Asphalt Aggregate Mixtures

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In France, mechanical tests are used essentially for characterizing the performance of bituminous concretes for mix design purposes, production control requiring retroaction times that are much too short. Compacting characteristics are studied with an imposed angle gyratory shear compacting press; an indication of the results obtained on the job site is obtained by correlation with a pilot compactor. A number of plate samples are prepared with a laboratory-tired compactor. Resources of increasing complexity are used for the study of permanent deformation characteristics. The repeated compression test with a lateral load is used for research purposes, and the wheel-tracking rutting test is used for mix design studies. Because the concern here was fatigue performance, the bending test was used to study the influence of composition factors. More recently, a shear fatigue test, which is more representative of the loads to which the thin surface courses are subjected, has been employed. However, fatigue tests are too costly and time consuming to be used for mix design studies, so a new test has been developed to measure stiffness moduli and to estimate fatigue properties. Secant moduli at different temperatures, linearity loss, and strength at 0°C are determined by a full tensile test on each sample. An estimate of the bending fatigue curve at 10°C is obtained by two regressions. For the mix design, the diversity of functions to be provided and the cost of testing make it necessary to rank the problems according to importance and to define a methodology that can be adapted to different cases.

The various mechanical tests used in France for the practical mix design of bituminous materials may be classified according to the type of property concerned and the quality of evaluation of this property. The focus of this paper is the essential elements defining current French mix design technology:

- Production of samples: mixing, preparation of plates with the laboratory-tired compactor, and sampling;
- Study of compacting characteristics with the gyratory shear compacting press (PCG);
- Study of resistance to permanent deformation by the rutting test;
- Study of rigidity and fatigue resistance; and
- Definition of mix design methodology.

PRODUCTION OF MECHANICAL TEST SAMPLES

Conventional tests, such as the Marshall test and the Laboratoire Central des Ponts et Chaussées (LCPC) unconfined compression test, which use small cylindrical samples, have been replaced by tests better adapted to the new requirements that must be met by bituminous mixes (rutting, compactibility, and direct tensile strength). Samples are taken from laboratory-prepared bituminous mix plates of homogeneous density, which are more representative of conditions at the job site (identical void content and comparable mechanical characteristics). The Laboratoires des Ponts et Chaussées (LPC) laboratory-tired compactor is preferable to the smooth roller compactor or a static system insofar as it gives homogeneous samples in which the element arrangement pattern and level of void content come close to those obtained on the job site.

Preparation of Asphalt Concretes

Of the various laboratory mixers, all based on the same principle (epicycloidal movement of the tool in a heated or nonheated vessel, incorporating a lateral scraper), the following types are used: vertical blade mixer with rotating 25-kg capacity vessel and epicycloidal helix-type mixer with 80-kg capacity vessel. The bituminous concrete is manufactured according to the following rules: aggregates are taken from homogeneous dry batches; materials are prepared at appropriate temperatures; the binder is treated in two phases to reduce binder evolution to a minimum and the final temperature is defined by binder hardness; and the mixing time is between 1 and 3 min.

Preparation of Plates

The LPC laboratory-tired compactor is used to produce plates of different dimensions by placing spacers in the bottom of the molds (*1*, *2*) (Figure 1). The tired wheels are moved in three directions: vertically to load them, longitudinally to displace

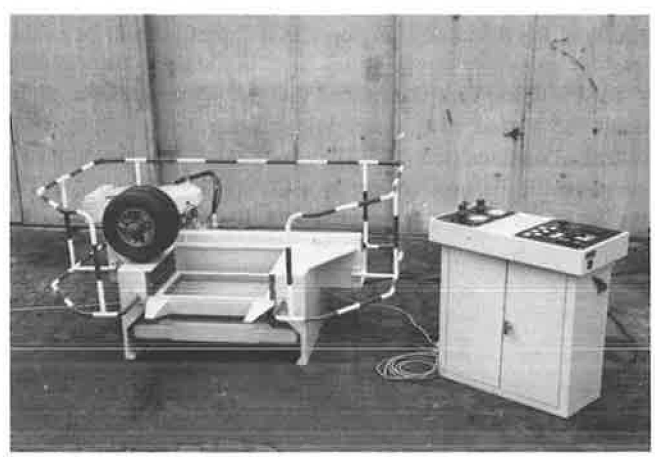


FIGURE 1 Laboratory-tired compactor.

Laboratoire Central des Ponts et Chaussées, 58 Boulevard Lefèbvre, 75732 Paris, Cedex 15, France.

them and obtain compacting action; and transversely to ensure that the total surface of the plate is worked.

A compacting program comprises a set of sequences in which the following test parameters are defined: tire pressure, load, compacting path, and number of passes to give a choice of two compacting intensities (I = high, II = low). The void content is tested by using a gamma densimeter. Adequate homogeneity is sampled 50 mm (width) and 100 mm (length) from the edges of a plate measuring 400 × 600 mm. It may be noted that the two compacting intensities bracket the degree of void content obtained on the job site for normal bituminous concretes: the void content at a high compacting intensity is less than that on the site, which is less than that at the low compacting intensity. The voids percentage difference ΔV between the two processes varies with the type of bituminous mix:

Mix Type	*ΔV (%)*
Sand bitumen	2
Bituminous for resurfacing	4
Bituminous, initial application	5
Bituminous road base	5

Preparation of Samples

The following may be prepared from plates 600 mm long, 400 mm wide, and 120 or 150 mm deep: cylindrical samples for tensile testing following a given coring plan; trapezoidal samples for fatigue testing following a given cutting plan; and any other samples as required at the time, provided that they are taken from a zone with the correct density. Sample quality is characterized by the void content scatter: the greatest difference between samples taken from the same plate is 1.3 points for a bituminous concrete with a high compaction factor and a void content of 5 percent.

