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and Performance*

Porous Asphalt Pavements: An International Perspective 1990

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Contents

Foreword

The 11 papers in this Record were presented in Sessions 202 and 214 of the 69th Annual Meeting of the Transportation Research Board, held in 1990. All papers were developed jointly and sponsored by two Permanent International Association of Road Congresses (PIARC) committees and three TRB committees. Thomas Deen, Executive Director of TRB, and Bernard Fauveau, General Secretary of PIARC, each introduced one of the sessions by emphasizing the international cooperation represented. The papers were prepared by authors from Belgium, France, Great Britain, Italy, the Netherlands, Spain, and Switzerland.

Porous asphalt pavements in Europe are 4 to 5 cm thick, about twice as thick as open-graded asphalt surfaces in the United States. Otherwise they are similar. In addition to reducing splash and spray and helping to maintain high friction levels between vehicle tires and wet pavements, porous asphalt pavements are recognized for their ability to reduce light reflectance and to decrease tire and vehicle noise by 3 to 4 dB(A). Topics covered by the papers are mix design (including polymer additives), placement, repair, performance, measurements of reduced noise and other perceived benefits, and measurement of physical properties related to the engineering performance of these pavements.

Sound Absorption and Winter Performance of Porous Asphalt Pavement

GABRIELE CAMOMILLA, MAURO MALGARINI, AND SANDRO GERVASIO

Sound-absorbent porous asphalt pavements have been used extensively on Italian motorways to reduce traffic noise; improve skid resistance in case of precipitation by eliminating aquaplaning, especially in zones with limited runoff; and eliminate the risk of the spray effect. The Autostrade Company carried out large-scale tests for safety, economy, maintenance, and sound absorption over some 1,200,000 m^2 or porous asphalt pavement. Laboratory control measurements and snow simulations were also studied. The data indicate why porous asphalt attenuates noise, which may lead to new ways to develop porous asphalt pavement mixes. The measures that should be taken to remove snow and ice are also reported.

On such fast-transit roads as motorways, highways, ring roads, bypasses, and so on, traffic conditions generally are such that one main source of noise is "rolling noise," that is, the complex of vibrational and fluido-dynamic phenomena that arises from the interaction between vehicle tires and the road surface. Indeed, it has been ascertained that tire-on-road noise is the predominant source of noise for passenger cars traveling more than 50 to 60 km/hr and for industrial vehicles traveling at more than 60 to 70 km/hr (Figure 1) (*1*, *2*).

The Autostrade Company has become increasingly interested in analyzing this phenomenon to develop a pavement that can reduce rolling noise, and simultaneously maintain good safety and durability characteristics. Research has clarified many, if not all, aspects of the problem which, in summary, is affected by the following parameters:

- Aerohydraulic vorticity phenomena that result from the roto-translational movement of wheel itself,
- Tire vibrations caused by impacts between the grooves of the tread and irregularities in the pavement surface (micro- and macrotexture), and
- Air-pumping phenomena, that is, the sudden lamination of the pressurized air trapped in the spaces between the tread grooves and the road surface.

The various simulation models developed so far are approximate, such that it is not possible today to theoretically determine the combinations or solutions which will ensure low noise levels.

SOUND ABSORBING PAVEMENTS: HOW THEY FUNCTION

In recent years, experts have paid increasing attention to "porous asphalt pavements." The Autostrade Company has carried out extensive experiments involving porous asphalt pavements, and in 1988 conducted large-scale tests for safety, economy, maintenance, and sound absorption over some 1,200,000 m^2 of pavement. The tests on sound absorption have yielded some interesting data which may well open up new horizons for the development of this type of mix.

Numerous hypotheses have been advanced to explain the noise attenuation produced by porous asphalts. The more feasible are as follows:

- The porosity of the road surface strongly limits the air-pumping effect, and, insofar as there is communication between the cavities in the pavement, and therefore the air between the tread grooves and pavement is not compressed.
- The macrotexture of the porous pavement is characterized by optimal wave length and roughness, so as to minimize tire vibrations. See Descornet's theory (*3*).
- The sound absorption coefficient is such that along the path of sound propagation between the sound source and the point affected by the noise, an additional attenuation occurs because of the reduced acoustic reflection from the road surface.

Among these hypotheses the least important is usually considered to be sound absorption (*4*). Passing from a mean value of 10 percent (traditional pavement) to an *am* coefficient of 60 percent (porous pavement), the maximum theoretical overall attenuation is about 1.3 dB(A) (Figure 2)—a figure considerably lower than the 4 to 6 dB(A) generally obtained experimentally.

Tests and Results

The test program included both measurements taken on site and measurements taken in the laboratory on samples.

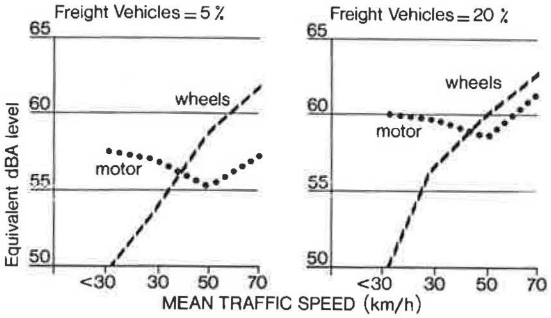

FIGURE 1 Rolling noise as a function of vehicle speed.

G. Camomilla and M. Malgarini, Autostrade S.p.A., Via Bergamini, 50, 00159 Roma, Italy. S. Gervasio, Fimit Ipse, Via Bologna, 87, 10154 Torino, Italy.

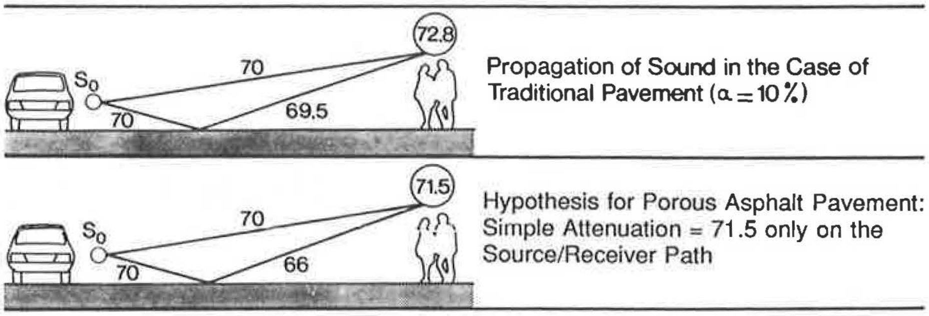

FIGURE 2 Sound absorption.

On-site Measurements

The on-site measurements were carried out on the Adriatica Motorway in the vicinity of Vasto Nord, where several sections were paved with traditional and sound-absorbent materials under identical environmental and wear conditions.

Two similar microphone arrangements were set up at points 100 m apart as measuring positions, on the two types of pavement. Measurements were taken at 3.5 and 7.5 m from the axis of the normal traffic lane and in such a way as to obtain free field acoustic conditions.

The following noise sources were used:

- Two standard vehicles: a Fiat Uno and an OM 130 truck, both in transit at constant speed, first in gear and again with the engine turned off.
- A noise generator: A loudspeaker mounted on the roof of a car, powered with white noise from 100 to 5,000 Hz, producing a loudness that exceeded the vehicle noise by at least 10 dB.
- Actual motorway traffic. Given the proximity of the two microphone units and the type of road section in question (slight negative slope and straight path), it could be assumed that there would be no significant variation in the parameters affecting noise, (i.e., traffic composition, average speed of vehicles, engine speed, and weather conditions) between recording positions. Consequently, any attenuations would be attributable exclusively to the different nature of the pavement surfaces.

The test results are summarized in Tables 1–3 (each attenuation value is the average of three tests). Figure 3 shows db(A) levels measured using the standard vehicles at the different test speeds and conditions. Figures 4–6 show the statistical parameters measured at the two receiving units, and specifically spectra (mean value), probability distribution, and the cumulative distribution. Figure 7 shows the development of the sound level as a function of its position relative to the measuring point and the noise spectra recorded for one of the vehicles in transit. The time windows included either the

TABLE 1 TESTS WITH STANDARD VEHICLES

Vehicle	Speed km/h	Attenuation 3.5 m dB(A)	Attenuation 7.5 m dB(A)
FIAT UNO	40	3.2	6
	60	3.1	3.6
	80	2.6	4.5
	120	2.8	4.5
	60 engine off	1.8	3.3
OM 130	40	3.8	6
	80	2.2	3.3
	60 engine off	3.1	2.6
	MEAN	2.8	4.2

TABLE 2 TESTS WITH NOISE GENERATOR

Test No.	Attenuation at 3.5 m, dB(A)	Attenuation at 7.5 m, dB(A)
1	0.8	0.2
2	0.3	0.3
3	0.4	-
MEAN	0.5	0.1

TABLE 3 TESTS WITH REAL TRAFFIC

Attenuation, dBA (on 15 minutes of analysis)				
L5	L50	L90	Lmean	Lequivalent
3.5	4.7	3.5	4	4

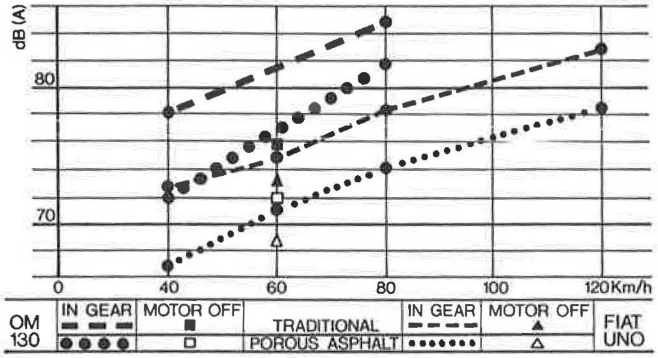

FIGURE 3 DB(A) levels for standard vehicles.

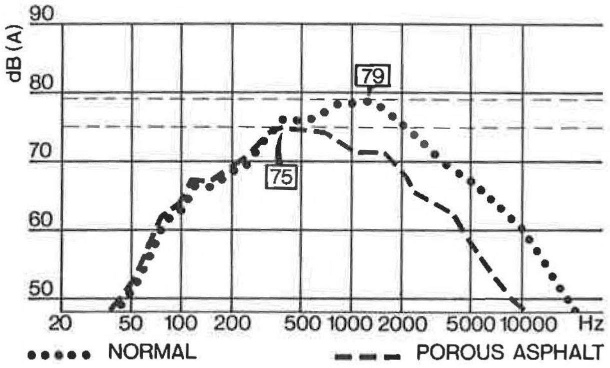

FIGURE 4 Spectra (mean value) at two receiving units.

entire approach and departure period (top) or just the instant of passage past the pickup microphone (0.125 sec) (bottom).

The following observation can be deduced from these figures and tables: the overall effect of the pavement cannot be attributed solely to the reduction in rolling noise. In fact, as shown in Figure 3 and Tables 1–3, the attenuation is almost constant and independent of the vehicle speed, whereas, as previously indicated, the "weight" of the rolling noise increases rapidly with the rise in speed. In other words, a modification that would affect only the rolling noise will not result in attenuations of 4 to 5 dB(A) even at 40 km/hr (i.e., in conditions in which the primary noise sources are the engine and exhaust).

This observation is further supported by comparing the measurements performed when vehicles were in gear with the measurements performed when the vehicles' engines were shut off. For both standard vehicles in both test modes, reductions of the same magnitude were obtained. In theory, when the rolling noise is the only source of noise (the test with the vehicle engine turned off), the attenuation should have been much more evident.

All this led to the formulation of the hypothesis shown in Figure 8, which can be expressed as follows: the overall effect of the porous asphalt pavement is caused by an attenuation obtained by sound absorption, operating first on the noise generated by all sources (motor, exhaust, fans, tires) and successively rebounding between the floor pan and pavement, and then along the source and receiver propagation path. A noise reduction from 3.5 to 4.7 dB(A) follows from this hypothesis, depending on the number of successive rebounds between floor pan and cabin and pavement. The approximation between the theoretical data and the experimental results is good. (Details about the theory of sound propagation between the two parallel surfaces and model calculations are available by contacting the authors.)

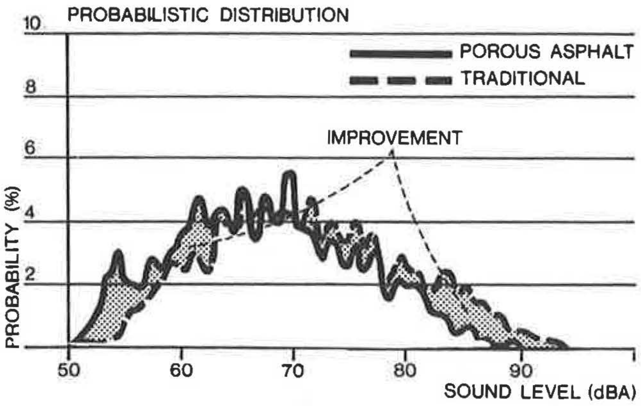

FIGURE 5 Probability distribution of dB(A) for porous asphalt and traditional pavements.

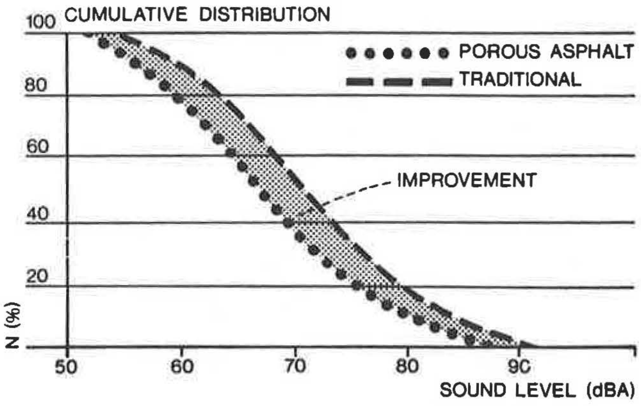

FIGURE 6 Cumulative distribution of dB(A) for porous asphalt and traditional pavements.

A first partial verification of this thesis is found in the field measurements, which show (Figure 7) that the attenuation at the approach and departure stages is greater compared with the reduction related to the transit only. In addition, passenger cars are more sensitive to the effect of the porous

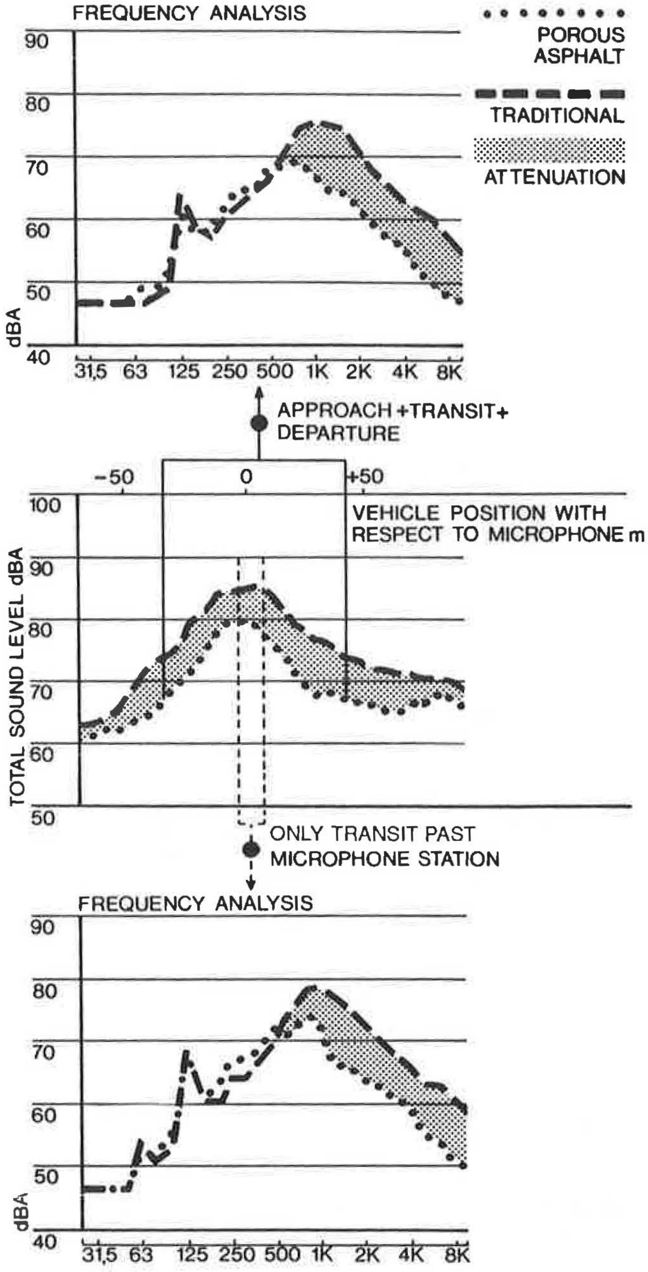

FIGURE 7 **Sound levels for vehicles in transit.**

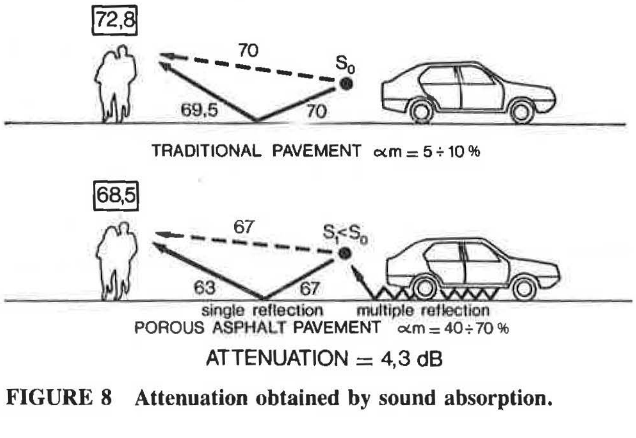

FIGURE 8 **Attenuation obtained by sound absorption.**

asphalt than are trucks and industrial vehicles as shown in the following table.

Vehicle Type	*Test Conditions*	*Mean Attenuation (dB(A))*
Passenger car	Approach, transit, and departure	5.2
Passenger car	Transit only	3.4
Industrial Vehicle	Approach, transit and departure	3.4
Industrial Vehicle	Transit only	2.4

Laboratory Measurements

Several control measurements were subsequently taken in the laboratory. The first step was to use the standing wave apparatus (Figure 9) to determine sound absorption coefficients on normal incidence of different pavement samples. Different measurements were taken on each type of mix to account for dispersions owing to differences in production and laying of the materials.

The results are shown in Figure 10. Porous pavements have much higher values than traditional pavements, particularly in the frequency range where the mean noise spectra begin to vary significantly.

