	1.4	-	-
k César	1.2	1.4	1.2	1.2	-	-
Procedure 7 k Alizé	1.1	1.2	1.4	1.3	-	-
k César	0.8	0.9	1.1	1.1	-	-

to 50 percent cracking on the pavements of the circular test track (values interpolated for Sectors I, II, and III and extrapolated for Sector IV) is equal to the number of cycles associated with 50 percent risk as determined by calculation with Alizé and César-LCPC.

For the calculations done both with Alizé and with César-LCPC, it is found that

1. *k* determined for AC A is substantially greater than that for AC B (1.6 for AC A against 1.1 for AC B, the usual value of the shift factor for an asphalt concrete);
2. The ratio of coefficients *k* for GB A and AC B ranges from 1.25 to 1.55. This value is larger than the one normally used (namely 1.3/1.1 = 1.2), but the orders of magnitude are comparable; and
3. *k* is smaller for EME than for AC B; the ratio between the two coefficients is close to 0.9.

Use of the Fatigue Characteristics Based on the Controlled Stress Tests

The study is repeated here using results of the controlled stress fatigue tests. The σ_6 values are corrected for temperature according to

$$\frac{\sigma_6(\theta)}{\sqrt{E(\theta)}} = C^{ste}$$

and referred to 15°C.

The tensile stress at the base of the asphalt layers determined by the calculations of Alizé and César-LCPC for 15°C and 10 Hz, used to determine the number of loading cycles, is the maximum of the longitudinal and transverse stresses. It is most often the longitudinal stress. These results are given in Table 5.

As previously, the coefficients *k* are determined (Table 5). When values of *k* are chosen to duplicate by calculation the life durations observed on the circular test track, some tendencies appear:

1. By Procedure 4, substantially different values of *k* are found for the two ACs (ratio approximately 1.5). The *k* found for EME is lower than those of the ACs; that of GB A is higher than that of AC B.
2. By Procedure 6, the *k*'s for the two ACs are closer together (ratio approximately 1.2). For EME, *k* is of the same order of magnitude as for AC B. There is no value for GB A (no fatigue tests).
3. By Procedure 7, the *k*'s for the ACs are similar. That for EME is slightly greater. No value is available for GB A.

These remarks are valid for the calculations done with Alizé and with César-LCPC.

Conclusions Concerning the Mechanical Analysis

This mechanical analysis points to the following conclusions:

1. When the loads are represented by circular wheel imprints, the calculation model gives strain values substantially different from those measured in the experimental structures. The model is improved by using rectangular imprints.
2. If only the conventional design method is considered, it is found that the large differences in life prediction between Sectors I and II result primarily from the differences in the values of ϵ_6 determined from the controlled strain tests. In addition, analysis of the relative behavior of the structures observed on the circular test track in the course of this first experimental phase appears to indicate that the value of the shift factor usually used for EME (1.1) is too high; a value of 0.9 to 1 appears more appropriate.
3. The results of the controlled stress fatigue tests by Procedures 6 (without rest periods) and 7 (with rest periods) lead, with similar coefficients *k*, to life durations comparable with those observed on the circular test track. This finding needs to be confirmed by a larger number of tests.

CONCLUSION

This experiment compared the behavior of four asphalt materials (two asphalt concretes made with 60/70 asphalt, one EME, and one asphalt-bound granular material) on the basis of their fatigue resistance as determined in the laboratory by different testing procedures and on the basis of full-scale tests on the circular fatigue test track. It was found that the test procedure strongly influences the ranking of the materials according to their fatigue behavior observed in the laboratory.

Analysis of the behavior of structures on the circular test track, using the design method normally used in France, shows the following:

- The relative behavior of AC B and AC A observed on the circular test track cannot be explained from the values of ϵ_6 determined by the continuous controlled strain fatigue test.
- It appears that the shift factor to be applied to EMEs, in light of the behavior observed on the circular test track, should be less than for asphalt concretes. The new proposed value is 1.
- The controlled stress fatigue tests give results for the two asphalt concretes AC A and AC B that appear to be in better agreement with the observed behavior of the pavements tested on the circular test track.

This experiment also served to determine the economic utility of solutions using high-modulus asphalt mixes (EME) in base courses, by comparison with conventional approaches using asphalt-bound granular materials. These are the lessons learned by Scétauroute, which will include new solutions including EMEs in the next issue of the Motorway Pavement Design Manual.

To confirm some conclusions and refine the analysis, it was decided to repeat the same experiment on the circular fatigue test track with the same materials. This experiment was run on the circular test track between October 1991 and January 1992, and the laboratory studies are still in progress (1993). The corresponding results and the comparison with the first experiment will be published later.

ACKNOWLEDGMENTS

This research program involved the participation of several organizations: for LCPC, the Circular Fatigue Test Track section, the Pavement Materials Laboratory section, the Pavement Design section, and the Road Binders section. The LRPC of Angers and Bordeaux have also been involved in the laboratory tests. For Shell, the research laboratories of Grand-Couronne (Rouen, France) and KSLA (Amsterdam, the Netherlands) participated.

REFERENCES

1. Autret, P., A. Baucheron de Boissoudy, and J.-C. Gramsammer. The Circular Test Track of the Laboratoire Central des Ponts et Chaussées—Nantes, First Results. Conférence internationale sur le dimensionnement des chaussées souples, Ann Arbor, Mich., July 1987.
2. Ramond, G., B. Dupeyrray, M. Pastor, and C. Such. Relation Between the Composition of Bitumens and Their Rheological Properties. *Proc., 11th International Congress on Rheology,* Elsevier Science Publishers BV, 1992.
3. Francken, L. Module complexe des mélanges bitumineux. Bull liaison Labo. P. et CH., spéc. V, Bitumes et enrobés bitumineux, 1977, pp. 181–198.
4. Moutier, F. Etude statistique de l'effet de la composition des enrobés bitumineux sur leur comportement en fatigue et leur module complexe. Bull liaison Labo. P. et CH., No. 172, March–April 1991, pp. 33–41.
5. Autret, P., A. de Boissoudy, and J.-P. Marchand. Alizé III, Practice. Fifth International Conference on the Structural Design of Asphalt Pavements, Delft University of Technology, the Netherlands, 1982, pp. 174–191.

Publication of this paper sponsored by Committee on Characteristics of Bituminous Materials.