EVALUATION OF COMPACTING CHARACTERISTICS

PCG Test

The PCG test was devised to study the compacting performance of bituminous mixes (*3, 4*). The press applies a compacting pressure close to that applied by tired compactors with a simultaneous kneading action obtained by gyratory shearing of the bituminous mix in its mold; this simulates the effect of the job site compactor. Not all conventional compacting tests give a good idea of the void content values observed on the job site. For example, the Marshall or LCPC void content is obtained relatively easily where the layer is thick (7- to 8-cm wearing course), but it is extremely difficult or even impossible to obtain in the case of a thin layer (3- to 4-cm wearing course). The PCG test, however, makes it possible to evaluate compacting performance and also to estimate the void content that would be obtained in situ, according to layer thickness. This is the test most widely used in France for optimizing the composition of hot-laid bituminous concretes. It is used to make a preliminary selection before the mechanical tests, which are more costly, are performed.

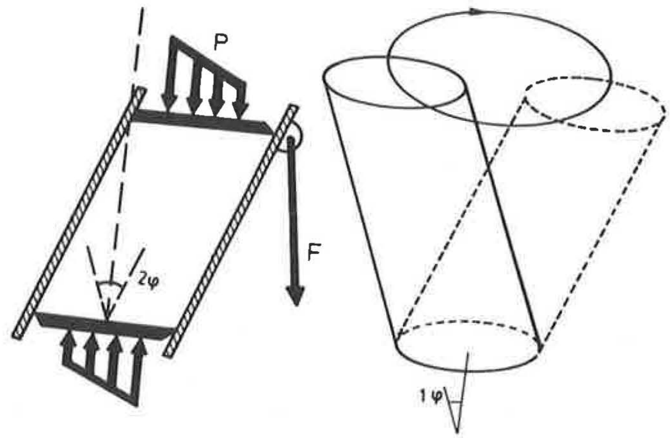


FIGURE 2 Principle of compacting with the gyratory shear compacting press.

Test and Operating Conditions

The bituminous mix is enclosed in a cylindrical mold, the axis of which describes a cone during the test. As shown in Figure 2, the form of the sample is an oblique cylinder with parallel ends, one of which is fixed, whereas the other describes a circle. The values of two principal parameters for the test are as follows: (a) the vertical compressive load gives a mean applied vertical pressure of 0.6 MPa and (b) the angle of inclination ϕ is 1 degree (constant during compacting). In addition, temperature is regulated during the test, and rotational speed is set at 6 rpm. Mold diameter is 160 mm, and final sample height is approximately 150 mm. The following values are measured during the test:

- Reduction in sample height, giving void percentage V versus number of revolutions n (Figure 3), and
- Evolution of inclination force F, which is the load required to maintain angle ϕ constant at 1 degree.

The test is stopped automatically after 200 revolutions. A half day is required to execute four test sequences.

Relation Between PCG Test Curves and Pilot Compactor Curves

Correlation studies between the void content given by the gyratory shear compacting and that produced by a tired pilot compactor operating under normal conditions have been run on a real-size basis (*5, 6*). For the bituminous concrete class and

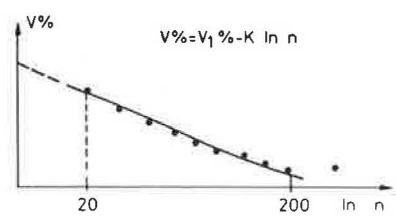


FIGURE 3 Variation in void content versus number of revolutions.

thicknesses between 3 and 12 cm, the number of revolutions corresponding to the number of passes executed by the tired compactor is given reasonably accurately by the formula

$$N_g = 0.0625\ e \cdot N_p$$

where

N_g = number of PCG press revolutions,
e = thickness (mm), and
N_p = number of compactor passes.

When the thickness of the layer is known, this expression makes it possible to calculate the number of revolutions for which the void content obtained in the laboratory will be equal to the void content obtained on the job site for a given number of passes of the compactor. Thus, if the intended job site thickness is 100 mm and the number of passes is 16, the reference number of revolutions is 100. Therefore, it is possible to verify whether the predicted void content in situ is correct and to adjust the mix composition if necessary. If it is assumed that the mean number of compactor passes is 16, the expression may be reduced to the following, which has been largely confirmed by experience:

$$N_g = e$$

It should be noted that vibrocompactors are more efficient than tired compactors. Thus, for a given number of revolutions, the expression $N_g = 0.0625\ e \cdot N_p$ frequently gives a pessimistic estimate of void content. Nevertheless, the correlation appears to take the following form for these materials:

$$N_g = k \cdot e \cdot N_p$$

where k is a factor depending essentially on the nature of the compactor and increasing with compactor efficiency. Globally, a vibrating drum with a linear static load of 3.5 N/mm subjected to the action of a cam wheel of about 10 tonnes and a frequency of 25 to 30 Hz gives a k-factor value of about 0.25. The expression then becomes

$$N_g = 0.25\ e \cdot N_p.$$

Repeatability and Reproducibility

A study of the repeatability and reproducibility of the PCG test involving 19 laboratories and 3 different materials led to the following repeatability and reproducibility variances for the test for the measurement of void content at a given number of revolutions, N_g (40, 80, and 120):

- Repeatability variance: 0.24, and
- Reproducibility variance: 0.49.