A second control test was conducted in the Fimit-Ipse semianechoic chamber (Figure 11). An automobile on the roller

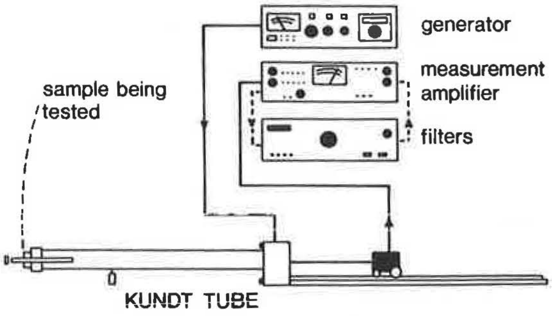

FIGURE 9 **Standing wave apparatus.**

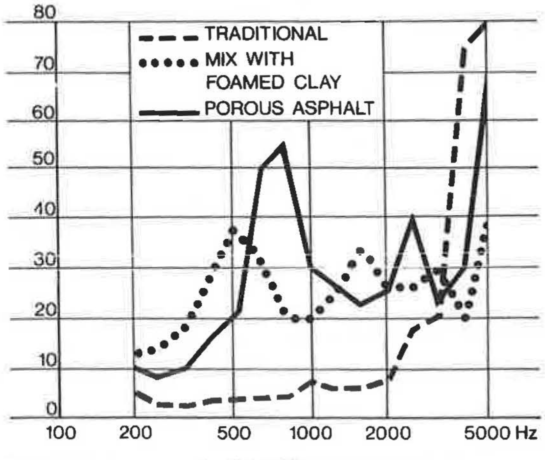

FIGURE 10 **Sound absorption coefficients of pavement samples determined in laboratory.**

FIGURE 11 **Fimit-Ipse semianechoic chamber.**

bench was driven at 120 km/hr in direct gear under conditions simulating a flat road. Subsequently a thin layer of sound-absorbing material was placed on the chamber floor directly beneath the floor pan, and external noise measurements were taken to evaluate the effect of such treatment. The polar diagram shown in Figure 12 fully confirms the level of attenuation recorded on the motorway section.

Implications for Further Research

The work undertaken and the positive results obtained cannot be thought to solve the problem of vehicle noise, but certainly they represent an encouraging starting point for further research into the more important physical phenomena affecting the overall noisiness of vehicles—the components of rolling noise as well as that of the engine and the drive-line.

The hypothesis on porous asphalt pavements must be examined and checked further. Some of the important implications include the following:

- Porous asphalts could be used successfully in urban environments, insofar as the sound-absorbing effect is not linked to vehicle speed. Indeed, in theory, the attenuation could be even greater in the cases of idling vehicles (at stoplights) or slow or "hiccuping" traffic.
- When noise barriers are combined with porous asphalt pavement, it might be necessary to review the various insertion-loss calculation models. In fact, for example, the effect of the sound-absorbing surface could alter the conventional height of the noise source, today set at 0.8 m above ground level.
- The sound-absorbing pavement substantially modifies the mean noise spectrum, significantly attenuating the frequencies from 500 to 6,300 Hz. This could also lead to a standardized road noise spectrum rather different from that established, for example, in the French and German standards (*5*, *6*).

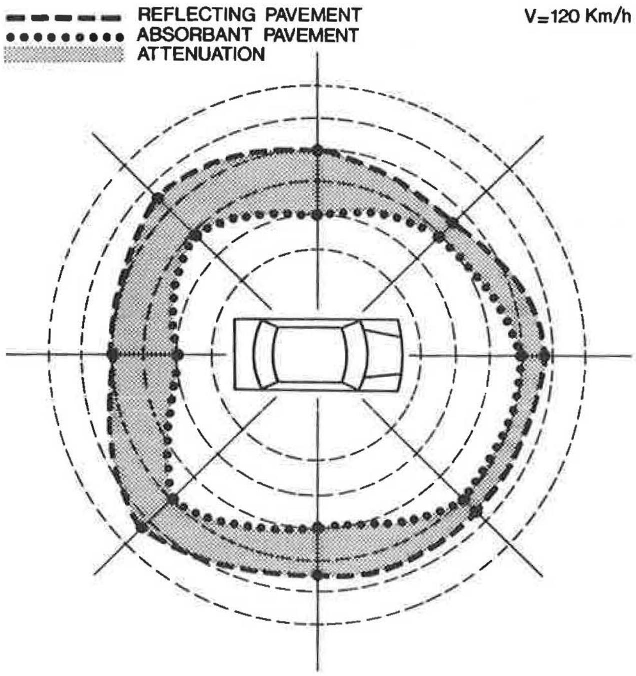

FIGURE 12 **Attenuation in Fimit-Ipse semianechoic chamber.**

Future research should also be directed along the following lines:

- Evaluation of the eventual deterioration of acoustic properties resulting from the possible compaction of the asphalt under traffic loads; reduction of porosity caused by dirt, dust, or chemical action (salts, oils, hydrocarbons, etc.); and behavior under wet surface conditions.
- Development of pavements which offer better sound-absorption characteristics, mainly at low frequencies.
- Development of sound-absorbent pavements with low rolling noise characteristics.

PERFORMANCE OF POROUS ASPHALT PAVEMENTS UNDER WINTER CONDITIONS

The advantages of porous asphalt pavements require closer attention to their performance under winter conditions, especially because their porous structure may lead to changes in ice formation and in ice and snow elimination. Over several winters, it has been noted that on several motorway sections paved with porous asphalt, snow attaches more easily and lasts longer, often with very rapid ice formation.

In order to study this phenomenon and determine valid criteria for winter maintenance intervention, it was decided to conduct a series of tests with the following specific aims:

- To study more thoroughly the physical process which, under certain specific weather conditions, results in the formation of ice on porous asphalt surfaces and
- To analyze the phenomenon by means of laboratory tests to determine the cause of ice formation from snow.

Winter Conditions Testing

The tests were conducted on two different pavement samples—porous asphalt surface and normal surface—having the characteristics shown in Table 4. For each test, the temperature variation was recorded for increasingly longer time intervals at the surface, −1 cm, −3 cm, and binder levels.

The tests were conducted using (a) four digital thermometers with microprocessor temperature control. (Each thermometer was equipped with two external K-type thermocouple sensors. Temperature indication conformed to National Bureau standards.), (b) a thermostatic chamber for temperatures ranging from 0° to +350°C, and (c) a thermostatic chamber for temperatures ranging from +7° to −15°C.

The porous and normal samples responded differently to physical transformation stresses occurring on the surface. In particular, the porous sample

- Cooled more rapidly because of its high porosity and high specific surface area; in fact, road tests show that porous pavements are often colder than normal pavements;
- Showed high wettability;
- Showed significant thermal resistance throughout, with significant delay in warming as environmental temperatures rose;
- Assumed a high thermal capacity because of the presence of the melt water which soaked it and the thermal capacity appeared to vary as a function of the concentration of the solution and the quantity of solvent;
- Used little if any of the thermal reserves of the underlying pavement layers;
- Proved relatively unaffected by normal preventive treatment.

To obtain performance approaching that of the normal sample, it was necessary to apply almost triple the amount of NaCl. The main reasons for this are the following: (a) the salt is deposited in the voids and only partially comes into contact with the snow, and (b) the saline solution resulting from the melting of the snow is lost through drainage, and in its descent partially leaches out the salt deposited in the pores, thus increasing its concentration as it flows.

Increasing the quantity of NaCl is not recommended. In addition to delaying the rise in temperature, it could also have the effect of further chilling the drain water that results from the high concentration of salt solution which, in washing over the vast internal surfaces, subtracts additional heat from the deeper layers of the porous asphalt wearing course. Ice removal treatment with NaCl is also of little effect, because the frozen surface becomes "cratered" around the salt granule. In passing over these craters, the salt solution is thus only partially

TABLE 4 CHARACTERISTICS OF SAMPLES EMPLOYED

		WEARING COURSE	
	BINDER	POROUS ASPHALT	NORMAL
1) Thickness of Layer	5 - 7	4 cm	5 cm
2) Bitumen Content	4.7 %	5.8 %	4.9 %
3) Aggregate Specific Weight	2.68 gr/cm^2	2.80 gr/cm^2	2.73 gr/cm^2
4) Volume Weight	2396 gr/cm^2	2260 gr/cm^2	2403 gr/cm^2
5) Percentage Voids	4.56 %	11.57 %	5.08 %
6) Sample Weight	-	7.88 kg	8.94 kg
7) Sample Diameter	-	200 mm	200 mm
8) Sample Height	-	115 mm	115 mm
9) Granulometry	According to Technical Standards		
10) Thermal Coefficient	Values to be Determined		
11) Thermal Conductivity	" " " "		
12) Thermal Capacity (C.S.)	" " " "		
13) Specific Surface	" " " "		

deposited on the attack surface. The remainder is lost through drainage, and consequently the ice layer is only altered in certain zones (Figure 13).

Conclusions Regarding Winter Performance

- In conditions of intense cold and sharp frosts, the porous pavement presents several disadvantages,
- Preventive treatment, given the granulometric characteristics of salts currently used, is not particularly effective, but certainly not useless,
- Ice removal treatment can perhaps be more effective using liquid chloride solutions,
- The passage of the snowplough blade compresses and presses the snow into the pores of the porous asphalt, and subsequent traffic brings to the surface part of the snow in the form of semi-liquid slush which easily freezes under low temperatures.
- Attention must be given to the problems which arise at the transition points between the normal pavement and the porous asphalt pavement, because of the different behavior of the two mixes.

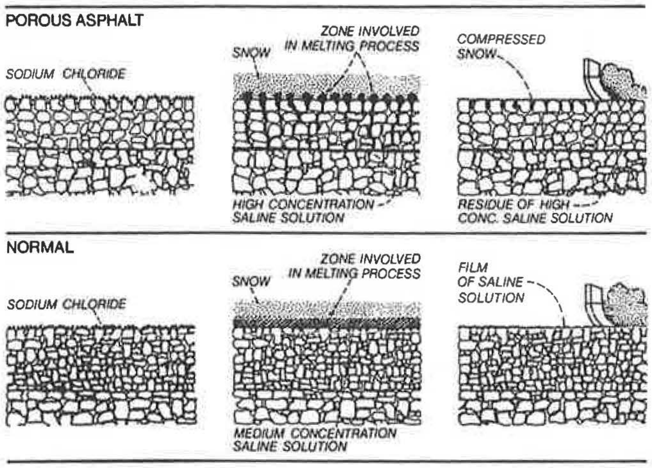

FIGURE 13 Preventive treatment and snowploughing process on wearing course.

Given current knowledge, and pending results of more detailed studies, the following winter operations are advisable:

1. In the case of porous asphalt pavements, it is necessary to provide strong preventive treatments consisting of almost three times the amount of salt used for normal pavements,
2. To facilitate accurate dosing on the part of the salt-spreader operator, it is useful to post signs at the beginning and end of the porous asphalt sections,
3. It is necessary to alert staff in ample time to ensure immediate and rapid snow removal operations before the snow can penetrate to depth, and
4. Once the snowploughs have cleared the snow, it is necessary to proceed immediately with successive and repeated treatments with reduced quantities of NaCl.

Research should be continued to devise new specifications for both preventive treatments (granulometric characteristics of the salts) and ice removal treatments.

Laboratory Simulation Tests and Results

A simulation test was conducted on porous asphalt pavement in a thermostatic snow precipitation chamber and simulated outside weather conditions, which occur, for example, along the eastern coast of Italy prior to snowfalls. (See Figure 14.)

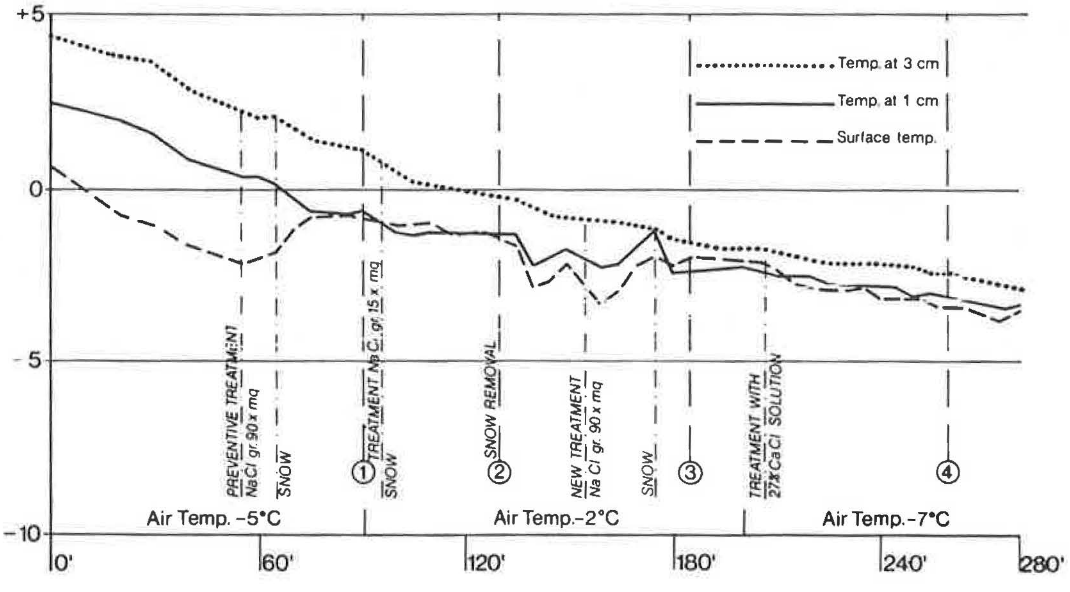

FIGURE 14 Snow simulation in climate-control chamber on porous asphalt wearing course at low temperatures.

Overall, the test included simulation of the preventive treatment, the snowfall itself, snowploughing, and snow removal treatment with NaCl and CaCl; recording the development of temperatures on the sample pavement and visual observation of the behavior of the snow and the sample.

The step-by-step test procedure was as follows. The sample was first kept at room temperature for 24 hr, subsequently insulated with a thick layer of polystyrene foam (except for the upper surface of the wearing course), and finally placed in the climate control chamber at a temperature of −5°C. The demonstration value of the test required a precise chronological description to pinpoint the critical moments of a "snow operation."

Because of the cold winter winds from the northeast and east, the normally brief snowfalls occurring on Italy's eastern coast are preceded and followed by sharp temperature drops causing sudden frosts. In view of this, the sample was gradually cooled by applying an air temperature of −5°C.

At the instant when the surface temperature reached −2°C, a preventive treatment was applied, using 3 gr of NaCl (equivalent to 90 gr/m^2). At that moment, temperatures within the sample were recorded as follows: +0.4°C at a depth of −1 cm, and +2.3°C at −3 cm.

Ten min after the salt was applied, a snowfall was simulated, maintaining an air temperature of −5°C. The lower layers of the wearing course were still above 0°C, and hence in condition to contribute warmth to the surface.

It was assumed that the snowploughing operation occurs within 30 min of the snowfall. About 25 min after the simulated snowfall, the snow was transformed into ice, attaching itself to the surface (point (1) in Figure 14). The preventive treatment proved to be of little effect, although the temperatures in the lower layers of the porous asphalt wearing course had not yet reached values such as those encountered on the road and reported in Figure 14. After the ice was removed, the air temperature was returned to −2°C.

Some salt still remained in the pores, so the sample was given another preventive treatment with 0.5 gr of NaCl (equivalent to 15 gr/m^2). Another snowfall was then simulated, compacting the existing snow. The process of melting began, with both surface and −1 cm depth temperatures remaining stable at around −1°C. The temperature at −3 cm, however, continued to fall to about zero. After 30 min, the snow was removed, using a brush which pressed the snow into the surface pores and removed the excess (Figure 14, point 2).

Temperature variations continued to occur such that after about 10 min, the surface temperature reached a maximum of −2.8°C and that at −1 cm reached −2.2°C. The physical process thus also involved the deeper layers. It was observed that the snow remaining in the surface pores took the form of semiliquid slush, without liquefying completely.

After 25 min, it was decided to perform another treatment operation with NaCl (90 gr/cm^2). The air temperature remained at −2°C. At this point, the surface temperature fell to −3.3°C, and then rose slowly to −2°C. At −2°C, another snowfall was simulated, again compressing the existing snow. After 10 min (Figure 14, point 3), the upper surface of the snow began to ice over, but the snow in contact with the pavement tended to melt, without attaching to the surface. About 20 percent of the snow melted.

After 15 min, the snow froze completely. It was then decided to bring the air temperature down to −7°C and to effect an ice removal treatment using a 27 percent CaCl solution with a temperature of 0°C. For the entire observation time of 55 min, the ice, which had formed earlier, remained in a semiliquid state, certainly at the borderline between the solid state and liquid state. The ice solidified when the sample was kept at −7°C for a longer period.

The following observations can be added to the advisable snow operations given previously. Because the noncompacted snow reacted very little with the salt deposited in the pores it is advisable to use a quantity of NaCl no more than 90 gr/m^2 for the first treatment. The quantities to be used for subsequent treatments depend on the percentage of salt remaining undissolved. Finally, at low temperatures, the snow slush is particularly dangerous because of its rapid freezing potential.

DISCUSSION

The analytical model for sound propagation employed here is not suitable for use in predicting the noise pollution produced by traffic, for its application would require a real measure of all possible noise sources (different motors, tires, mufflers, and etc.), both as levels and as a spectral composition. Further analytic studies and experimentation, however, can lead to better knowledge of vehicle noise generation and propagation phenomena. Additional research should be directed toward the variation of the sound absorbing coefficient of porous asphalt pavements as a function of the angle of incidence, effect of the thickness of the porous asphalt, effect of the porosity, effect of specific resistance to the passage of air, and effect of the shape factor.

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Acoustical Properties of Porous Asphalts: Theoretical and Environmental Aspects

M. BERENGIER, J. F. HAMET, AND P. BAR

The acoustical aspects of porous road surfaces as studied in France are described in this paper. The first part discusses the advantages of porous asphalt and shows how and why, in France, two experimental approaches are carried out: thin porous layers (~4 cm) for the interurban and urban network, and thick porous layers (40 to 50 cm) for the urban network. The second part presents a theoretical model: the absorption coefficient as a function of frequency is obtained from the layer thickness and three physical parameters representative of the porous medium. The influence of these parameters on the absorption is described. It is clearly shown that above a certain value, thickness has no influence on the absorption properties (i.e., increasing the thickness becomes acoustically useless). This is called the "superthickness" condition. In the third part, experimental results obtained in the laboratory and in situ are compared with the theoretical calculations. The influences of humidity, gaps in the grading, binder content, and number of layers are also presented. The last part deals with noise reduction as measured with rolling vehicles (pass by, coast by). Experimental programs in progress are described and some results are given. Evolution of noise level versus road aging is also discussed.

In the last 10 years, vehicle noise has been substantially reduced. For light vehicles, the maximum noise level decreased from 81 dB(A) in 1982 to 77 dB(A) in 1988, and for heavy vehicles, from 91 dB(A) to 84 dB(A) (measurements performed following the ISO R 362) (*1*).

These important noise reductions have been primarily obtained by reducing engine noise, developing a better conception of transmission, and constantly improving silencers. In these conditions, the rolling noise tends to predominate, particularly on expressways and uncongested urban roads where the traffic speed exceeds 50 km/hr. This is especially the case at night, when traffic noise is the most disturbing (i.e., in its effects on sleep).

The spread of noise levels measured on different road and vehicle configurations can reach 10 dB(A) (*1–3*). Therefore, it is worthwhile to reduce traffic noise by an appropriate conception of pavements, particularly the wearing course.

In urban areas, where management of vehicle flow is not sufficient to significantly lower noise levels, it is not possible to consider noise protection devices such as barriers: acoustical improvement of building facades has been until now the only way to protect dwellings from traffic noise. It is, however, just a partial solution because it is efficient inside, but only with closed windows. A reduction of several decibels in noise emission itself, because of a suitable pavement, would be real progress (*4*).

In a periurban area, a noise-reducing pavement would make it possible to avoid excessively high noise barriers. This presents two advantages: (a) better integration into the landscape and (b) lower cost [noise barriers cost about 2000 FF (U.S. $300)/m² and the amount usually increases with height].

Such road surfaces might also complement efforts by car manufacturers to reduce the noise inside the vehicle.

EXPERIMENTAL APPROACHES

The use of porous asphalts for wearing courses has been explored for about 20 years. The use of new binders and the results of research on the acoustic efficiency of these pavements can explain recent developments.

In France (*5*), two experimental approaches have been carried out. One is a thin porous asphalt wearing course (about 4 cm thick) combined with an integral porous structure from the road subbase to the surface (about 40 to 50 cm thick). The thin porous layer is used on both interurban and urban networks. In the interurban domain, several experiments are in progress to determine adequate formulations and study the problems of aging and maintenance. Numerous experimental tracks have been established in various places in France, for instance,

- In 1986–1987, 200 km on the heavily trafficked A1 Motorway between Paris and Lille, and
- In 1988, 20 km between Orléans and Vierzon, and 18 experimental tracks (500 m long) on A 63 (Bordeaux-Bayonne) where different thicknesses (2.5 cm to 6 cm), binders, and gradings (0/10, 0/14, 0/20) have been tested. On the latter site, gripping, evenness, and texture were measured simultaneously with the acoustic measurements. During the next few years, a follow-up study will be carried out in order to control how these pavements behave over time.

The second approach, a thick porous structure, represents more ambitious research. These structures are built similarly to "reservoir pavements," whose purpose is to absorb rainwater and delay water flow evacuation (i.e., during heavy rains). One site is located near Nantes, France. A second site, experimental, is situated in the Lyon area. In this case, properties of thick structures were theoretically evaluated by using the model discussed later (*6, 7*) and experimentally confirmed (*8*). Following this work, four experimental tracks (50 m long) were built during the summer of 1989. Three are 40 cm thick and one is 50 cm thick. Several gradings between 0/10 and

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0/20 and binders (pure and modified bitumen and hydraulic, or porous, concrete) were used. A first set of measurements is in progress. A follow-up of the behavior under winter conditions is also planned in order to ensure correct maintenance. The first results will be published in 1990.

ADVANTAGES OF POROUS ASPHALTS

It is now established by specialists on rolling noise and confirmed by recent experiments carried out in several countries that porous asphalts (4 cm thick, 15 to 20 percent voids) provide noise attenuation relative to classical surfaces and dressings (*3*) whose values fluctuate between 3 and 6 dB(A). Their main advantages are to

- Reduce the noise emission (exterior noise), which can be particularly attractive in urban areas;
- Reduce noise inside vehicles;
- Reduce vibrations inside vehicles, which can increase the level of comfort for the users and the electronic devices;
- Reduce water splash and spray (which is a safety factor);
- Improve skid resistance on wet pavement in the high-speed domain, and
- Provide temporary water storage.

These qualities must not mask some problems with winter maintenance that must be adapted to the specificity of such pavements. In other respects, some questions must still be answered about layer optimization, the mechanical behavior of the structure under heavy traffic (resistance to rutting and clogging), and finally water flow in urban road systems.

Because of these qualities, porous asphalt will probably be more extensively used in urban and periurban networks.

MODEL FOR ACOUSTICAL PROPERTIES OF POROUS ROADS

The acoustic absorption coefficient of a road surface representing the proportion of acoustic energy not reflected by this surface for a monochromatic plane wave impinging normally on it is referred to here as absorption coefficient a_0.

First, a brief review of how a_0 can be determined from acoustical characteristics of the media (for a multilayered system) is given. Then how these acoustical characteristics are obtained from physical parameters, how to measure these parameters, and how the physical parameters influence the absorption coefficient are reviewed.

Absorption Coefficient and Acoustical Characteristics

The absorption coefficient a_0 of a surface can be determined from the acoustic impedance Z (complex quantity) of this surface (Equation 1). For a layer of thickness e backed by an impedance Z_T, the surface impedance is given by Equation 2.

$$a_0 = 1 - \frac{|Z - \rho c|^2}{|Z + \rho c|^2} \tag{1}$$

$$Z = W \frac{Z_T \coth\gamma e + W}{Z_T + W \coth\gamma e} \tag{2}$$

where

ρc = characteristic air impedance,
W = characteristic impedance, and
γ = propagation constant.

W and γ are the acoustical characteristics of the medium.

Remark. The complex convention adopted in this paper for harmonic time dependence is $e^{i\omega t}$.

Equation 2 is used to evaluate, through an iterative procedure, the surface impedance of a multilayered system: one needs to know the W and γ for each layer and the end (bottom) impedance of the system.

Acoustical Characteristics and Physical Parameters

The acoustical characteristics W and γ of a porous medium can be obtained from physical parameters. For the case of mineral fibers, Delany and Bazley (*9*) have shown that the only physical parameter to consider was the specific airflow resistance R_S. Various authors have tried to extend these results to other media such as soil (or sand, asphalt, etc.) in the presence of snow or vegetation. Predictions and measurements did not always agree. An explanation is that acoustic characteristics of a medium do not depend only on the airflow resistance (friction forces) but also on the porosity (proportion of air in the medium) and on the path the air has to follow (between the fibers, the particles, etc.) (*10*). The fiber materials studied by Delany and Bazley had a porosity near unity and an air path almost unaffected by the presence of fibers.

For porous roads, the medium is assimilated to a homogeneous fluid. The solid structure is supposed rigid, nonmoving. This approach is a macroscopic one: the dimensions of pores and particles must be small enough with respect to the wavelength (which in air is ~17 cm at 2,000 Hz). This limits the validity of the model up to about a few kilohertz.

The fundamental equations of state, continuity, and motion are used to evaluate, at each frequency, the acoustical characteristics W and γ from three physical parameters representative of the medium. The general philosophy follows Morse and Ingard (*11*). The equation formulations are given elsewhere (*10*). Details have been given by Hamet (*6*). The results are [compare work by Von Meier (*12*)]

$$W = \rho c \frac{\sqrt{K}}{\Omega} \left(1 - i \frac{R_S}{\omega\rho} \frac{\Omega}{K}\right)^{1/2} \tag{3}$$

$$\gamma = i \frac{\omega}{c} \sqrt{K} \left(1 - i \frac{R_S}{\omega\rho} \frac{\Omega}{K}\right)^{1/2} \tag{4}$$

where

Ω = porosity ($\Omega \leq 1$),
R_S = specific airflow resistance, and
K = shape factor ($K \geq 1$).

Porosity Ω

The porosity is introduced in the continuity equation, which states that the rate of mass increase of air in a volume results from a mass flux of air through the surface limiting the volume. If it is stated that the air occupies a fraction ΩdV of the elementary volume dV, the equation reads

$$\iiint \frac{\partial \rho}{\partial t}\,\Omega dV = -\iint \rho u\cdot dS$$

where ρ is the density of the fluid and $u\cdot dS$ is the volume flow rate of the fluid through the surface dS normal to this surface (taken > 0 for outward flow).

From this formulation, it is clear that the porosity Ω must correspond to connected pores and is therefore defined as

$$\Omega = \frac{\text{volume of connected pores}}{\text{total volume}}$$

The porosity is actually measured with a gamma-ray technique (*13*). It is therefore implicitly assumed that the measured "air volume" corresponds to connected pores, which is reasonable because the porous medium is made of (asphalt) coated particles.

Specific Air Flow Resistance R$_S$

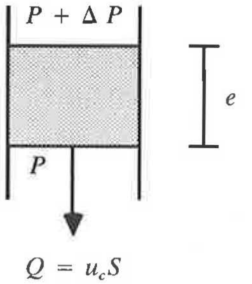
The equation of motion takes into account the "frictional retardation to flow through the pores" (*14*). In the x-direction, the equation reads

$$R_S\, u = -\frac{\partial p}{\partial x} \qquad (5)$$

where p is the acoustic pressure in the medium and u is the volume flow rate in the x-direction.

R_S can be measured using a steady flow technique (*14*):

$$R_S = \frac{1}{u_c}\frac{\Delta P}{e} \qquad (6)$$



If ΔP is the pressure difference created between the two faces of a layer of thickness e and $u_c = Q/S$ is the steady volume flow rate of fluid per unit area through the sample, one gets R_S from Equation 6.

Remark 1. In order for the measurement conditions for Equation 6 to correspond to the acoustic conditions for Equation 5, the flow velocity u_c must be sufficiently small (laminar flow conditions (*14*). If not, R_S will depend on the velocity u_c, as can be seen from Figure 1.

Remark 2. R_S is expressed in Nm^4 in the mks system. The cgs system with the unit rays per centimeter is used here. (1 rayl/c = 1kN/m^4.)

Shape Factor K

The shape factor is used to take into account the facts that

- The air paths through the layer do not always follow the normal direction (they are more or less tortuous), and
- The pore cross-sections can vary along the paths.

It is introduced in the inertial term of the equation of motion in the following way:

$$K\rho\,\frac{\partial u_{\text{pore}}}{\partial t} = -\frac{\partial p}{\partial x} \qquad K \geq 1 \qquad (7)$$

where u_{pore} is the average velocity of the air in the pores in the x-direction (average taken over the surface normal to x). It is related to the average flow rate per unit area u by the relation $\Omega\, u_{\text{pore}} = u$.

If one considers both the inertial term (Equation 7) and the friction term (Equation 5), the equation of motion reads

$$\frac{K}{\Omega}\,\rho\,\frac{\partial u}{\partial t} + R_S\, u = -\frac{\partial p}{\partial x}$$

The authors do not know of any direct way to measure the shape factor K. It is indirectly determined from the absorption curve measured for a single layer of material, as will be indicated later.

Relations Between Physical Parameters

Each physical parameter has been introduced to take into account given physical phenomena:

- Relative air volume ($0 < \Omega < 1$),
- Flow resistance to motion (R_S), and
- Inertial modifications ($K > 1$).

As will be seen, each parameter has a specific effect on the absorption coefficient. This does not mean that these parameters are otherwise independent of each other.

The following relation, for instance, is proposed for aggregate media (*15*):

$$R_S = A\,\frac{\tau}{\Omega^3 d^2}$$

where τ is tortuosity and d is the particle diameter.

Tortuosity quantifies the average developed length (l_d) of a flow path between the two faces of a sample, with respect to the actual distance (l_m) between two faces: $r = l_d/l_m \geq 1$.

Acoustic Absorption of Porous Asphalt

General observations can be made for the case of single layers only.

The porous asphalt is laid on an impervious surface whose acoustic impedance is practically infinite. The surface impedance of the layer is obtained from Equation 2 by solving $Z_T = \infty$. One obtains

$$Z = W \coth \gamma e \qquad (8)$$

where W and γ are given by Equations 3 and 4.

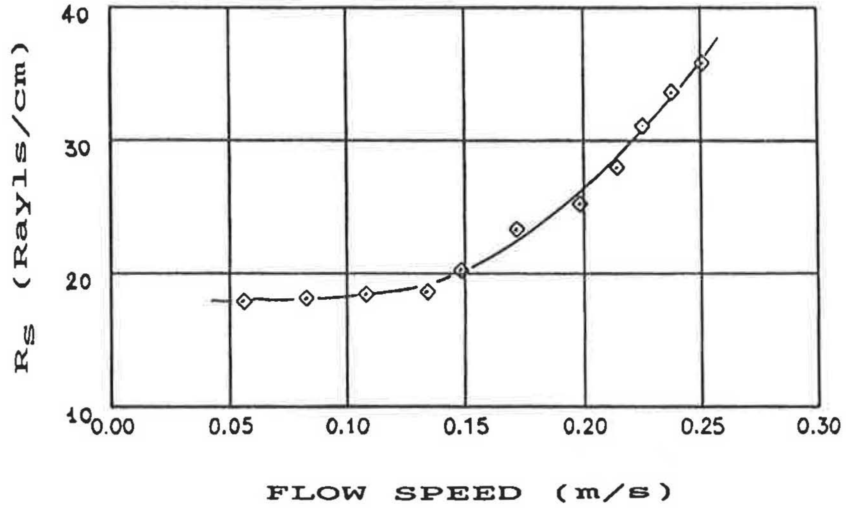


FIGURE 1 Measured R_S (rayls/cm) as function of u_c (m/sec).

If one defines a critical frequency,

$$f_c = \frac{1}{2\pi} \frac{R_S}{\rho} \frac{\Omega}{K}$$

These relations can be written

$$W = \rho c \frac{\sqrt{K}}{\Omega} \left(1 - i\frac{f_c}{f}\right)^{1/2} \tag{9}$$

$$\gamma = i\frac{\omega}{c}\sqrt{K}\left(1 - i\frac{f_c}{f}\right)^{1/2} \tag{10}$$

For example, for porous asphalt with $R_S = 20$ rayls/cm, $\Omega = 0.20$, and $K = 3.5$ (which are usual values), one gets $f_c = 150$ Hz.

In the domain $f >> f_c$ the following approximations can be made:

$$W = R + iX \qquad \frac{R}{\rho c} \approx \frac{\sqrt{K}}{\Omega} \qquad \frac{X}{\rho c} \approx -\frac{1}{2}\frac{1}{\sqrt{K}}\frac{R_S}{\omega\rho} \tag{11}$$

$$\gamma = \alpha + i\beta \qquad \alpha \approx \frac{1}{2}\frac{\Omega}{\sqrt{K}}\frac{R_S}{\rho c} \qquad \beta \approx \frac{\omega}{c}\sqrt{K} \tag{12}$$

These approximations will often be used in the analysis. The absorption curves, however, will always be calculated using the exact formulations (Equations 3 and 4).

Influence of the Total Airflow Resistance $R_T = R_S e$

One can show (*6*) that the absorption coefficient dependence is of the form

$$a_0 \equiv a_0\left(K, \Omega, \frac{R_T}{\rho c}, \frac{f}{f_c}\right)$$

If R_S and e vary in such a way that $R_T = R_S \cdot e$ = constant, there will be

- No modification of the curves' shape, and
- A simple frequency translation (in logarithmic scale) of the curves.

An illustration is given in Figure 2 for a layer with R_T = 200 rayls.

REMARK. A rayl cgs = 10 rayls mks. For example, ρc = 41.5 rayls cgs = 415 rayls mks.

These curves are typical: the absorption coefficient starts from low values at low frequencies, then increases steadily to a maximum value, and oscillates afterwards as frequency increases.

In the $f >> f_c$ domain the maximum value is given by

$$a_{0\ \max} = 1 - \left(\frac{D-1}{D+1}\right)^2 \qquad \text{with}$$

$$D = \frac{\sqrt{K}}{\Omega}\tanh\left(\frac{\Omega}{\sqrt{K}}\frac{R_T}{2\rho c}\right) \tag{13}$$

For most of the materials tested, the Ω and K-values observed were such that $\Omega/\sqrt{K} < 0.2$. In consequence, the $a_{0\ \max}$ value reaches unity if $R_T \approx 2\ \rho c = 83$ rayls and $a_{0\ \max} > 0.95$ if $0.7 < R_T/2\rho c < 1.4$, that is, $58 < R_S \cdot e < 116$ rayls cgs. About $a_{0\ \max} = 1$, the maximum value of absorption is not very sensitive to R_T variation.

For very low R_T, *the maximum value of absorption is low. It increases with* R_T *and reaches unity for* $R_T \approx 2\ \rho c = 83$ *rayls cgs. For higher values of* R_T *it diminishes and tends to the asymptotic value*

$$a_{0\ \text{asympt}} = 1 - \left(\frac{\sqrt{K}/\Omega - 1}{\sqrt{K}/\Omega + 1}\right)^2 \tag{14}$$

Single Layers with Low Thickness

The oscillations of the absorption coefficient with frequency come from the coth (γe) term in Equation 8. For a high enough thickness, this term tends to unity and $Z \approx W$. Thus it is possible to say that the "superthickness" condition has been reached. This case will be treated later. First thicknesses such that coth γe is not close to unity are considered. The absorption curve presents oscillations.

Influence of Specific Airflow Resistance R_S From the earlier analysis, R_S influences the shape of the curve. In the domain $R_S\, e/2\rho c < 1$, an increase of R_S will increase the $a_{0\ \max}$ value, which will reach unity when $R_S \approx 2\ \rho c/e$ and then, as R_S increases, will decrease to reach ultimately the asymptotic value (Equation 14). An illustration is given in Figure 3.

The three curves correspond to R_T = 200, 400, and 600 rayls, respectively, that is, to $R_T > 2\ \rho c = 83$ rayls. The increase of R_S tends to decrease the $a_{0\ \max}$ values and increase the minimum values: the curves have a tendency to "flatten."

Relating to R_S influence, one notes that the frequencies at which the maxima of absorption occur are not modified by R_S. This is typical: later it can be seen that these frequencies depend only on K and e.

Influence of Porosity Ω From Equation 13 (high-frequency approximation) and taking into account that, for most of the materials tested, it was found that $\Omega/\sqrt{K} < 0.2$, one sees that

- For not too high values of $R_T/2\rho c$, the porosity has almost no influence on the maximum values of absorption, and
- The Ω influence on maximum values becomes important for very large $R_T/2\rho c$ (cf. Equation 14).

Large $R_T/2\rho c$ usually means large thicknesses. This case will be considered in the "superthickness" case. For usual cases, the situation is as shown in Figure 4.

The increase of porosity from 0.1 to 0.3 widens the curves in the vicinity of the maximum values, and increases the

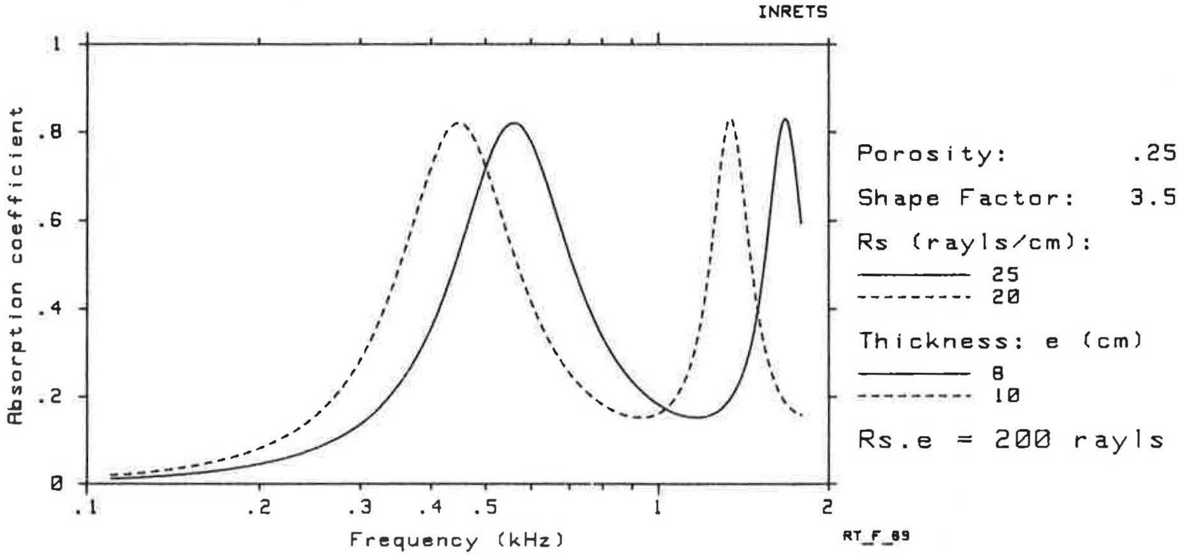


FIGURE 2 Influence of R_S and e on absorption with $R_T = R_S e = 200$ rayls.