Repeatability variance is obtained by repetitions executed in the same laboratory. Reproducibility variance is the sum of repeatability variance and interlaboratory variance.

For this test, the laboratory for which repeatability is assumed correct obtains four sets of results for the same material; the arithmetic mean is $\bar{x}$. The true interlaboratory value, m, for this material falls within the following confidence interval with a probability of 95 percent: $\bar{x} = \pm 1.09$ percent. Comparison of the two means, m1 and m2, from two different laboratories is as follows:

$$m1 = m2 \text{ if } 0 < \bar{x}1 - \bar{x}2 < 1.54$$

Utilization of PCG Test

The thickness of the bituminous concrete course is a parameter known to the mix designer, who sets an initial in situ void content target according to the type of bituminous concrete, traffic, and climate. Thus a void content of approximately 3 to 4 percent is sought for a bituminous concrete subjected to severe winter constraints (e.g., a mountain road). The target differs slightly for a bituminous concrete used in a hot region, where a stiffer mixture is needed, one with a void content of approximately 6 to 7 percent.

For easier comprehension of the procedure adopted, an example will be used (Figure 4). Assume that a wearing course 6 cm thick with an in situ void content target of 5 percent is to be applied. The PCG compacting curve for the formula to be selected should give a PCG void content of approximately 5 percent at 60 revolutions. Formula 1 (Figure 4) gives a void content exceeding 5 percent at 60 revolutions, and it is therefore considered insufficiently workable. It must therefore be modified to improve its compacting characteristics. The methods most frequently used include

- Increase bitumen content,
- Increase filler content,
- Use rounded river sand, or
- Decrease percentage of medium-sized aggregate fractions or even gap grading.

On the other hand, if the formula appears too easily workable (as in the case of Formula 2), reverse formulation factors are then applied to obtain a compacting curve like that for Formula 3.

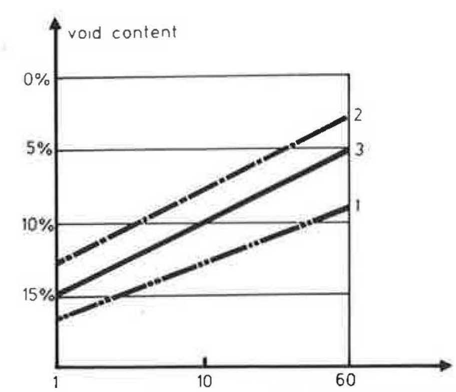


FIGURE 4 Compacting curves showing different workability for three bituminous mixes.

RESISTANCE TO PERMANENT DEFORMATION

LPC Wheel-Tracking Rutting Test

A repeated triaxial compression test and a uniaxial creep test are used for research purposes (*7, 8*). For practical mix design studies, a wheel-tracking rutting test is used, which measures the rut created by the repeated passage of a wheel over a prismatic bituminous concrete sample. The laboratory simulation of the rutting phenomenon must approach actual pavement stress conditions so that the result obtained can provide one of the selection criteria for a mix design. The test is associated with the LPC rutting-test machine (Figure 5), which can test two samples simultaneously at a fixed temperature.

Presentation of the Rutting Test

Sample

The sample is a plate measuring 500 × 180 mm with a thickness of 100 mm. It is placed in a metal frame and rests on a steel base plate. The assembly is placed in the rutting-test machine. The test may be carried out on a sample taken from an actual pavement; however, the test plate is generally prepared in the laboratory and compacted in its frame by using the LPC laboratory-tired compactor and the high- and low-intensity standard compaction procedures.

FIGURE 5 LPC wheel-tracking rutting-test machine.

Three samples are compacted and tested for each compaction level. Plate thickness should be between 95 and 105 mm. Density is measured before the test by using the LPC gamma densimeter 25, 50, and 75 mm from the bottom of the plate; three different points are measured for each depth. The mean void content of the plate and the void content value for the three repetitions are indicated in the results.

Wheels

The wheels are fitted with smooth tires (400 × 8) inflated to a pressure of 6.10^5 Pa and loaded at 5000 N. The wheels pass over the center of the sample twice per second, executing an alternating movement with an amplitude of 205 mm. The cycle period is 1 sec. Load time at the center of the plate is approximately 0.1 sec, comparable with roadway loading conditions. Tire pressure is checked at the beginning and end of the test at test temperature. Pressure readings should not deviate from specified pressure by more than 5 percent.

Temperature

Temperature is regulated by circulating hot air with a probe placed in the sample. It has not been possible to be sure that temperature scatter in the sample plate does not exceed ±1.5°C for bituminous concrete. Temperature stabilization time is 12 hr. The test temperature selected is 60°C for wearing-course bituminous concrete and 50°C for base courses. These temperatures are chosen to be relatively high to reproduce the most unfavorable pavement conditions.