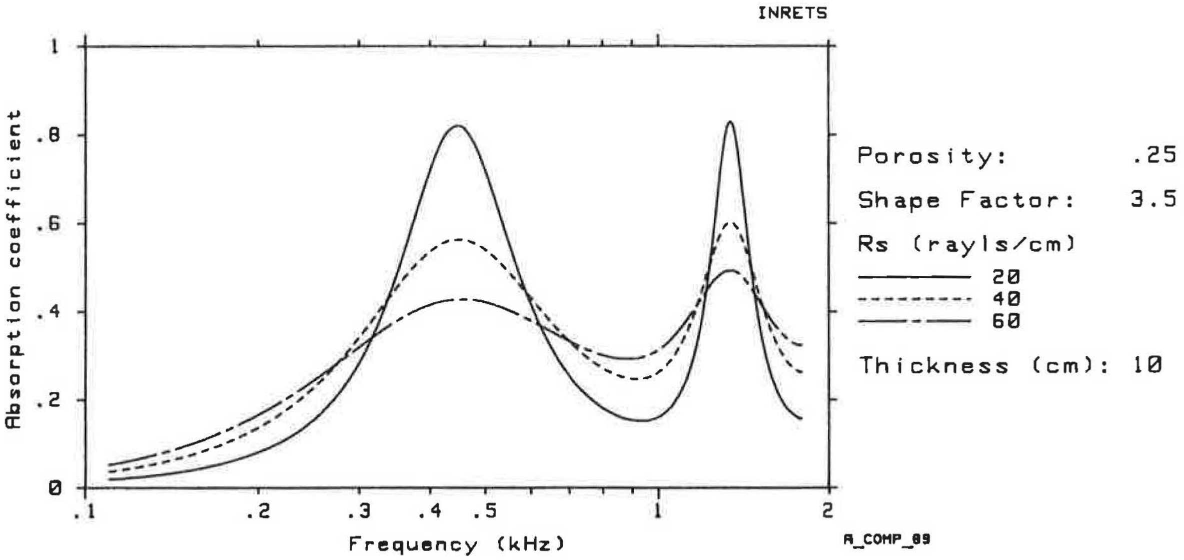


FIGURE 3 Influence of R_S on absorption coefficient.

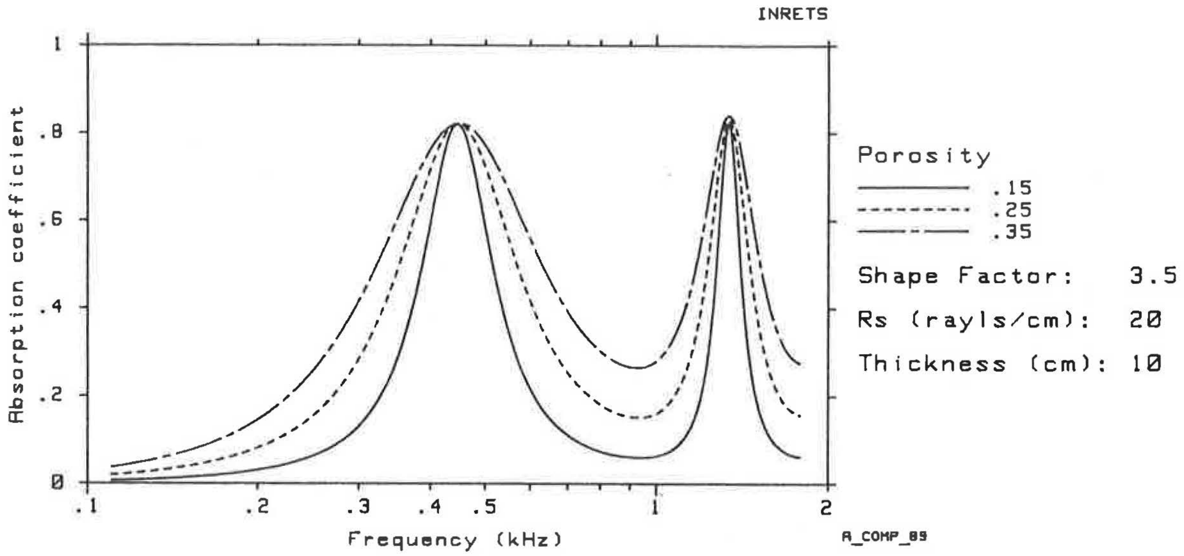


FIGURE 4 Influence of porosity on absorption with $R_T/2\rho c \approx 2.4$, that is, not too large.

minimum values. It has almost no effect on the maximum values and no effect on the frequencies at which these values occur.

A high porosity favors a high absorption between the maximum values.

Influence of the Shape Factor *K* With the high high-frequency approximations (Equations 11 and 12), one finds (*6*) that the maximum values of absorption occur at frequencies such that

$$f_{2n+1} = (2n + 1)\frac{c/\sqrt{K}}{4e} \qquad n = 0, 1, 2, \ldots \tag{15}$$

frequencies that depend only on the shape factor *K* and on the thickness *e*. This result is used to determine *K* (compare Figure 5).

$$K = \left[\frac{2n + 1}{4}\frac{c}{ef_{n+1}}\right]^2 \qquad n = 0, 1, 2, \ldots \tag{16}$$

Experimental observations show that the estimated *K*

- Does not depend on the value of *n*, and
- Does not depend, for a given material, on the thickness of the layer. This implies that the layers are homogeneous (the characteristics are independent of the thickness).

Concerning the influence of *K* on the absorption curves, it can be said that (see Figure 6)

- A variation in *K* modifies the frequency positions of the absorption peaks (Equation 19),
- *K* has almost no influence on the value of the peaks [for not too high values of $R_T/2\ \rho c$ (Equation 13)], and
- An increase in *K* narrows the width of the curves in the vicinity of the maximums of absorption and decreases the minimum values of absorption (effect opposite to the Ω influence, Equation 13).

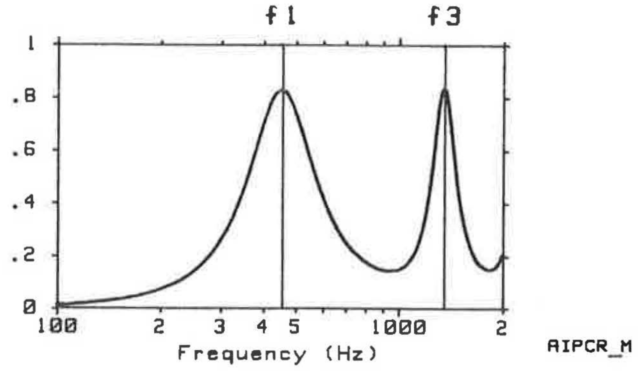


FIGURE 5 Maximum values of absorption occur at frequencies f_1 and f_3.

Influence of Thickness *e* Thickness has an effect on

- The shape of the absorption curve, and
- The frequencies at which the maxima occur—increasing the thickness lowers these frequencies (Equation 15).

As for the R_S case, an increase of *e* will increase the $a_{0\max}$ values (as long as $R_Se < 2\rho c = 83$ rayls) until unity (when $R_Se = 83$ rayls). As *e* still increases, $a_{0\max}$ will decrease to the asymptotic value (Equation 14). An illustration is given in Figure 7.

Superthickness (7)

When the thickness becomes large enough, coth $(\gamma e) \rightarrow 1$ and $Z \rightarrow W$. The absorption no longer depends on thickness. This is called the superthickness condition. Increasing *e* further will have no effect on the absorption coefficient given by

$$a_0 = 1 - \left|\frac{W/\rho c - 1}{W/\rho c + 1}\right|^2 \tag{17}$$

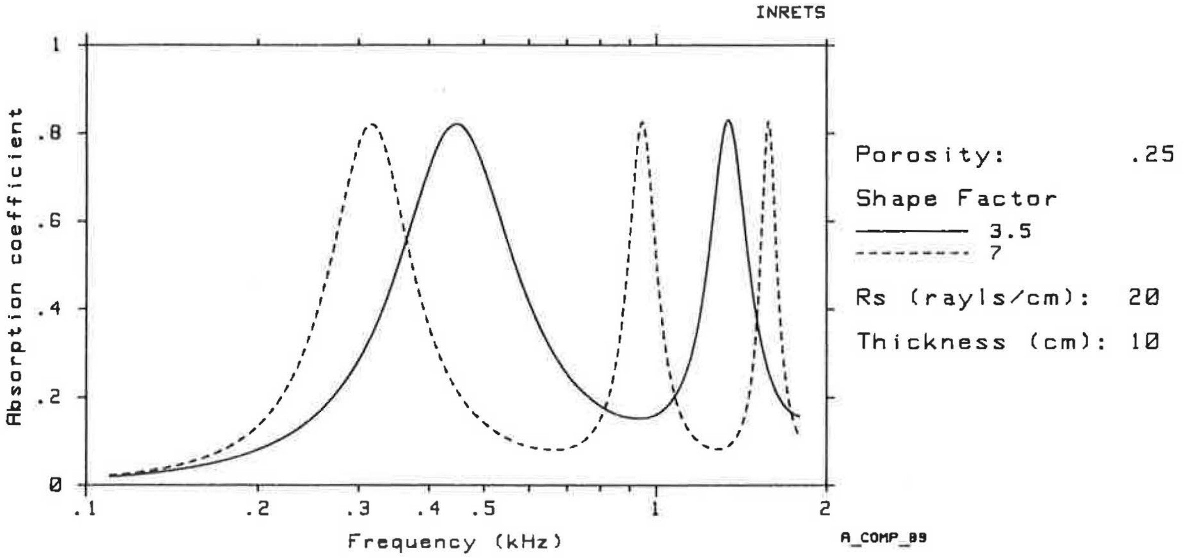


FIGURE 6 Influence of the shape factor on absorption.

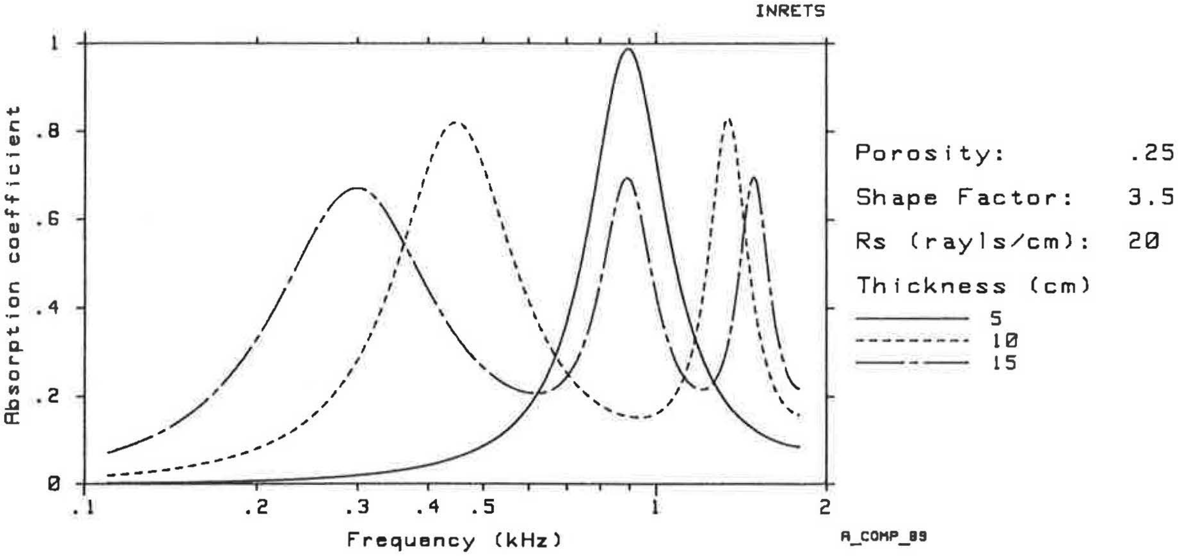


FIGURE 7 Influence of thickness on absorption.

which, using the high-frequency approximations (Equation 11) can be written

$$a_0 = 1 - \frac{\left(\frac{\sqrt{K}}{\Omega} - 1\right)^2 + \frac{1}{4K}\left(\frac{R_S}{\omega\rho}\right)^2}{\left(\frac{\sqrt{K}}{\Omega} + 1\right)^2 + \frac{1}{4K}\left(\frac{R_S}{\omega\rho}\right)^2}$$

The absorption increases monotonically with frequency (no oscillations) up to an asymptotic value $a_{0\,\text{asympt}}$, which happens to correspond to Equation 14. $a_{0\,\text{asympt}}$ does not depend on R_S. But, in terms of frequency, it will be reached "earlier" (i.e. at lower frequencies) if R_S is lower. (See Figure 8.) The curve corresponding to Equation 14 is given below (Figure 9). For a high absorption, one needs high Ω and low K. (Remember that $O < \Omega < 1$, $K > 1$.)

When is the superthickness condition reached? The condition $\coth(\gamma e) = \coth[(\alpha + i\beta)\, e] \rightarrow 1$ implies αe large enough. If not, the absorption curve will oscillate around the limit curve of Equation 17. The larger the αe, the smaller the amplitude of the oscillations. If the superthickness condition is practically said to be reached when the oscillation amplitudes become lower than 0.05 (the absorption coefficient does not differ by more than 0.05 from the limit values of Equation 17), this implies (7) that

$$\frac{R_S e}{\rho c}\frac{\Omega}{\sqrt{K}} \geq 3 \quad \text{super-thickness condition} \qquad (18)$$

The thickness to be reached depends on the medium: if R_S is high, it can be a few centimeters. (See Figure 14.)

For a porous medium where $\Omega = 0.25$, $K = 3.5$, and $R_S = 20$ rayls/cm, one needs $e \gtrsim 47$ cm (Figure 10).

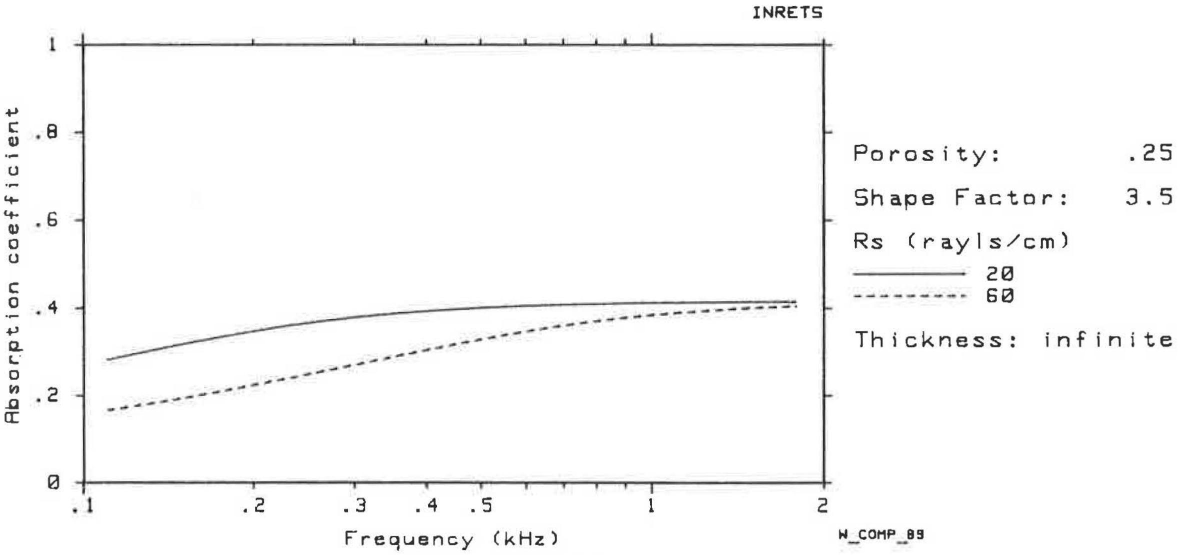


FIGURE 8 Influence of R_S on absorption for an infinite thickness.

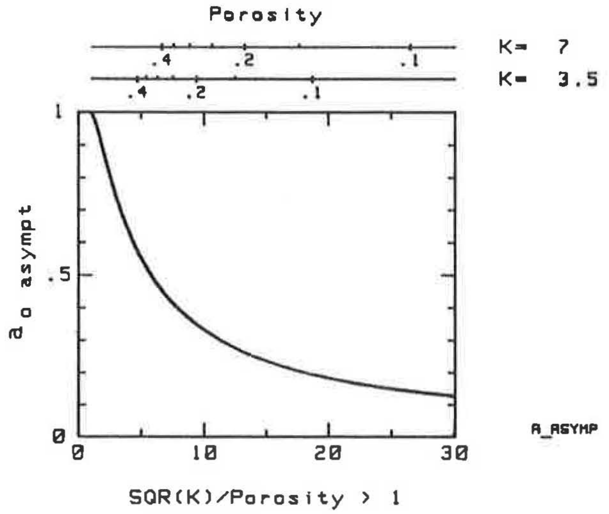


FIGURE 9 Asymptotic value of absorption (Equation 14).

Practically, for thickness

$$e \geq 3 \frac{\rho c}{R_S} \frac{\sqrt{K}}{\Omega} \tag{19}$$

- The absorption curve presents small oscillations, and
- Increasing the thickness will bring no practical improvement in the absorption.

EXPERIMENTAL VERIFICATION OF THEORETICAL MODEL

Experiments have been performed in the laboratory on single and multilayer samples (10-cm diameter) and outdoors on circular road tracks. Measurements on samples were essential to qualify the influence of the different physical parameters and study the effect of factors such as the number of layers, the humidity, the grading, and the binder. In situ measurements were taken afterwards, in order to verify the agreement between the laboratory results and those obtained on actual porous pavements.

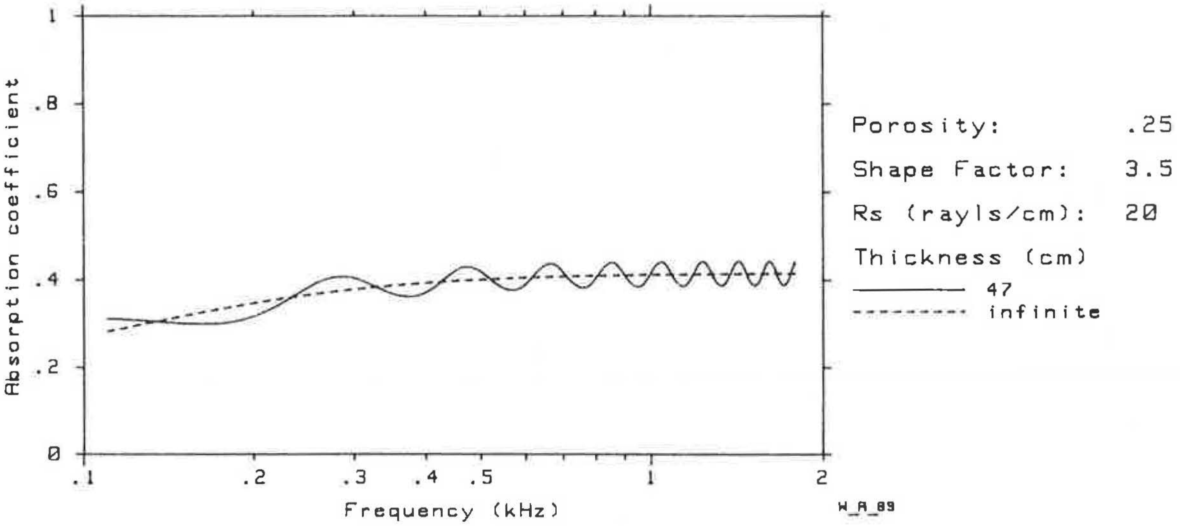


FIGURE 10 "Superthick" layer (47 cm) compared with an infinitely thick layer; absorption coefficient.

Influence of Physical and Intrinsic Parameters of Porous Asphalt Samples on Variation of Absorption Coefficient

The absorption coefficient measurement was carried out on laboratory samples by using the Kundt tube technique. The absorption coefficient is obtained from the maximum and the minimum sound pressure level values of the standing waves in the duct. In order to ensure as accurate measurements as possible, special care must be taken in positioning the sample at the duct end. Maximum and minimum sound pressure values must be precisely read.

As indicated earlier, the amplitude of the absorption peaks depends on the total airflow resistance $R_T = R_S \cdot e$ and is near unity for $R_T \approx 2\rho c = 83$ rayls cgs. In Figure 11, measurements are plotted with respect to frequency for two samples with $R_T = 93$ and 300 rayls cgs, respectively.

Reasonable agreement is found with theoretical curves. A small discrepancy at the higher frequencies may probably be attributed to the difference in the arrangement of the aggregates between the modeled structure and the experimental sample.

Observation of porosity influence could not be made; samples with $\Omega = 0.25$ and $\Omega = 0.35$, for instance, did not present the same shape factor ($K = 3.9$ and $K = 5.7$, respectively). The effect from the increase of Ω was partly "destroyed" by the corresponding increase of K.

The shape factor K directly influences the frequency positions of the absorption peaks. It depends on the sample composition (aggregate size and binder). In the experiments, the range of values was from 2.5 to 9. Figure 12 illustrates this phenomenon.

As shown in Figure 13, thickness has two effects:

- Modification of the frequencies of the absorption peaks: when e is doubled, the frequencies are shifted down by one octave (Equation 15), and
- Modification of the amplitude of the peaks: in the domain $R_T > 2\rho c = 83$ rayls, increasing the thickness diminishes the peak amplitude (minimum values of absorption are simultaneously increased).

When the thickness becomes large enough (superthickness condition, Equation 19), the result is a smooth curve increasing with frequency up to an asymptotic value (Equation 14). Such a phenomenon is observed in Figure 14 for a 15-cm-thick 0/2 porous sand asphalt sample (27 percent porosity) for which

$$\frac{R_S e}{\rho c}\,\frac{\Omega}{\sqrt{K}} = 30 >> 3$$

The superthickness condition is satisfied. (N.B.: The porosity comes from the absence of filler.)

The asymptotic value $a_{0\ \mathrm{asympt}} = 0.54$ (from Equation 14) is not reached at 2,000 Hz because of the high value of R_S. (See Figure 8.)

For the tested formulations, double layers did not show crucial differences when compared with single layers (same overall thickness in both cases). Figure 15 shows the comparison of a single layer (0/10) and a double layer (0/10, 0/40) with an overall thickness of 16.5 cm in both cases. The expected difference (from theory) is higher than what is measured.

For layers with smaller grading difference [for instance, (0/10, 0.14) or (0/10, 0.20)], no experimental difference between single and double layers is observed. (See Figure 16.)

The humidity, grading, and binder content influence the a_0-curve mainly through the variation of the shape factor and partially through the variation of R_S and Ω, which are directly connected to the intrinsic characteristics of the internal structure.

In the presence of humidity, each parameter is affected differently. The global result is a drop in absorption and a

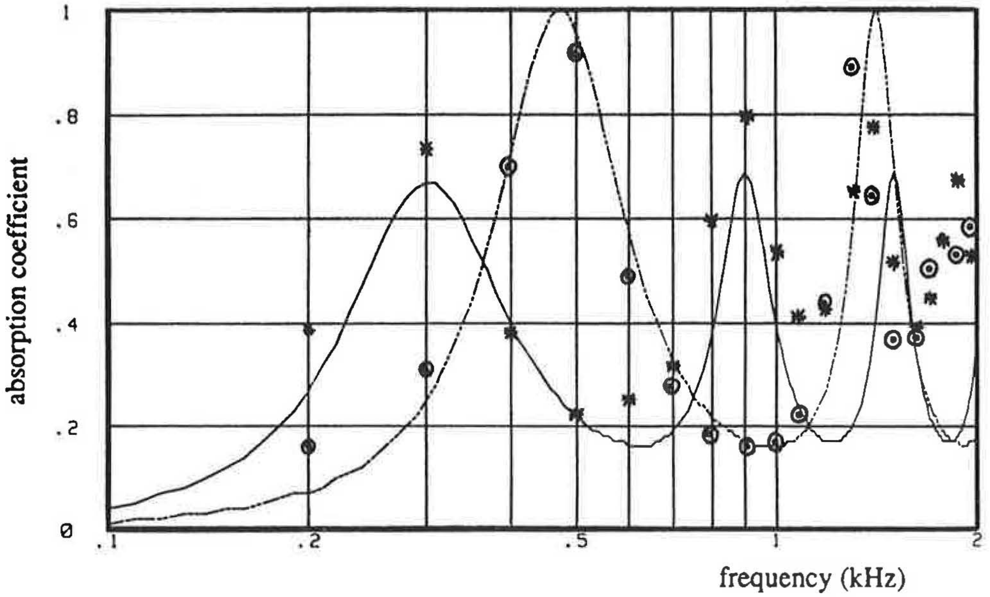


FIGURE 11 Influence of airflow resistance $R_T = R_s \cdot e$. ⊙ -----, R_S = 8 rayls/cm, e = 11.6 cm, R_T = 93 rayls. * ___, R_S = 20 rayls/cm, e = 16.5 cm, R_T = 330 rayls. Ω = 0.25, K = 3. (When not specified otherwise, ⊙ and * are actual measurements and the dashed and solid lines are theoretical values.)

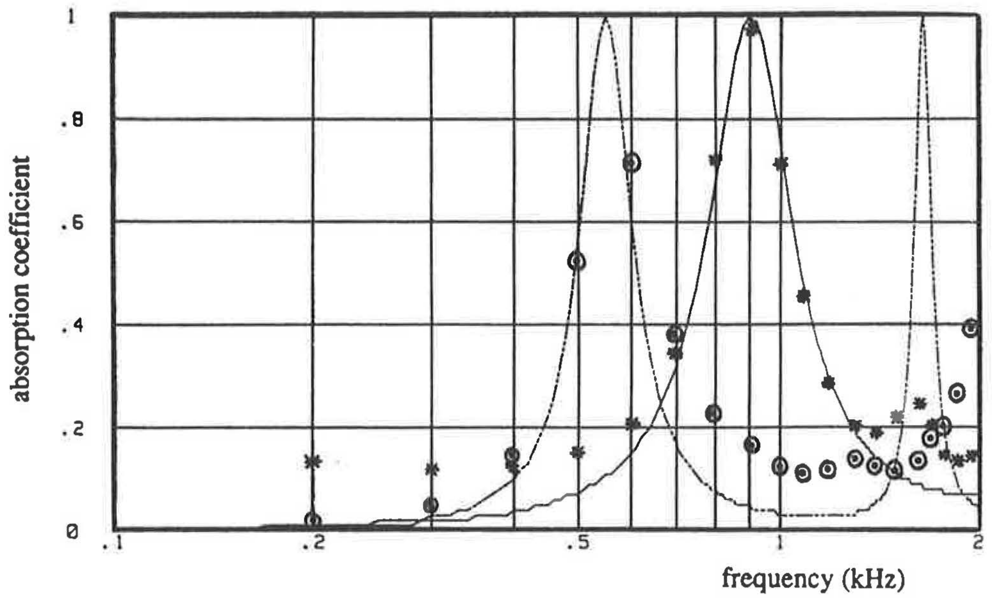


FIGURE 12 **Influence of the shape factor K. * ___, $K = 3.5$; ⊙ -----, $K = 9$. $R_S = 20$ rayls/cm, $e = 5$ cm, $\Omega = 0.25$.**

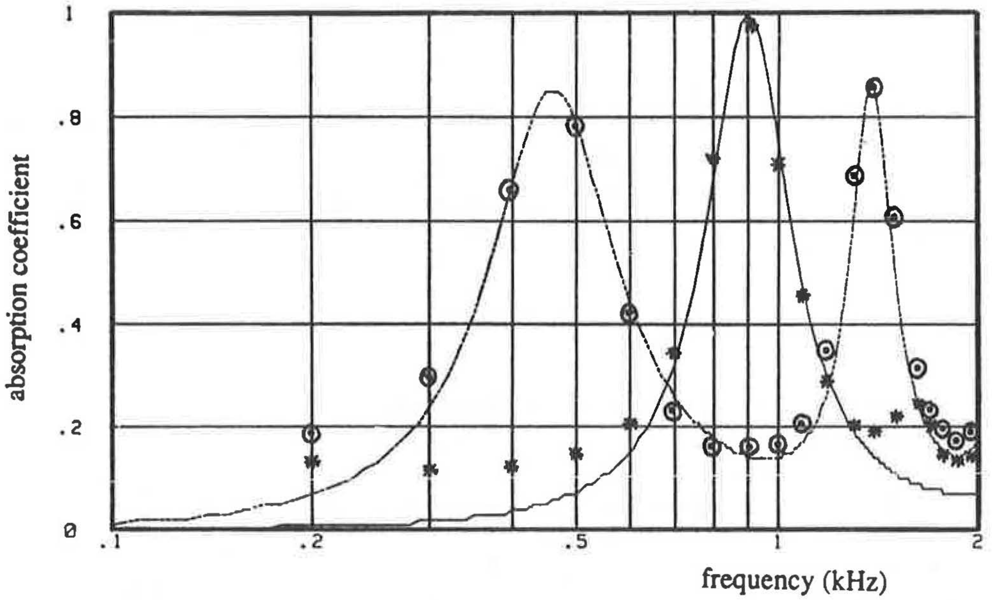


FIGURE 13 **Influence of thickness. * ___, $e = 5$ cm; ⊙ -----, $e = 10$ cm. $R_S = 10$ rayls/cm, $\Omega = 0.25$, $K = 3.5$.**

shift of the peaks as shown in Figure 17. This fact must be taken into account, if it is considered that the pavements are not always completely dry.

For the experiments (Figure 17), measurements were first performed on a dry sample. The wet condition was achieved by immersing the sample in water, shaking it manually, and letting it dry naturally for one day.

As expected, the discontinuities in the grading do not seem to affect the absorption much. For a fixed grading (0/14), three different discontinuities were tested (2/4, 2/6, 2/10). The shape factor values were practically not affected (the measured relative variation was lower than 5 percent).

The modification in the binder content probably affects the direction and the section of the connections between the pores, which automatically changes the shape-factor value. This effect was already shown in Figure 12.

Outdoor Measurements

In order to qualify new porous asphalt roads, an important set of measurements was made. The aim of such a work was to test the reliability of the theoretical model for a large portion of the road (about 3 m^2) and the representativeness of the small-sample measurement results (from a standing wave tube) to evaluate the global absorption coefficient of a road surface.

The measuring procedure used outdoors is based on an impulse technique (*16*): a_0 is evaluated from the transfer func-

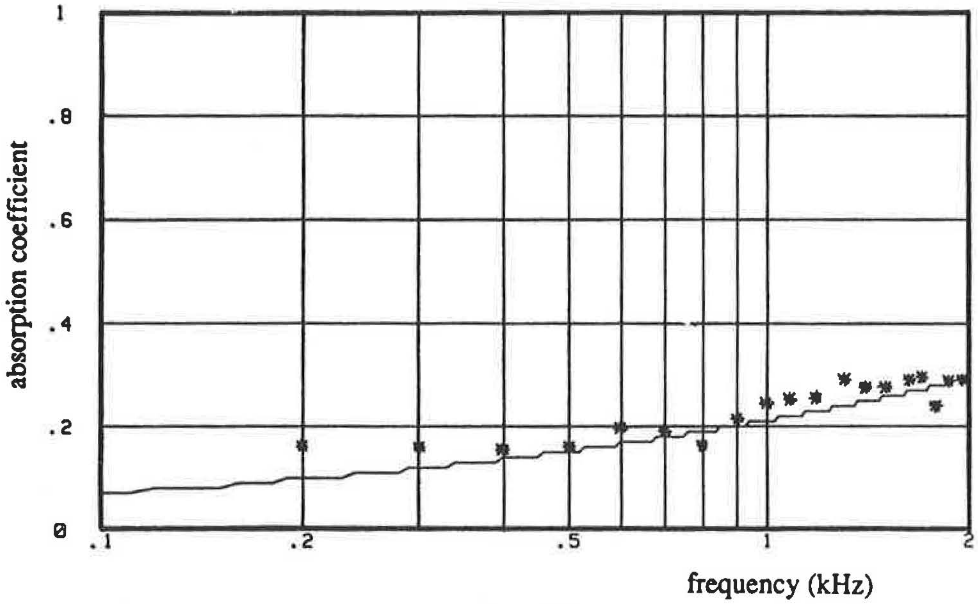


FIGURE 14 Superthickness effect. $e = 15$ **cm,** $R_S = 440$ **rayls/cm,** $\Omega = 0.27$**,** $K = 2$**.**

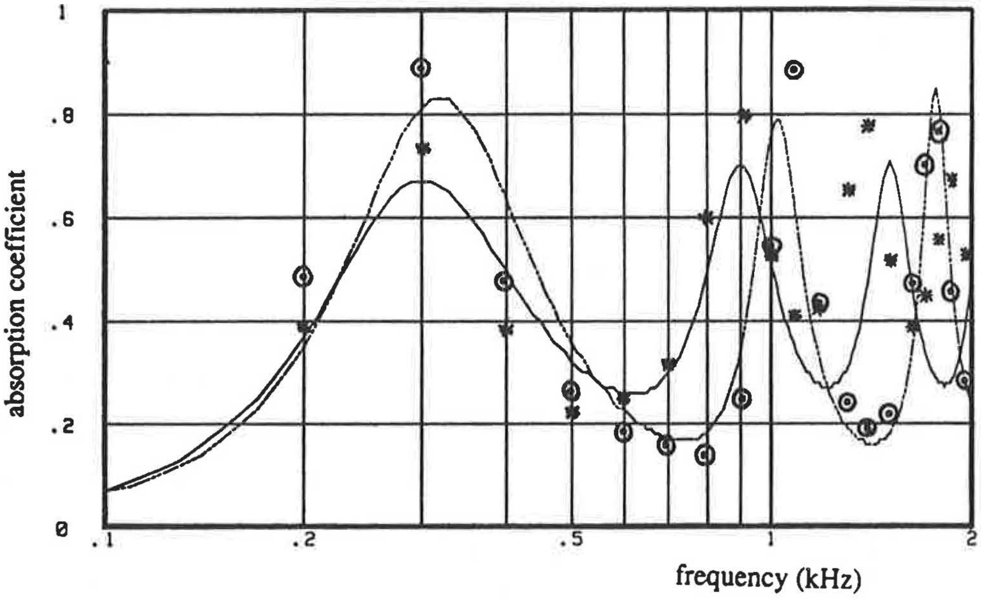


FIGURE 15 Double layer compared with single layer. * ___, single layer [1/10]; ⊙ -----, double layer [0/10, 0/40]. Same overall thickness: 16.5 cm.

tion, in normal incidence, between a direct and a reflected transient signal generated by an 8-mm alarm pistol. The results obtained by this technique compare well with those obtained with the standing wave duct on cores from the road (Figure 18).

However, one problem connected with the thickness of the wearing course must be pointed out. In road construction, the unevenness of the road base is taken care of by the porous asphalt (wearing course) spreading operation: the upper surface is made even. In the case of think layers, this means that for a 4-cm-thick layer, for instance, one can obtain 2.5 cm in one area and 4.5 cm at another. This discrepancy is not very important if acoustic measurements are made on a 3-m² area, but it can cause large differences on 10-cm-diameter samples (a large $\Delta e/e$ yields large differences in the absorption peak positions; see Equation 15). Such phenomena were noticed during the experiments on some of the 18 different porous surfacings on the French A63 Motorway (Bordeaux-Bayonne) and on some of the 12 tracks of the RN 76 (Bourges-Vierzon).

For thicker porous structures (>20 cm), this problem is avoided: on the one hand, owing to the low relative thickness difference (< 10 percent) and, on the other, because of the modification of the absorption curve. Such structures can be used to temporarily store rainwater. An example exists in the Loire Atlantique department in France, in the city of Rezé, where a complete porous structure 61 cm thick (35 cm of 10/80 crushed stone, 20 cm of 0/20 aggregate mixture with hard bitumen, and 6 cm of 0/14 porous asphalt). Figure 19

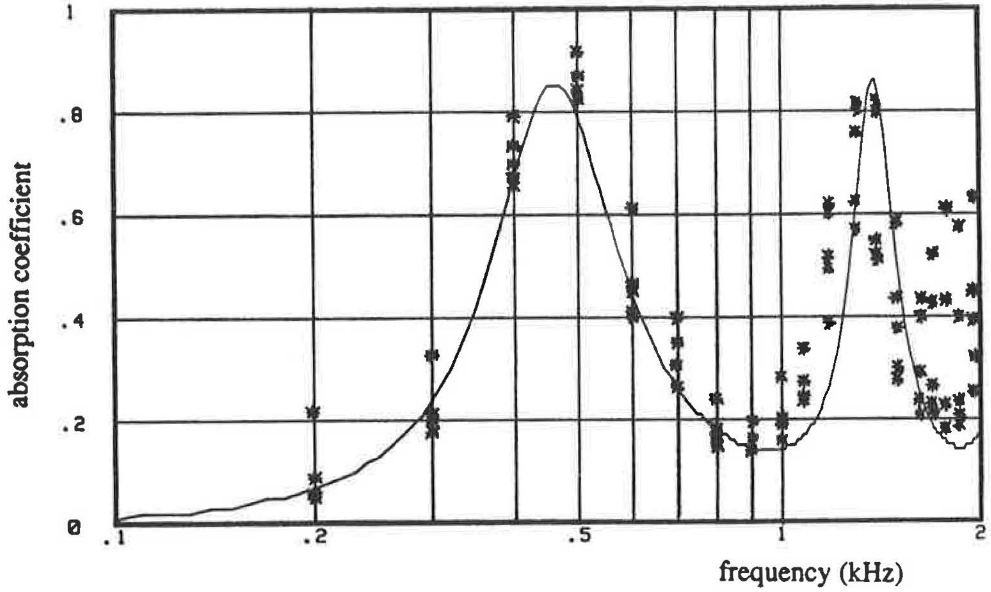


FIGURE 16 Double layer compared with single layer; *, double layer [0/10, 0/14] and [0/10, 0/20] measurements, ___, single layer [0/14], R_S = 20 rayls/cm, Ω = 0.25, K = 3.5. Same overall thickness: 10 cm.