Rut

A rut is defined by the relative percentage of reduction in the thickness of the plate on the wheel path. Measurements are taken by using a depth gauge with a resolution of 0.1 mm; the gauge reference point is linked to the sample-holder frame. Measurements are taken for five transverse profiles spaced at 75-mm intervals, each characterized by three points in the rut 25 mm apart. For the test sample, the rut is represented by the mean of 15 measurements. The initial profiles are obtained after 1,000 cycles cold, giving good contact between sample, frame, and base plate. The test is terminated after 10^5 cycles, unless rut depth exceeds 15 percent. To measure the rut, the test is stopped after 30, 100, 300, 1,000, 3,000, and 100,000 cycles.

Results

An example is shown in Figure 6. Test repeatability is about 10 percent of the rut obtained (standard deviation). The result may be obtained 2 weeks after procurement of the materials. To evaluate rutting sensitivity, the mix designer takes into account not only the rut depth occurring after a certain number of cycles at a specified job site void content, but also the form of the rutting curve and the sensitivity of this curve to a variation in void content.

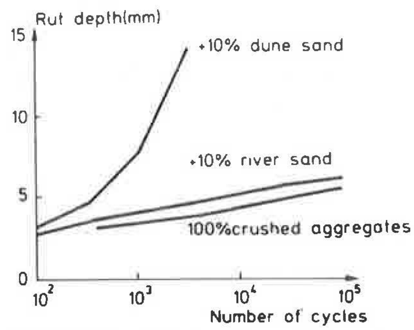


FIGURE 6 Effect of the addition of dune sand or river sand on rut depth.

FATIGUE RESISTANCE OF BITUMINOUS CONCRETES

Because fatigue tests are costly and time consuming, they are carried out only for research purposes; therefore only a brief description is given.

The first type of fatigue test used at LCPC is an imposed displacement alternating bend test (Figure 7). Four test samples may be tested simultaneously. This test consists of maintaining constant displacement amplitude and frequency for the free end of the test sample. During the test, continuous reduction of the stiffness modulus from accumulated fatigue damage is recorded. This is reflected by a reduction in the force required to maintain constant displacement amplitude. The test is continued until the initial force required to impose displacement is reduced by one-half. Test conditions are as follows:

- Frequency: 25 Hz;
- Temperature: 10°C;
- Strain level: 1.5×10^{-4}, 2×10^{-4}, or 3×10^{-4}; and
- Repetitions per level: 12.

Fatigue phenomena are represented by straight lines in bilogarithmic coordinates. The fatigue law is therefore expressed in the form

$$N = K\varepsilon^{-a}$$

where N is lifetime at imposed strain ε, and a and K are constants characterizing the fatigue performance of the material.

Among the characteristics that may be defined by conventional fatigue tests, the most useful for pavement calculations is admissible strain at 10^6, noted ε_6. The composition of bituminous mixes according to their function in the pavement structure clearly separates the fields of variation for ε_6-values:

- For bituminous road bases and sand-bitumen subbases, the range of ε_6 is 0.7 to 1.3×10^{-4};
- For bituminous concrete wearing courses with pure bitumen, the range of ε_6 is 1.3 to 1.5×10^{-4}; and
- For bituminous concrete wearing courses with polymer-modified binders, the range of ε_6 is 1.5 to 2.0×10^{-4} (bituminous mixes showing $\varepsilon_6 > 2.0 \times 10^{-4}$ are exceptional).

There is currently a trend toward shear fatigue testing at LCPC. This test is also run at imposed strain amplitudes (Figure 8). The shear fatigue test provides results showing less scatter than the bending fatigue test. It also takes more effective account of the types of load to which thin surface courses and interlayers are subjected. In connection with current research activities, this test is being used at LCPC to study the capacity of bituminous concretes for self-repair during periods at rest and the laws of damage accumulation.

DIRECT TENSILE LOAD TEST

A single-axle tensile load test has been developed for comparison of bituminous concretes from the point of view of fatigue resistance thickness design, where the critical stress in the pavement layer concerned may be assimilated to a tensile load. Strain, the form of which is parabolic in time, is applied. It is first applied in a minor strain field to define the moduli dependent on time and temperature and then in a major strain field to the point of rupture for the purpose of deducing a linearity loss. The significance of this loss with respect to fatigue properties will be seen later in the paper. Definition of a simplified test procedure incorporating several tests and carried out on a single sample substantially reduces cost and makes it possible to use the test in routine mix design.

Definition of Imposed Strain $\varepsilon = at^n$ and Moduli

The strain law adopted, $\varepsilon = at^n$, may be assimilated with the variations in time of elongation at the bottom of a pavement layer under a mobile load, considering the rise part of the strain

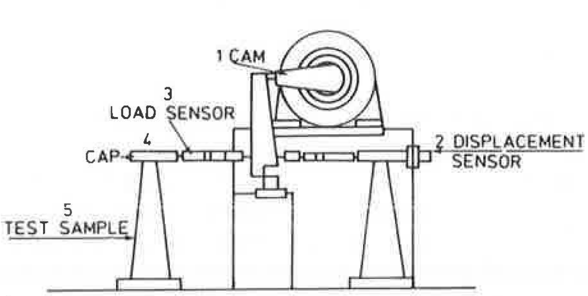


FIGURE 7 Bending fatigue test machine and fatigue test principle.

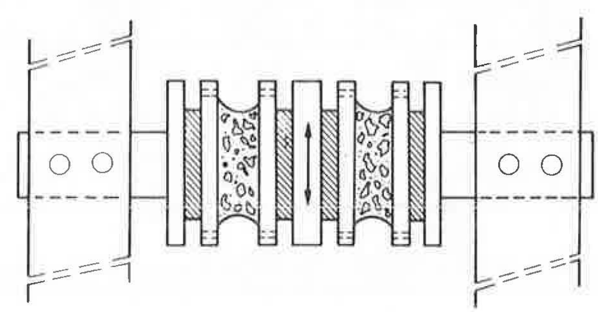


FIGURE 8 Principle of shear fatigue test machine.

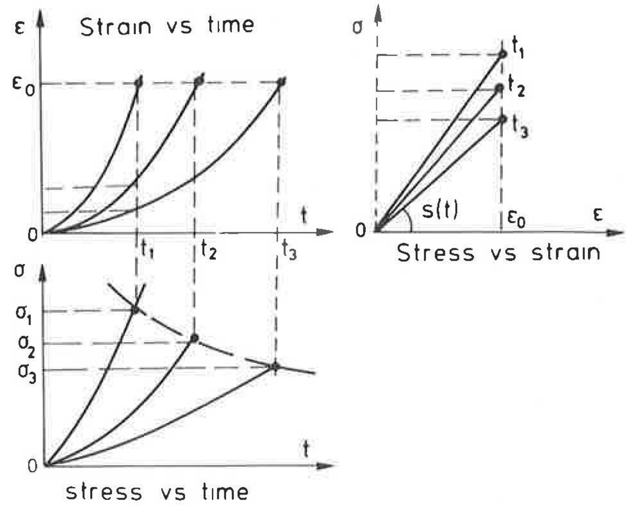


FIGURE 9 Principle of determination for secant modulus.

pulse only. When n is constant for all tests, it is possible to define secant modulus class S_n (Figure 9) for any test index i corresponding to various strain rates, v_i. The secant modulus is defined by

$$S_n(t) = \sigma_i(t)/\varepsilon_i(t)$$

It is only dependent on time for a given exponent n. When the bituminous concrete may be assumed linear viscoelastic, there follows:

$$S_n(t) = (n/t^n) \int_0^t r(t - \tau) \cdot \tau^{n-i} d\tau$$

where r(t) is the relaxation modulus. Master curve $S_n(t)$ is determined at 0°C with the –10°C, 0°C, 10°C, and 20°C isotherms (Figure 10) by using an iterative translation factor optimization process, which eliminates manual determination.

Nonlinearity Analysis

It is known that in the field of very small strains ($\varepsilon < 10^{-4}$), bituminous concretes may be considered to have linear viscoelastic characteristics. This behavior constitutes a first approximation of the nonlinear viscoelastic behavior during single-axis tensile load or compression tests (*9*, *10*). The following law of imposed strain behavior has been demonstrated:

$$\sigma(t) = 1 - g_0(\varepsilon) \cdot \int_0^t r(t - \tau) \cdot \dot{\varepsilon}(\tau) \cdot d\tau$$
$$- \int_0^t r(t - \tau) \cdot \dot{\varepsilon}(\tau) \cdot d\tau \int_0^t k(t - \tau) \cdot \dot{\gamma\varepsilon}(\tau) \cdot d\tau$$

In particular, where strain steps ε_0 are imposed,

$$\sigma(t) = \varepsilon_0 \cdot r(t) \cdot 1 - g_0(\varepsilon) - \gamma_0(\varepsilon) \cdot k(t)$$

Using the following empirical expressions:

$$\gamma_0 = \alpha_1\varepsilon + \alpha_2\varepsilon^2$$

$k(t) = lgt$ for $t > 1$ sec (experimental field)

Given the relations just mentioned, the expression of $\sigma(t)$ for type $\varepsilon = at^n$ tests, with $n > 0$, integer or not, is

$$\sigma_n(t) = \varepsilon(t) \cdot S_n(t) \cdot |1 - \Gamma_n\varepsilon(t)|$$

$$\Gamma_n = g_n(\varepsilon) + \gamma_0(\varepsilon)/lgt$$

Γ_n is the nonlinearity factor, and $1 - \Gamma_n$ is linearity loss. Determination of the law of behavior thus requires two nonlinearity tests. To make it possible to execute the process on a single sample, one test only is run (a second test on the same sample would be perturbed by the first, because ε_r is too close to 5×10^{-4}, constituting the upper bound of the strain interval under examination). An estimate of the nonlinearity factor is obtained using the hypothesis that the system of curves of equal strain in the plane ($lg\sigma$, lgt) is parallel. The error resulting from this approximation is small. The system of equal strain curves at the levels $\varepsilon j = 10^{-4}, 2 \times 10^{-4}, 3 \times 10^{-4}, 4 \times 10^{-4}$, and 5×10^{-4} is traced (Figure 11). The curve $S(\varepsilon)$ for a fixed time of 300 sec is then determined using a second-degree regression (Figure 12). S(0) is obtained by extrapolation. This gives the nonlinearity factor:

$$\Gamma(\varepsilon) = S(\varepsilon)/S(0)$$

To characterize the nonlinearity of a material, $\varepsilon = 5 \times 10^{-4}$ is used so that

$$\Gamma = S_5/S_0$$

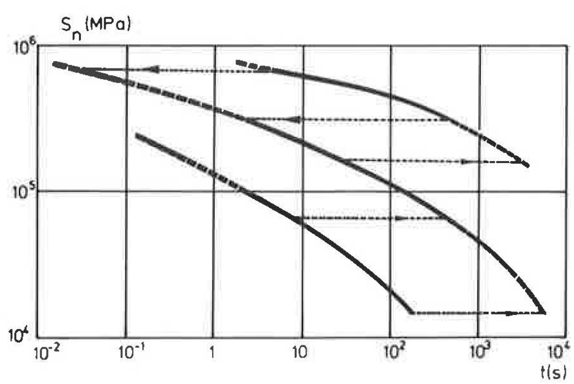


FIGURE 10 Construction of master curves for bituminous concrete modulus using isotherms.

Test Equipment and Simplified Test Procedure

The test uses core samples 80 mm in diameter and 200 mm high taken from laboratory plates and 250-mm-diameter cores cut in the pavement, recored horizontally, and sawed to the same dimensions. Steel caps are glued to the ends of the test sample; the strain is measured directly on the test sample by a strain sensor using three linear variable differential transformer

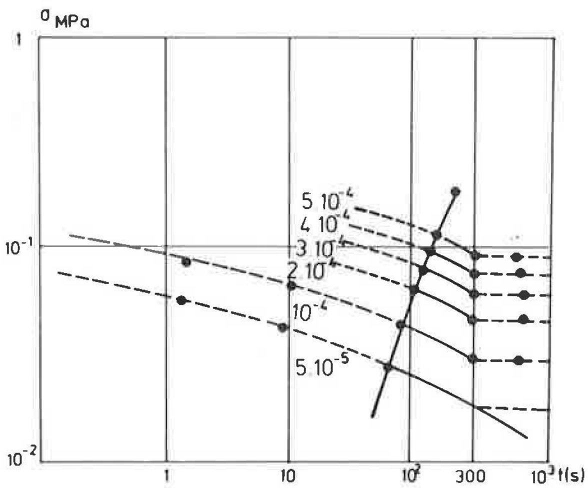


FIGURE 11 System of curves of equal strain in the plane ($lg\sigma$, lgt) used to determine the effect of strain on the secant modulus at 300 sec.

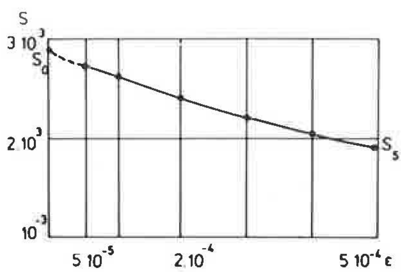


FIGURE 12 Secant modulus at 300 sec versus strain.

(LVDT) transducers. A servo-controlled testing machine, devised by LCPC, may be used to carry out tests where n = 1. With the simplified test procedure, all tests are first carried out that do not damage the sample at the different temperatures, following the order given in Table 1 and observing the maximum strain indicated. A sufficiently long recovery period is allowed between the tests and checks are made to ensure that the alignment conditions for the sample swivel attachment system are satisfied. The 26 consecutive tests on the same sample are carried out automatically by the testing machine without any operator intervention. The break test is left to last (*11, 12*).

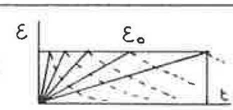
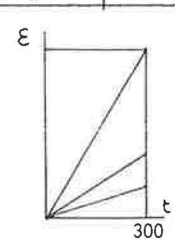
A varied range of bituminous concretes has been tested using both the direct tensile load test and the bending fatigue test (with imposed strain amplitude at 25 Hz and 10°C). The best regression on the admissible strain at 10^6 load cycles, ε_6, was found with explanatory variables $1 - \Gamma$ and modulus S as follows:

$$\varepsilon_6 T = 10^{-4} \,|a_0 + a_1(1 - \Gamma) + a_2 \cdot 10^{-10} S|$$

$\varepsilon_6 T$ designates the tensile load test estimate for admissible strain under bending fatigue at 10°C and 25 Hz. Measured at 0°C and 300 sec, $1 - \Gamma$ and S (expressed in pascals) represent the linearity loss between $\varepsilon = 0$ and 5×10^{-4} and the modulus measured at around $\varepsilon = 10^{-4}$, respectively. This regression gives correlation factor R = 0.973, and the confidence intervals calculated on the three factors at the 5 percent probability threshold are as follows:

$a_0 = 2.40 \pm 0.24,$

TABLE 1 DEFINITION OF TEST CONDITIONS FOR SIMPLIFIED PROCEDURE

ORDER	θ (° C)	STRAIN RATE (10^{-6}. s^{-1}) 						STRAIN MAGNITUDE (10^{-6})
1. 1,..,5	- 10	/	16.66	5.	1.666	.5	.05	50
2. 1,..,6	10	100.	33.3	10.	3.33	1.	.333	100
3. 1,..,6	20	200.	66.6	20.	6.66	2.	.666	200
4. 1,..,6	0	100.	33.3	10.	3.33	1.	.333	100
5.1	0							50
5.2								100
5.3								500 BREAK

$a_1 = 4.45 \pm 0.63,$

$a_2 = (1.24 \pm 0.19) \cdot 10^{-10},$

$\varepsilon_6 T \pm 0.30 \cdot 10^{-4}$ for the field $1 - \Gamma \geq 0.2$, and

$S \leq 10^{10}$ Pa.