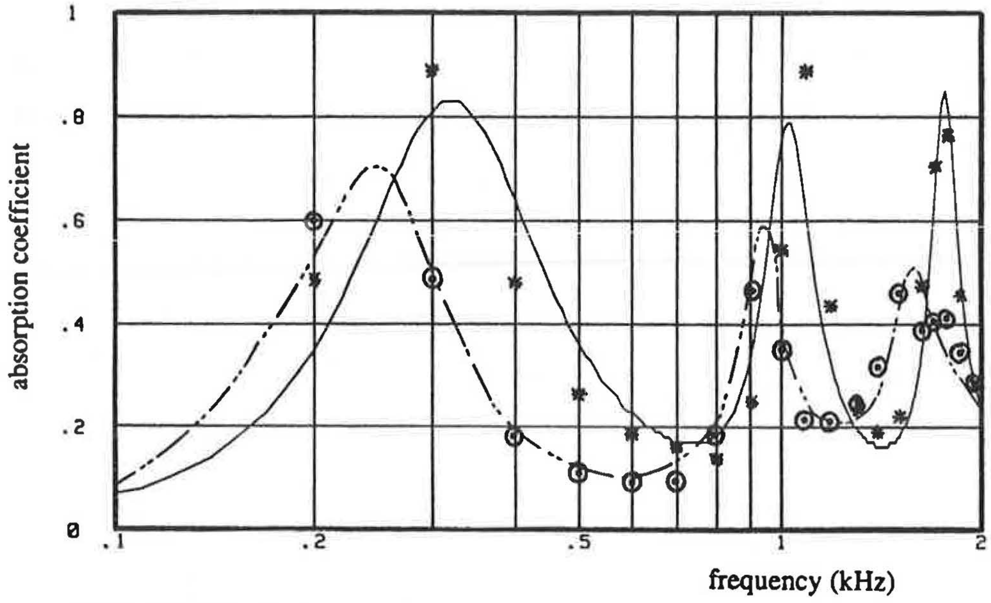


FIGURE 17 Humidity effect; -----, wet; ——, dry.

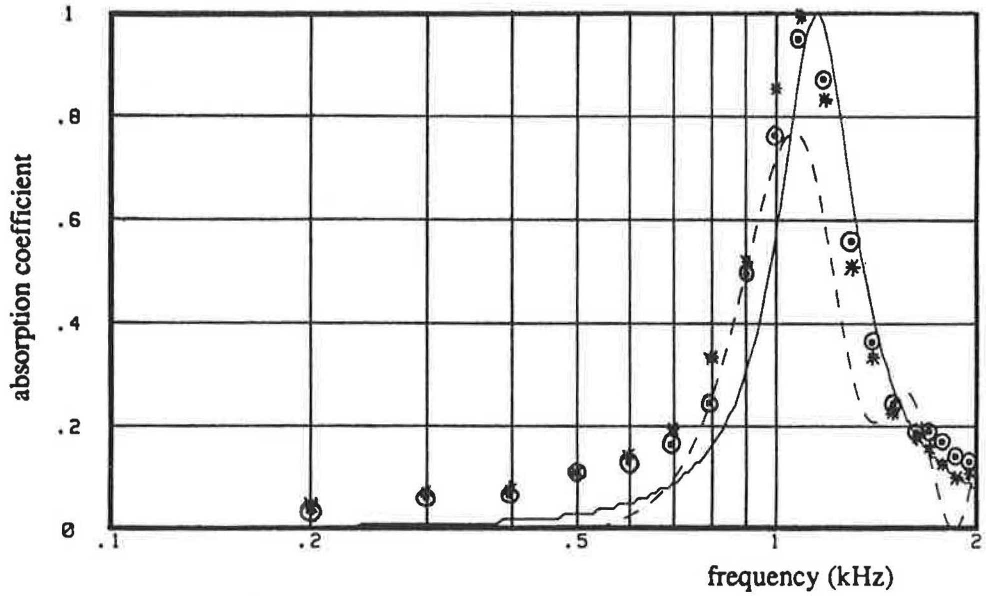


FIGURE 18 Absorption of some RN 76 wearing course. x, ⊙: standing wave results; -----: impulse technique; ——: theory.

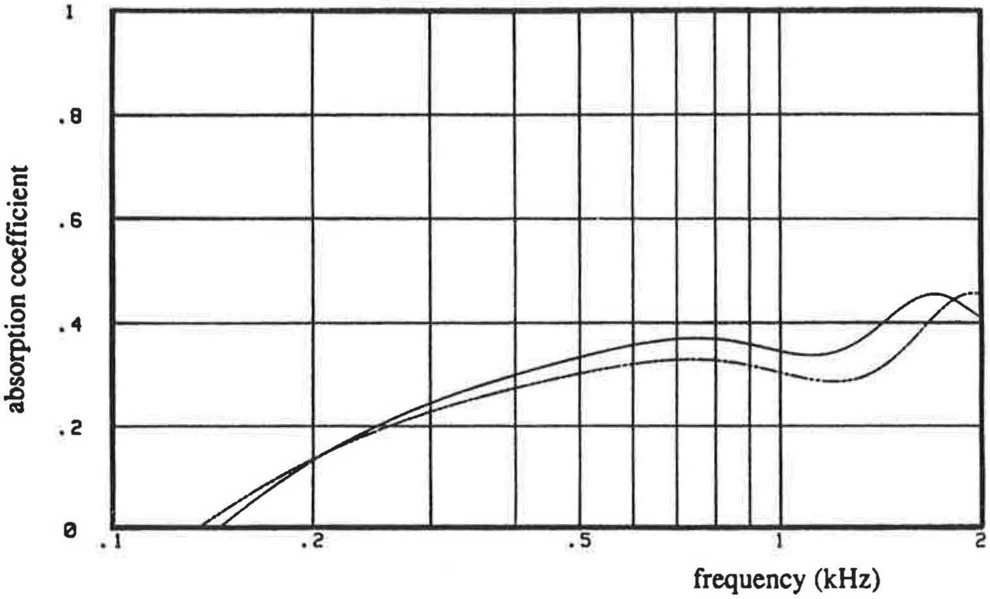


FIGURE 19 Absorption of a 61-cm-thick structure; measurements performed at two different locations in situ (Rezé, France).

presents the absorption coefficient measured at two locations using the impulse technique. This result is in good agreement with predicted and laboratory values.

Another experimental thick porous structure is in progress near Lyon. Theoretical investigations have been performed on the constitution of these porous structures in order to improve the acoustical properties.

The studies presented here deal with identification of the absorptive properties of porous asphalts and improvement of the composition. Knowledge of these characteristics is important for engineers, but it is obvious that qualification of the environmental impact on the neighborhood is also essential. This is the purpose of the next section.

ENVIRONMENTAL IMPACT OF A POROUS ASPHALT

Porous asphalts are becoming known as noise-reducing pavements. In fact, this quality results not only from their absorptive capacity, but also from the modification of the rolling noise source.

Basically (*17*), the acoustic emission is generated by a (tire) vibrating field and an air resonance process. The first is predominant in the low and medium frequencies (100 to 1200 Hz), and the other produces the main part of the energy in the high part of the spectrum.

On a concrete pavement or on a regular dense bituminous asphalt, the vibrations come from tire strains during rolling, the impact of the tire treads on the road, and the slip-and-stick effect. The air resonance is mainly generated by air pumping. Because of their porosity, porous asphalts behave differently. On the one hand, the vibrations transmitted to the tire are less important owing to a lower surface texture (and consequently a lower indenting of the aggregates in the tire surface), which can induce adhesion problems at low speeds, and a reduction of the slip-stick phenomenon. On the other hand, air pumping is widely reduced.

All these factors affect tire noise generation and are the main reason for the noise reduction. The other reason is the absorption of the structure itself. The excess attenuation is caused by the absence of multireflections between the tire and the road (horn effect) (*18*) and between the body of the vehicle and the road. If one takes into account both phenomena (low rolling noise and absorption effect), one measures, following ISO R 362 (coast-by method), for a single vehicle, a noise level that is approximately 2 or 3 dB(A) below the noise level found for a dense bituminous asphalt. This is a mean value obtained from about 20 measurements on thin-layer surfaces. When the porous structure is thick (around the superthickness condition), the absorption is almost constant on the whole frequency range ($\alpha \sim 0.4$ to 0.5) (Figure 19), which yields better excess attenuation. In this particular case, the global attenuation reaches 5 to 6 dB(A) (*19*).

To take into account a more realistic traffic flow, two vehicles (with engine on) and three types of tires are used. The noise level at 90 km/hr is estimated by linear regression on the maximum sound pressure level values ($L_{p\ \max}$) for several (constant) speeds between 70 and 110 km/hr. This method was first tested in a French-German twin cooperation framework (tests done in 1986 near Strasbourg, France, with 15 vehicle-tire configurations on five different experimental tracks (*20*)). Round robin tests are performed on real roads.

Porous Asphalt in an Urban Area

One application of such noise-reducing pavement is in urban areas, particularly on the streets with buildings on each side. In this case, there is an important number of reflected paths. According to the acoustic condition in a diffuse field (*21*), one can expect that an absorbing pavement can "trap" partially or completely, depending on the thickness of the structure, the acoustic energy after a few reflections.

Some calculations of the acoustic field in a canyon street with an absorbing pavement, using a finite-element technique with a complex acoustic source (one spherical source for the radiation of each tire and one for the engine) show that the acoustic level in front of the facades relative to the level in the same street with a nonabsorbing pavement (dense bituminous asphalt, for example) is inferior by several decibels: 1 to 6, depending on the thickness of the absorbing layer.

The physical theory is similar to the one used in room acoustics. In this case, the lower surface is covered with an absorbing material (porous asphalt), and the top surface has an impedance = ρc. The facade surfaces are perfectly reflective.

One experiment has already been conducted in Paris (*22*); two others are in progress in Paris and Nantes on different types of road systems with different traffic volumes. For each case, an adequate thickness is investigated. Acoustic measurements must be performed day and night before and after construction in order to evaluate the gain on a real traffic flow. In parallel with those measurements, inquiries are being made among the neighbor population as to the subjective impact. Inquiries are focused not only on the acoustical aspect, but also on other factors such as water spray, aquaplaning, comfort, and so forth.

The first results will be published in 1990.

Evolution of Noise Level Versus Pavement Aging

In the first 6 months after spreading, the porous asphalt evolves quickly, producing a modification in the mechanical properties of the structure and also in the rolling noise level. With the single car coast-by method (80 km/hr, tires under 5,000 km wear), the difference between two sets of measurements (the second set is made 6 months later) can approximately reach ± 2 dB; these observations were made on the 18 surfacings of the French A 63 motorway (Bordeaux-Bayonne) (See Figure 20). After 1 year under traffic, the evolution of the acoustic level is less important (within 1 dB). Nevertheless, it is necessary to pay attention to the clogging, which can transform an open pavement into a dense one and in the same way increase the noise level. Our experience on motorways shows that the clogging is not very important in the rolling tracks when the road is continuously trafficked. In this case, there is a self-cleaning of the pores by the tires themselves. In urban areas, not enough information is available, but it seems that clogging is a more worrisome problem than on suburban or country roads.

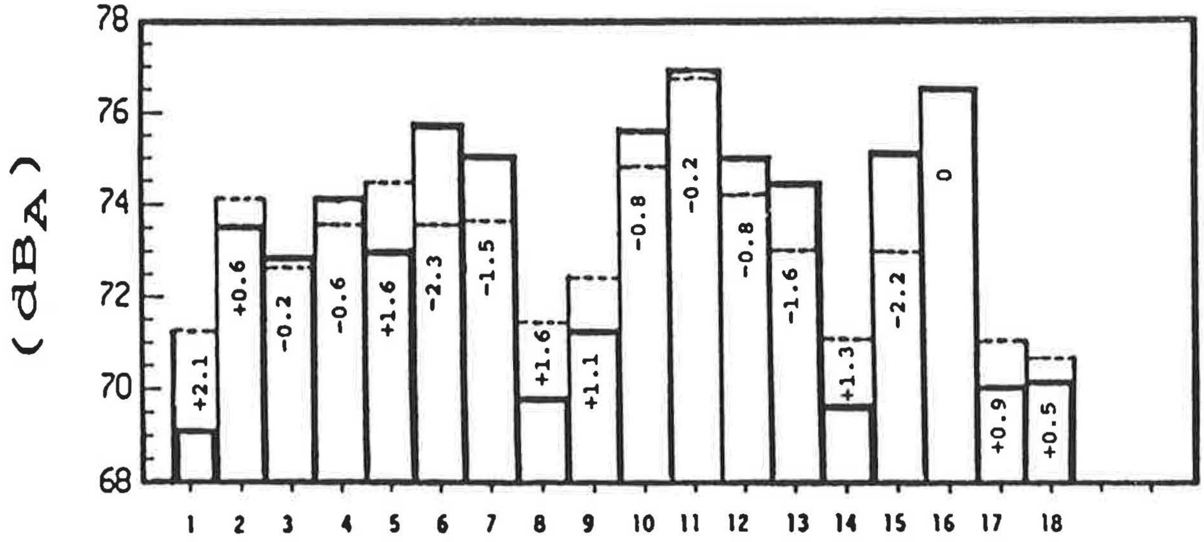


FIGURE 20 Evolution of the acoustic behavior of porous asphalt in the first year measured on 18 surfacings: ——, first set; -----, second set (6 months later).

In any case, it is necessary to follow the acoustic evolution of all the sites on which work was done. More elements should be available in the next 3 or 5 years.

Case of Heavy Vehicles

The results presented in this paper concern light vehicles, the main acoustic source (more than 60 km/hr) for which is rolling noise. This source is very near the surface and, therefore, the noise propagation is largely affected by the presence of the absorbing pavement.

For diesel heavy vehicles, the noise source is differently located. The rolling noise is in fact responsible for a small part of the global acoustic energy (*3*), which is mainly produced by the engine and the mechanical noise (vibrations, gears, brakes, maybe exhaust); that is why it is believed that the influence of an absorbent pavement on heavy vehicle noise is less important. Nevertheless, the absorbing effect on the multi-reflections between the body of the vehicle and the road is still effective. But for how much?

More studies on this topic are in progress; it is hoped that the first results will be available very soon.

CONCLUSION

The calculations and measurements presented in this paper permit the conclusion that a porous asphalt can be realistically modeled by physical parameters: airflow resistivity (R_S), porosity (Ω), shape factor (K), and thickness (e), and, that its environmental impact can be very important. Following the type of road, the vehicle speed, type of vehicle, noise mechanisms, and source location, the porous asphalt pavement can be more or less efficient. At any rate, it seems that the gain is always positive. The excess attenuation is between 1 and 6 dBA.

All the acoustic properties combined with good adhesion in the high-speed domain, good visibility on rainy days, and the elimination of water spray and aquaplaning according to the drainage qualities suggest that porous asphalt will be widely used in the future.

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Acoustical Performance of Pervious Macadam Surfaces for High-Speed Roads

P. M. NELSON AND P. G. ABBOTT

A full-scale performance trial of pervious macadam laid on the A38 Burton bypass has been underway since September 1984. The trial, being carried out by the Materials and Construction Division of the Transport and Road Research Laboratory, will compare the durability and performance of a number of proprietary and nonproprietary materials made with a range of polymer-modified and unmodified bitumens. However, these surfaces are also good sound absorbers, so the opportunity was taken to monitor the noise emitted by vehicles traveling on these surfaces. Reporting results of the acoustical measurements covering the first 4 years of exposure to traffic is the primary concern of this paper. Other aspects of performance are also briefly discussed. The results show that the noise from vehicles running freely on pervious macadam is reduced when compared with equivalent nonporous surfaces by between 5.5 and 4.0 dB(A) on average. This result was not found to be influenced significantly by binder content variations in the range 3.7 to 5.0 percent or by the presence of binder additives. After 4 years of exposure to heavy traffic, the surfaces showed slight deterioration in noise performance, although improvements over conventional surfaces were still averaging 4.0 dB(A). This occurred despite a substantial fall in the hydraulic conductivity and the surface texture depth of the trial surfaces over the same exposure period. Even so, the stabilized surface textures remain high and acceptable for high-speed road applications, and the fall in hydraulic conductivity did not give rise to a concomitant fall in the spray suppression properties of the surfaces.

The Transport and Road Research Laboratory (TRRL) first adapted pervious macadam for road use more than 20 years ago (*1*). Although this surface material successfully reduced spray, it has not been adopted for commercial use mainly because the spray-reducing properties of pervious macadam deteriorate with time. The open nature of the surface also leaves much more of the surface material open to the atmosphere, causing weathering of the bitumen, leading to embrittlement and eventual disintegration. This open structure, however, makes the surfaces good sound absorbers and they have considerable potential for reducing traffic noise. This aspect is the main focus of this paper.

Despite these specific concerns about the durability of the surface, substantial improvements have been made and pervious macadam using a 20 mm stone and 100-pen bitumen has been included in a British Standard (BS 4987) (*2*). This material is expected to have a spray-reducing life of about 6 years under medium traffic (i.e., 2,500 commercial vehicles per day).

To further improve the durability of pervious macadam, a series of performance trials are being conducted by the Materials and Construction Division of TRRL on a heavily trafficked section of dual carriageway near the town of Burton-upon-Trent. The trials are still in progress and the objective is to compare the performance of a range of pervious macadams made using conventional and polymer modified bitumens toward identifying the most durable of the materials (*3, 4*). Although this was essentially an experiment to examine performance and durability aspects of the surface material and spray-suppression performance, the opportunity was also taken to monitor the noise emitted by vehicles traveling on these trial surfaces. Noise generated by vehicles running on pervious macadam surfaces during their first 4 years of exposure to traffic is the main concern of this paper, although other aspects of the materials performance during the same period are reviewed where they relate to the acoustical performance. It should be stressed that because the trials are still in progress, the results presented here do not necessarily represent the performance of the surfaces over their effective life. It follows that because the first 4 years of trafficking is significantly shorter than the anticipated life of the material, it will be some time before the acoustic and material performance can be fully evaluated.

SITE DETAILS

The road site chosen for this study is located on the A38 where it bypasses the town of Burton-upon-Trent, about 30 km north of Birmingham. The road is a dual carriageway and the pervious surfaces are located on the southbound carriageway on a section approximately 2.8 km long.

A total of 15 sections each 100 m long were laid on both lanes of the carriageway during August and September 1984 and an additional 8 trial pervious macadam surfaces were laid in 1987. Besides the pervious macadams laid in 1984, three conventional hot rolled asphalt (HRA) surfaces were laid and used to compare noise levels from vehicles traveling on adjacent pervious surfaces. The HRA surfaces were constructed according to the specification given in (BS 594) (*5*). Figure 1 shows a location map of the area and Figure 2 presents a plan of the layout of the trial sections laid in 1984.

The average daily traffic flow taking the nearside lane of the southbound carriageway at the start of the trails was approximately 7,500 vehicles with 45 percent of them being heavy vehicles (for this study, "heavy" vehicles are defined as vehicles with unladen weight exceeding 1.5 tonnes, excluding passenger cars).

SURFACE DESCRIPTION

All surfaces were laid on a strong impermeable base of asphaltic concrete of nominal thickness (55 mm). The surfaces,

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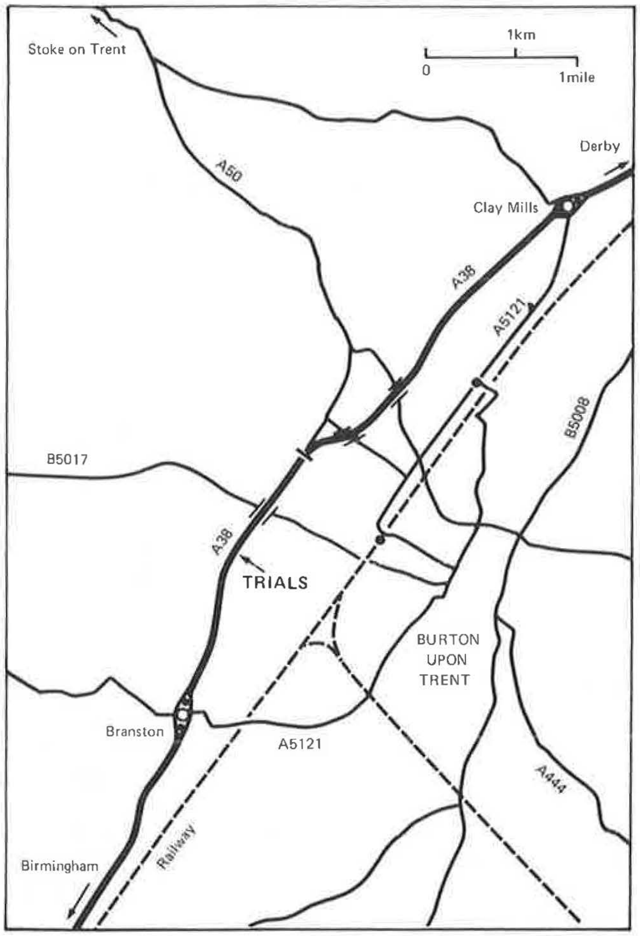


FIGURE 1 Location of pervious macadam trials on A38 Burton bypass.

constructed using a 20-mm grading, were laid to a compacted thickness of 45 mm. The specified aggregate gradings common to these surfacings is given in Table 1.

Of the 15 sites laid, 11 were chosen for vehicle noise assessment. Table 2 lists the relevant surface parameters of these surfaces at the time the road opened to traffic.

Binder Type

To improve the durability of the surface, polymers were added to the binder at some sites prior to mixing. It was hoped that with the use of appropriate additives, the binder would be less susceptible to hardening through oxidization.

Table 2 gives a brief description of the binders used at the 11 sites studied. A 100-pen viscosity binder was used at all sites, except Sites 8 and 11 which used a softer 200-pen bitumen. Sites 2, 3, 4, 12, and 14 contained various additives, while Sites 5, 6, 8, 9, and 11 used polymer-modified bitumens. Site 15 used a conventional binder containing no additives or modified polymers.

It can be seen from Table 2 that the overall binder specification can be classified into 3 binder content groups: 3.7, 4.2, and 5.0 percent by weight of the total mix. The intention was to examine the effectiveness of the binder content on the maximum binder retained by the mix as well as the durability and spray-reduction life of the surface.

Void Content

Cores were extracted from the surfaces along the nearside lane wheel track before the road opened to traffic. The void content was determined for each trial surface from measurements of the bulk density and specific gravity of the material. As expected, the surfaces with the highest binder content had the smallest void volume. An increase in the binder content from 3.7 to 5 percent was found to reduce the void volume by 3.5 percent on average (*4*). Overall, the percentage voids achieved with the 20 mm pervious macadam were highly satisfactory at about 20 percent.

MEASUREMENTS

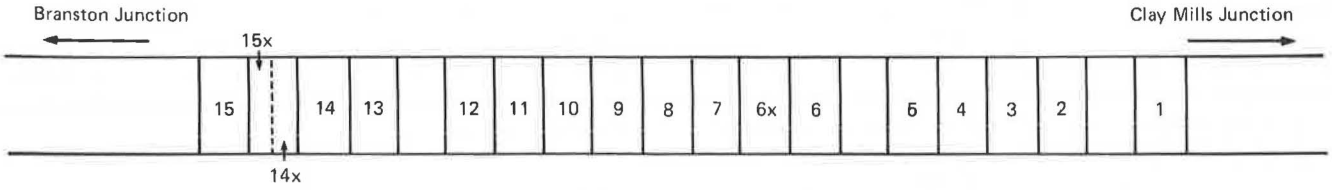
Texture Depth

Texture depth was measured in the nearside wheel track of the nearside lane using the sand patch test (BS 598) (*6*). For each road section, approximately 10 patch measurements were made at 1-m intervals spanning the noise measurement position and the average value determined. The average texture

TABLE 1 SPECIFIED AGGREGATE GRADING FOR PERVIOUS MACADAM TRIALS (A38)

British Standard Sieve (mm)	Mass Passing (%)
20	95–100
14	65 ± 10
10	—
6.3	25 ± 5
3.35	10 ± 3
75m[a]	4.5 ± 1

[a] Specified to contain 2 percent (by mass of the coarse and fine aggregate) of hydrated lime (except Sites 2, 3, 4).



14x, 15x and 6x: Non experimental hot rolled asphalt

FIGURE 2 Schematic layout of pervious trial sections A38 Burton bypass southbound carriageway.

depths obtained prior to opening the test sections to traffic are listed in Table 2 for each section studied. The textures achieved were high, ranging from 2.49 to 5.48 mm, giving an average of 3.3 mm for the 11 sites studied. Repeat measurements were taken periodically to coincide with the times when the noise measurements were taken.

Hydraulic Conductivity

Measurements of hydraulic conductivity (permeability to water) were made at 20-m intervals in the wheel path of the nearside lane in each section. The apparatus used, a falling head permeameter, allows a head of water to be placed in contact with the surface. The time taken for a known volume to pass into the surface is measured. The reciprocal of the time, when corrected for apparatus constants, gives a measure of the hydraulic conductivity. On average, an increase in the binder content from 3.7 to 5.0 percent leads to a reduction of approximately 50 percent in hydraulic conductivity (*4*).

Noise Levels

Noise levels were taken alongside each trial section using a method developed previously for road surface noise studies (*7*). Briefly, this method involves measuring the peak noise levels and speeds of between 50 to 100 vehicles traveling in the nearside lane at a distance of 7.5 m from the center of the lane. From the regression of noise level against speed, the noise level at 90 km/hr is determined and used to compare the surfaces. A separate regression is carried out for light and heavy vehicles. This method has been found to give results reproducible to less than 1.0 dB(A).

RESULTS

Changes over Time

Figure 3 shows the variation in the peak noise level for heavy and light vehicles as a function of time. Figure 4 shows similar

TABLE 2 DETAILS OF THE PERVIOUS SURFACES PRIOR TO TRAFFICKING

Site No.	Binder Type	Binder Content Target (%)	Voids (%)	Texture Depth (mm)	Relative Hydraulic Conductivity
2	100-pen bitumen (4.5% limestone filler)[a]	3.7	22.4	5.84	0.72
3	Shell bitumen + epoxy resin[a]	3.7	25.4	3.11	0.5
4	100-pen bitumen Inorphil fibers (9% of binder)[a]	5.0	20.2	3.57	0.24
5	100-pen bitumen + 5% 18–150 EVA[b]	4.2	21.0	3.25	0.33
6	100-pen bitumen + 5% 18–150 EVA[b]	3.7	19.2	3.14	0.32
8	200-pen bitumen + 5% 18–150 EVA[b]	3.7	21.2	2.63	0.24
9	100-pen bitumen + ESSO modified EVA[b]	4.2	18.1	2.49	0.25
11	200-pen bitumen + SBS[c]	4.2	18.9	3.65	0.41
12	100-pen bitumen + synthetic rubber	5.0	17.1	3.42	0.19
14	100-pen bitumen + Pulvatex natural rubber (8.3% of binder)	5.0	16.8	2.67	0.17
15	100-pen bitumen	3.7	21.3	2.89	0.42

[a] No hydrated lime.
[b] Ethylene vinyl acetate, 18% vinyl acetate content, 150 melt flow index.
[c] Styrene-butadiene-styrene block copolymer.

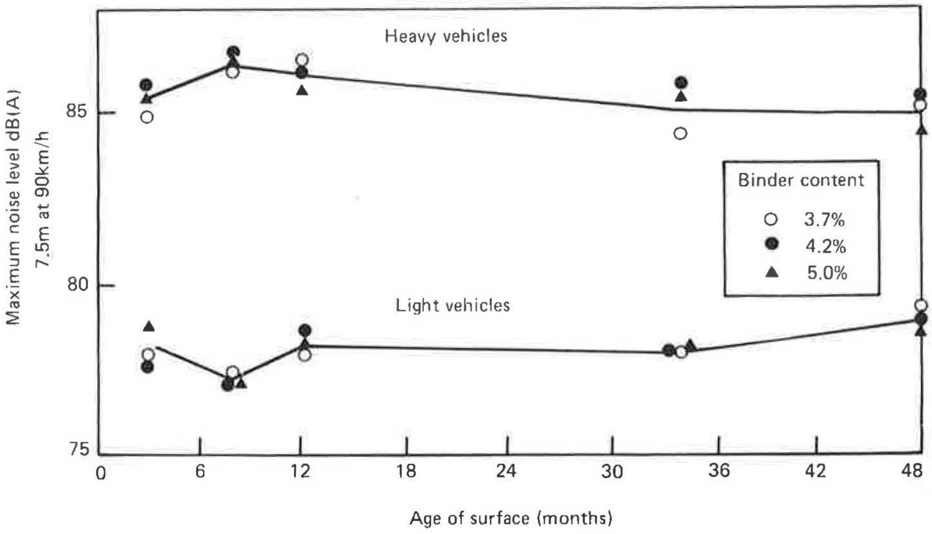


FIGURE 3 Peak vehicle noise level and age of the pervious surfaces.

plots for the hydraulic conductivity and texture depth variables as an indication of some of the physical changes which have taken place. Each data point represents a linear average of the values obtained for each binder content classification. Because there was no obvious effect of binder content on the results obtained, a single trend line has been drawn through the data points in each case.

The data clearly show that peak noise levels remained relatively constant over the 48 months of exposure to traffic and weathering, whereas substantial changes have occurred in some physical aspects of the surface, as evidenced by the changes in both the hydraulic conductivity and the texture depth. The texture depth, however, does appear to have stabilized at around 2 mm which represents a very high standard of macrotexture, ideally suited to high-speed road applications. Clearly, this was accomplished primarily because the initial texture achieved for these surfaces was very high, so that the inevitable losses incurred during the initial 12 months of trafficking still leave the surface with adequate macrotexture and an acceptable degree of skidding resistance.

The greatest reductions in the hydraulic conductivity of the surfaces occurred during the first 12 months the road was opened to traffic. On average, the reduction was 68 percent of the initial value. After 4 years of trafficking, the hydraulic conductivity fell to about 17 percent of the original level. It was thought that the probable cause for the reduction of hydraulic conductivity was the rapid silting of the finer drainage channels in the surface layer, followed by a slower blocking of the larger channels (*4*). Evidence for this comes from the analysis of the cores extracted from the road after 3 years. It was found that the increase in the proportion of small particles (fines) was of the order of 5 percent, which matched the observed reduction in void content. This suggests that the materials did not compact significantly under traffic, but rather that a large number of small drainage channels contributing relatively little to total void content had become blocked.

Although there was a substantial decrease in the hydraulic conductivity of the surfaces, the overall degree of spray suppression of the pervious macadam remained at a high level compared with rolled asphalt. There was about 90 percent less spray than with the hot rolled asphalt measured 2 years after opening the road to traffic. A typical spray record taken in October 1986, approximately 2 years after the road opened to traffic, is shown in Figure 5 (*4*). Measurements were carried

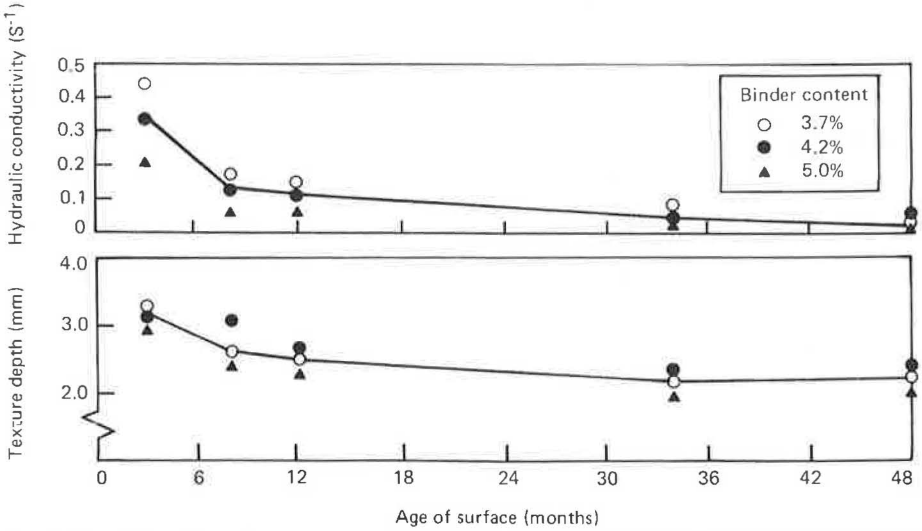


FIGURE 4 Variation of hydraulic conductivity and texture depth with age of the pervious surface.

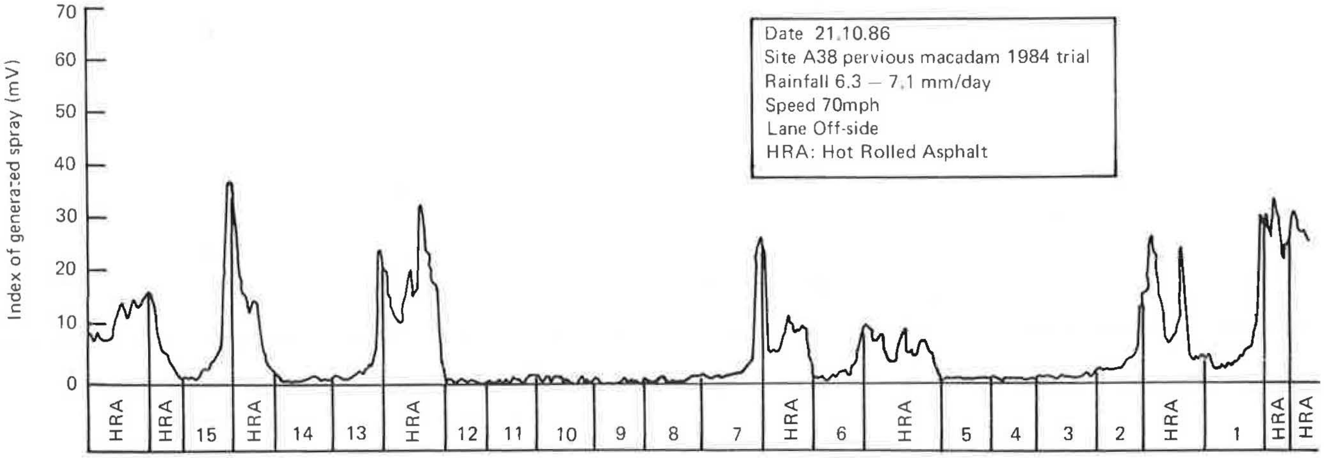


FIGURE 5 Typical spray record for the trial road sections laid on the A38.

out using a vehicle-mounted device that monitors the intensity of the back-scattered light from spray generated behind the rear wheel. High levels of spray for the hot rolled asphalt sections are clearly obvious from the record and the relative levels of spray from the pervious sections are small.

Changes with Skidding Performance

A previous study of noise from different nonpervious road surfaces attempted to relate the total noise generated by vehicles to the skidding resistance term Δ BFC for the road surface (*7*). Δ BFC is the change in the braking force coefficient (BFC) measured between the two test speeds of 50 km/hr and 130 km/hr. The Δ BFC is usually expressed as a percentage change and given by the formula:

$$\Delta \text{ BFC} = [(\text{BFC}_{130} - \text{BFC}_{50})/\text{BFC}/_{50}] \times 100 \qquad (1)$$

where BFC_{50} and BFC_{130} are the braking force coefficients at 50 km/hr and 130 km/hr, respectively.

It was found that for both the light and heavy vehicle categories, the average peak noise level in dB(A) at a standard distance of 7.5 m from the road and at a passing speed of 70 km/hr was linearly related to the logarithm of the Δ BFC variable and was not found to depend on surface material (i.e., concrete or bituminous). A subsequent analysis to examine the correlation at different vehicle speeds confirmed the earlier result (*8*).

The regression lines obtained for the light and heavy vehicle categories for vehicle speeds of 90 km/hr are reproduced in Figures 6 and 7, respectively. The two regressions are based on measurements taken at 63 different road sites involving a broad range of both bituminous and transversely textured concrete surfacings. The correlation coefficients and the 95 percent confidence boundaries associated with the regression analysis are also shown in the figures. At each of the 63 different road sites studied, the value of the skidding resistance Δ BFC was calculated from the texture depth values (TD) measured at each site using the following relationships:

$$\Delta \text{ BFC} = 90 \times \text{TD} - 70 \text{ for concrete surfaces} \qquad (2)$$

$$\Delta \text{ BFC} = 20 \times \text{TD} - 40 \text{ for bituminous surfaces} \qquad (3)$$

These formulas were determined empirically from measurements taken on a broad range of conventional surfacings (*9*).