Furthermore, there is no significant link between coefficients a_1 and a_2, for which the correlation factor takes a value of 0.1. This regression presents a good forecasting capability. In Figure 13 the $\varepsilon_6 T$ estimated from the tensile load test is compared with the $\varepsilon_6 F$ obtained directly from fatigue tests.

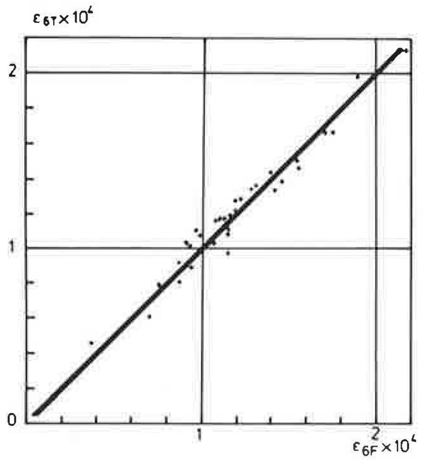


FIGURE 13 Comparison of estimated fatigue admissible strain (for 10^6 cycles) from direct tensile load tests and fatigue admissible strain from fatigue bending tests.

Forecasting of the fatigue straight-line slope is much more hazardous, essentially because of the inaccuracy of this slope, which is itself linked to the wide lifetime value scatter, as follows:

$$P_T = 0.068 + 0.130\ lg(\varepsilon_r/\varepsilon_6 T)$$

where P_T designates the estimated value of P, using the tensile load test, and ε_r is ultimate strain under the tensile load at 0°C and the lowest speed. The correlation factor is only 0.754. Nevertheless, it is more realistic to use this regression rather than the hypothesis p = constant = 0.185. The regression highlights the preponderant role of linearity loss $1 - \Gamma$ measured during a test with a single load resulting in a relatively high strain. Damage equivalent to that caused by the accumulated damage created by a large number of low-amplitude loads may be represented by $1 - \Gamma$. The origin of this nonlinearity is to be found in the macroscopically heterogeneous character of the bituminous concrete and the existence of mechanical phenomena of the coherent film into granular contact type. It should also be pointed out that the correlation factors between ε_6 and ultimate strain or stress or the modulus are low, irrespective of the tensile load test conditions. These quantities have a low potential for forecasting fatigue resistance, according to all these tests.

Utilization of Results

Definition of the elastic quality indicator (IQE) using the modulus and bending fatigue characteristics makes it possible to compare different bituminous concretes. This indicator is adapted for materials whose function is to reduce deflection and vertical strain of the subgrade, which should therefore have good fatigue resistance characteristics. This is the case when the modulus of the bituminous concrete is sufficiently high in relation to that of the subgrade and layer thickness is adequate. By definition, IQE is the thickness of bituminous concrete, which gives a theoretical lifetime of 10^6 130-kN axle passes when the modulus of the subgrade E_2 is 100 MPa. The IQE-value decreases as the quality of the bituminous concrete increases. The first IQE is obtained by entering $\varepsilon_6 T$ at 0.02 sec and 10°C in a linear elastic calculation of a two-layer pavement structure. This calculation assumes that the equivalent temperature of all bituminous concretes is close to 10°C, which checks out for the qualities normally used in France. The choice of E_2 = 100 MPa is not critical for comparison of bituminous concretes because the IQE (E_2) curves are almost parallel when E_2 varies between 30 and 300 MPa. To extend the quality indicator concept, a second IQE is defined using annual temperature spectra. For this, the hypothesis of the invariability of the product $\varepsilon_6 \cdot (S)^{1/2}$ temperature is adopted. Fatigue and tensile load tests, in insufficient numbers so far, nevertheless give rise to the hope that linearity loss measured at different temperatures will be usable at a later date. The estimation of the fatigue straight-line slope mentioned previously is used.

It should also be noted that the admissible vertical strain criterion on the subgrade is generally met when the thickness of the layer is at least equal to the IQE-value, except in the case of very high performance bituminous concretes (in which $\varepsilon_6 T > 200 \times 10^{-6}$ and $S > 20\,000$ MPa simultaneously).

A NEW METHOD FOR THE DESIGN OF BITUMINOUS MIXES

To obtain an optimum appreciation of the properties of bituminous mixes and their aptitude to provide a given function, the tests described provide suitable study tools. These tests are carried out following earlier identification of aggregates and binder. The procedure consequently involves two stages, (a) identification of ingredients, and (b) mix design study.

Identification of Ingredients

Aggregates: Coarse Aggregates and Sands

Coarse aggregates and sands must meet various specifications: hardness in the case of coarse aggregates (Los Angeles Wet Microdeval—Polished Stone Value for wearing courses), grading shape (angularity and flakiness), and cleanliness (sand equivalent—methylene blue test) for all aggregates.

Natural Fines and Filler

Apart from requirements concerning the grading of filler (100 percent elements below 2 mm and 80 percent below 80 microns), a fuller characterization of elements below 80 microns, whether natural or additional, has been found essential given the function provided by the mastic in a bituminous concrete. Thus six tests were selected following a general study covering a population of 45 samples that included natural fines obtained from ground or crushed sands and filler. These tests are given in Table 2, which also gives recommended threshold values for each test. These values make it possible to direct formulation, particularly for rigidifying capacity and water resistance, leading to improved adaptation of binder content. If a number of characteristics deviate from the values mentioned in Table 2, utilization of the filler concerned may lead to a major problem, which may be solved in some cases by the adoption of a suitable mix composition and in other cases by rejection of the material studied.

Bituminous Binder

This is generally a pure bitumen for which the following characteristics are to be determined: (a) penetration at 25°C and (b) ring and ball softening point. These are the main characteristics currently included in French bitumen specifications. Work is in progress aimed at completing these specifications with determination of the characteristics of the bitumen after RTFOT (rolling thin-film oven test) aging.

Mix Design

For obvious reasons of time and cost, it is not feasible to use the complete set of tests described here on a systematic basis. Therefore it has been necessary to define strategies for application of the tests to achieve an acceptable compromise between the volume of laboratory work and the quality and number of items of information sought. These different strategies have led to a new design methodology for bituminous mixes (*13, 14*) that is based on the search for a mix composition leading to a given level of job site void content. Once a particular mix has been selected, it must be verified that its mechanical properties are compatible with the technique in question; that is, that the compromise among resistance to permanent deformation, fatigue life, and water resistance of the selected composition is satisfactory in terms of the context (traffic density and climatic conditions). The new tests now available, more closely linked to the fundamental laws of material behavior, make it possible to select rationally from the various possibilities offered by the application of strategies adapted to the particular problem to be solved. The intended field of utilization determines the strategy to be applied, in accord with the spirit of the general methodology described.

Bituminous Concretes for Wearing Courses

Three examples corresponding to the cases most commonly encountered in France are described in Table 3, which gives the steps in the mix design methodology.

Road Base Bituminous Mixes

The choice of grading and binder content is made with the PCG test. The main objective is therefore to obtain a job site void content as low as possible. However, because a road base material that has a structural role in the pavement is concerned, compatibility between the performance achieved by the material (modulus and admissible fatigue strain) and the thickness of the layer as it is provided in the LCPC Catalog of Pavement Structures must be ensured. In the IQE sense, as defined in the section "Utilization of Results," two families of bituminous road base mixtures are found for the French context: those intended for laying in thicknesses between 15 and 20 cm have an IQE value below 20, and those intended for reduced layer thicknesses should have an IQE value below 16.

Given the diversity of factors involved in designing a pave-

TABLE 2 RECOMMENDED VALUES FOR FILLER CHARACTERISTICS

Material	Test	Recommended Value
Filler	Specific surface (Blaine method)	Between 3000 and 7000 cm^2/g
	Rigden voids index (IVR)	32 percent ≤ IVR < 40 percent
	Methylene blue test (quantity of blue absorbed per 100 g filler)	≤ 0.8 g
Mastic	Rigidifying capacity (TBA) (difference between ring and ball test softening temperature for a 60–70 penetration bitumen and for a mastic composed of 60 percent filler and 40 percent of the same 60–70 penetration bitumen)	10°C to 20°C
Mortar (0–2 mm)	Thin-film water resistance test (simple compression test executed on a mixture composed of 85 percent 0–2-mm washed sand and 15 percent of the filler under examination with the addition of 5 percent 60–70 penetration bitumen)	r/R ≥ 0.50
	Absorbing power (quantity of fines required to absorb 15 g of 60–70 penetration bitumen)	≥ 40 g

TABLE 3 GENERAL DIAGRAM OF THE NEW MIX DESIGN METHODOLOGY APPLIED TO THREE EXAMPLES

Step	Criteria	Laboratory Test	Example 1	Example 2	Example 3
1. Preliminary selection of a first group of compositions	Predicted job site void content (workability)	Gyratory compacting press	Mandatory	Mandatory	Mandatory
2. Selection of a particular composition among the first group of compositions	Resistance to permanent deformation	Wheel-tracking rutting test	Mandatory	–	–
	Predicted fatigue life	Direct tensile load test	–	Mandatory	–
	Resistance to immersion in water	Unconfined compression test (with/without immersion)	–	–	Mandatory
3. Verification of other properties of the selected composition	Resistance to permanent deformation	Wheel-tracking rutting test	–	Mandatory	Mandatory
	Predicted fatigue life	Direct tensile load test	Mandatory	–	As appropriate
	Resistance to immersion in water	Unconfined compression test (with/without immersion)	As appropriate	As appropriate	–

Note: Example 1—high resistance to permanent deformation; Example 2—high fatigue life; Example 3—high resistance to immersion in water.

ment layer, the IQE value is only used as an element for checking the quality of the material.

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