Figures 6 and 7 include results obtained from the trial pervious macadam road sites. In order to compare these results

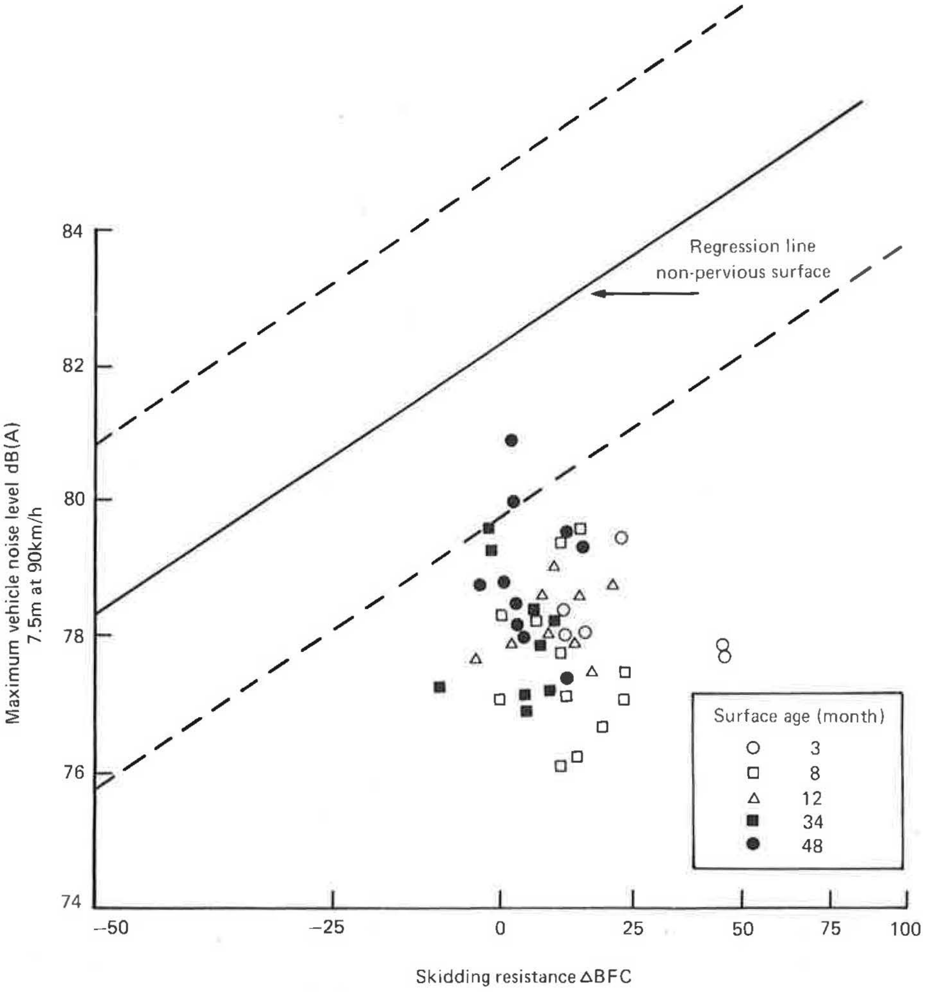


FIGURE 6 Light vehicle noise and Δ BFC.

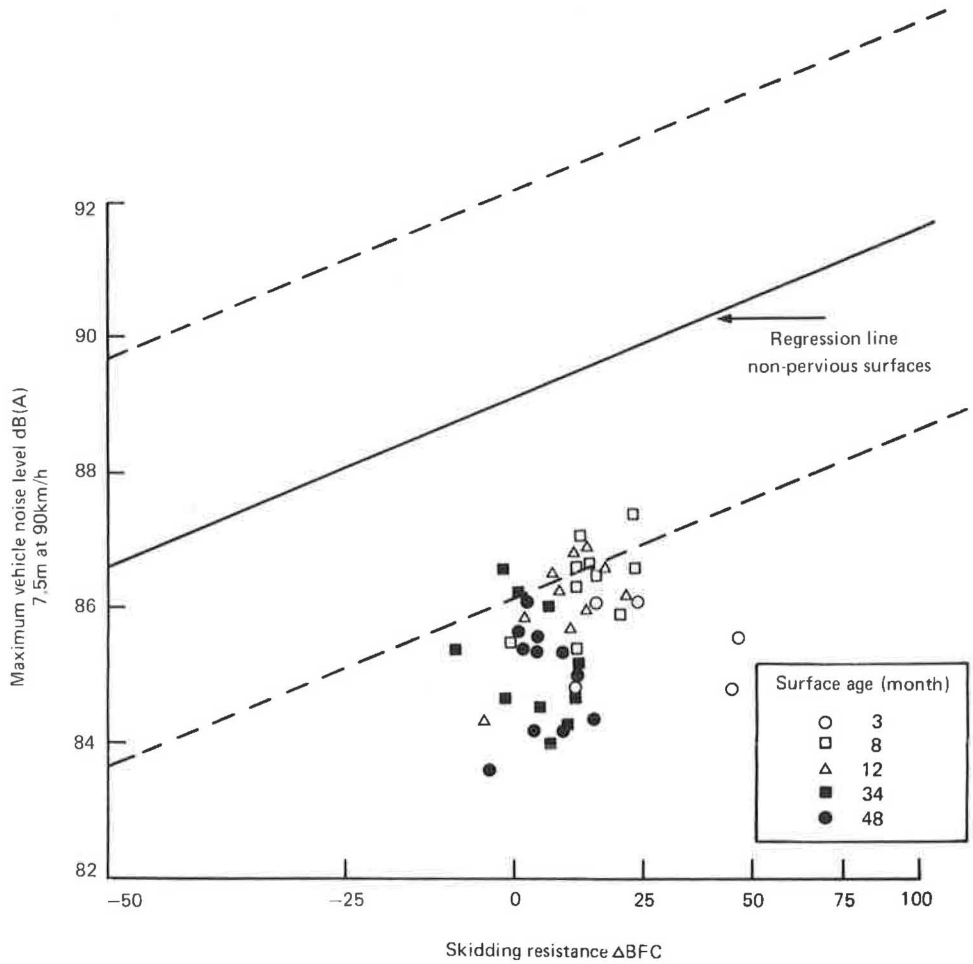


FIGURE 7 Heavy vehicle noise and Δ BFC.

with the nonpervious road surfaces, the values of Δ BFC have been determined from the measurements of surface texture taken at each site using the empirical formula given in Equation 2 for bituminous surfaces. (The texture depth values were supplied by the Materials and Construction Division of TRRL.)

The figures clearly show that the pervious macadams were, on average, substantially quieter than the conventional nonpervious surfacings at an equivalent value of skidding resistance, Δ BFC. Figure 8 shows the average reductions in noise obtained at equivalent values of Δ BFC as a function of the age of the surfaces. It can be seen that for light vehicles, a slight deterioration occurred in the noise reduction obtained over the period of the measurements. Initially, for the light vehicle category, the new surfaces gave improvements of approximately 5.5 dB(A) but this decreased over 48 months to just below 4 dB(A). This trend in performance is not reproduced for the heavy vehicles, which appear to exhibit little change over the exposure period, with the average reduction in noise remaining at approximately 4 dB(A).

Although the average noise reduction performance of the pervious macadams is good for both categories of vehicles, Figures 6 and 7 show that considerable variation exists in the noise levels observed for the different surfaces, although the apparent differences between the surface materials and specifications are only slight. This suggests that the simple measures of macrotexture, such as texture depth, and descriptors of the material, such as void content or binder content, are insufficient to account for a significant proportion of the observed variance in the noise level. It would appear, therefore, that more needs to be learned about the mechanisms governing noise suppression so that the opportunity can be taken to optimize the surface design to reduce noise emission further. (Additional experiments are now planned to examine in detail the mechanisms of noise propagation over pervious road surfaces and will attempt to link surface design and materials specification to the acoustic performance achieved.)

It can also be seen from Figures 6 and 7 that unlike the nonpervious surfaces, there is no evidence that noise from pervious macadams can be related to the skidding performance of the surface or the texture depth. A possible explanation is that because noise is a function of both the macrotexture and the absorbing properties of the road surface, a trade-off occurs between the two. A road with a high macrotexture will tend to generate more tire noise through vibration excitation of the tires, but will also tend to offer greater void volumes and hence higher absorption with associated lower noise levels. Clearly, this conflicting behavior will tend to reduce the possibility of a significant correlation of noise with Δ BFC. Furthermore, it follows from this argument that as the macrotexture of the surface is reduced through the action of trafficking, tire noise levels will also decrease, but because trafficking also causes a reduction in the voids because of

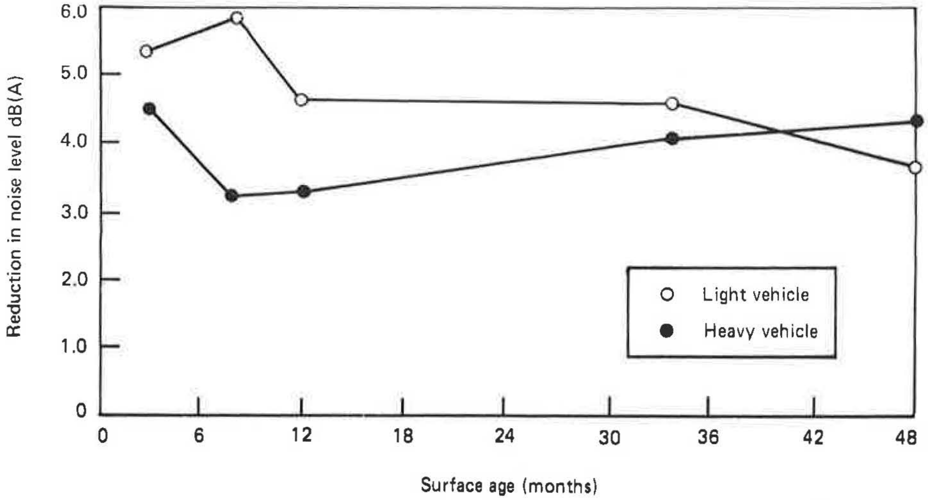


FIGURE 8 Average reduction in vehicle noise comparing pervious macadams and nonpervious road surfaces.

wheel track deformations and clogging, there will also be increased noise. Again because both mechanisms tend to produce opposing noise trends, inevitably there is some degree of trade-off with the result that noise from pervious road surfaces does not appear to change greatly with the age of the surface.

Vehicle Noise Spectra

Vehicle noise frequency spectra have been determined comparing the noise emitted by vehicles running on the pervious surfaces with that emitted on the hot rolled asphalt sections. Some 1/3rd octave spectra obtained for the light vehicles are given in Figure 9. The figure compares Surface 14, a pervious surface made with a rubberized binder and 5 percent binder content; and Surface 14X, laid in the adjacent bay, a hot rolled asphalt surface. In each case, the 1/3rd octave band peak levels were regressed against the passing speed of the vehicles. The values used to construct the spectra of Figure 9 are the peak noise levels interpolated from the regression line for a passing speed of 90 km/hr.

On the figure, the spectra have been constructed using data collected in September 1985 and September 1988. It can be seen that for the light vehicles and the pervious surface, there is generally a slight deterioration in the noise performance with age of the surface, with similar increases over the whole of the frequency range. In contrast, the hot rolled asphalt surface did not show any significant change over the same period. Clearly this observation matches the trend exhibited in Figure 8 where it can be seen that the noise advantage provided by pervious macadam over conventional nonpervious surfaces decreased slightly with the age of the surface for the light vehicle category.

A clearer indication of the differences in the frequency spectra between the two surface types can be seen in Figure 10. The figure gives the difference between the peak 1/3rd octave band levels obtained on the two surfaces. The figure shows that the main improvements offered by the pervious surface lie in the mid-frequency range between 600 Hz and 3 kHz, with the greatest improvements occurring in the range of 800 Hz to 1.25 kHz. This behavior agrees well with the known absorption spectra of these surfaces which are found to absorb strongly in this frequency range (*10, 11*).

As before, it can be seen that as the surface ages, there is some deterioration in the relative performance of the pervious macadam that appears to be present over much of the frequency range. It is interesting to note that for the low frequencies, the effect of trafficking is sufficient to cause the noise from the pervious surface to rise above that emitted by vehicles running on the hot rolled asphalt surface. It appears that the small advantage offered by the absorbing property of the pervious surface at low frequencies has diminished after the 3-year exposure to traffic to the extent that the component of the macrotexture that controls the low frequency tire-radiated noise has taken over as the dominant noise generating mechanism. It should be noted, however, that the surface texture depth behavior was similar for both surfaces and would, therefore, not account for the observed changes in the noise performance at low frequencies.

CONCLUSIONS

- The noise from vehicles running freely on pervious macadam is significantly less than the noise generated on conventional nonporous surfacings. The average reductions obtained when comparing new (untrafficked) pervious surfaces with conventional surfaces with equivalent skidding resistance performance were found to range between 5.5 and 4 dB(A).
- Trafficking was found to cause a slight deterioration in the noise performance of the pervious macadam, but the noise reductions achieved after 4 years exposure to heavy traffic were still averaging 4 dB(A).
- Binder content variations within the range of 3.7 to 5.0 percent and the addition of polymers to improve the durability of these surfaces did not appear to systematically affect noise emission performance. However, the noise levels observed for the different surface types did vary over significant ranges, indicating that further work could lead to a better understanding of the parameters affecting noise reduction and so provide

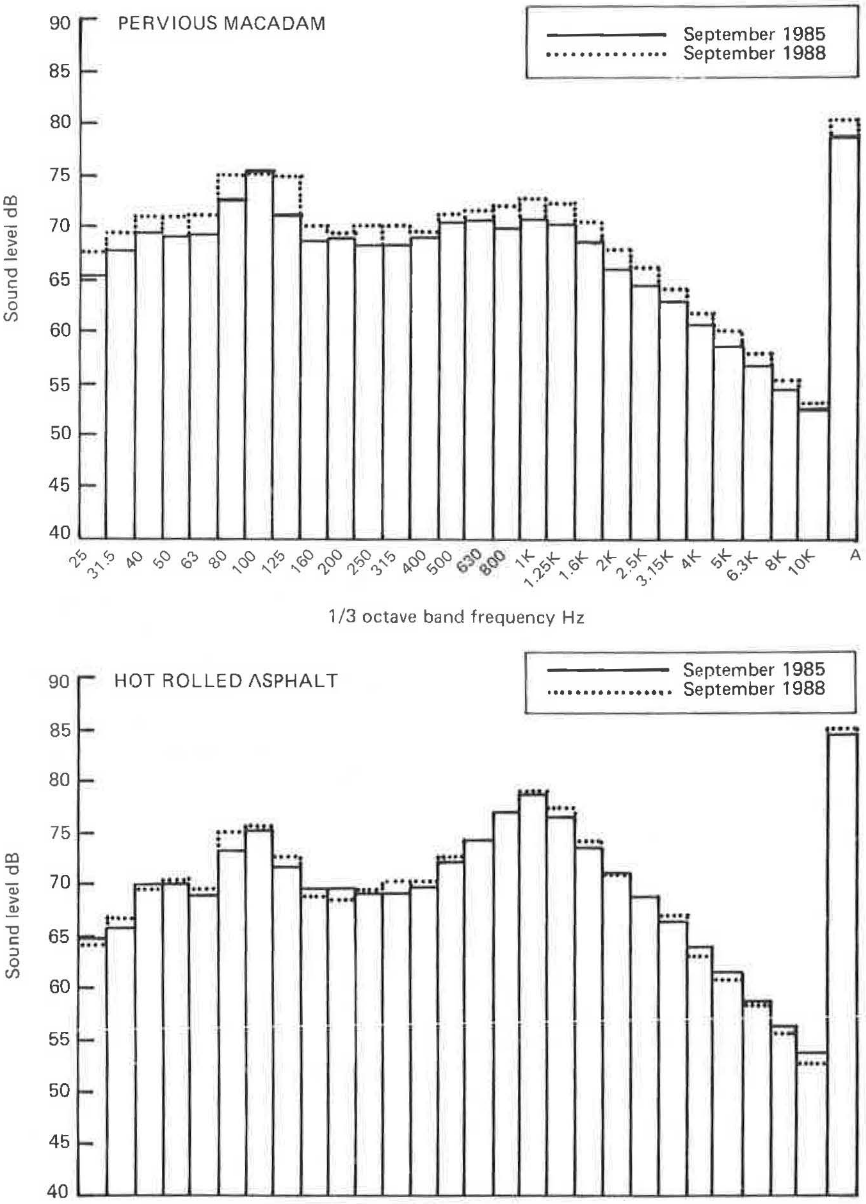


FIGURE 9 1/3rd octave spectra obtained for light vehicles traveling at 90 km/hr.

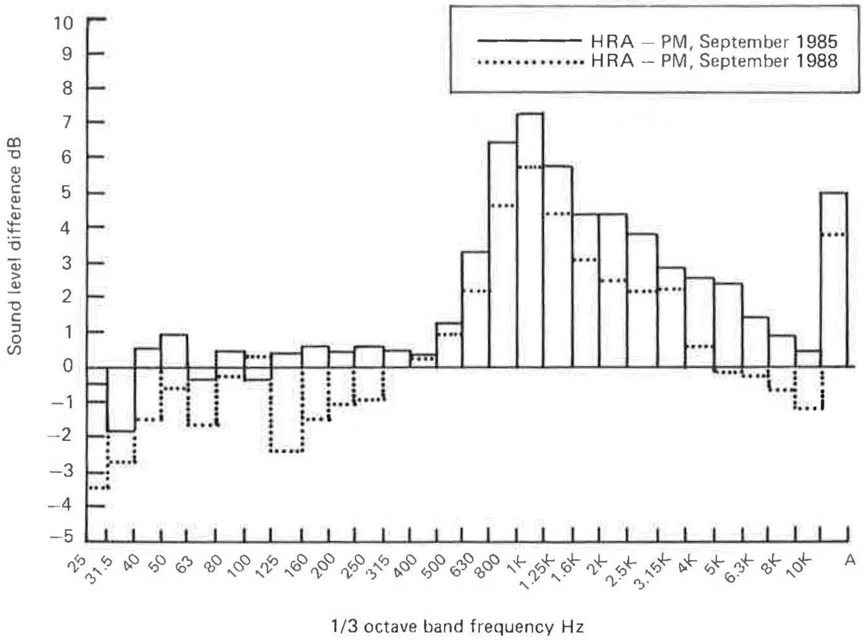


FIGURE 10 Difference between the 1/3rd octave spectra obtained on hot rolled asphalt (HRA) and pervious macadam (PM). (Light vehicles at 90 km/hr.)

an opportunity to reduce noise further by optimizing the surface design.

ACKNOWLEDGMENTS

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Ten Years' Experience of Porous Asphalt in Belgium

G. VAN HEYSTRAETEN AND C. MORAUX

Porous asphalt is a bituminous mix that because of its composition contains about 22 percent voids after compaction. In rainy weather, this results in the absence of aquaplaning, increased skid resistance, and reduced splash and spray behind vehicles. Additional advantages are reductions in rolling noise level, light reflection, and rolling resistance. In Belgium, this type of surface is used not only on roads, but also on airfields and in tunnels. The Belgian Road Research Centre has been conducting extensive research into various aspects of its use, such as mix design, the influence of binder type, manufacture and laying, the gradual loss of permeability, winter behavior, acoustic properties, specific features of applications in built-up areas and tunnels, and maintenance. Some of these aspects are briefly discussed in this paper.

The first application of porous asphalt in Belgium occurred in 1979 as part of a research project conducted by the Belgian Road Research Centre (BRRC).

It was a small job involving only 2,700 m² of two-lane pavement carrying daily traffic volumes of 700 vehicles in each direction. This first experiment immediately indicated all the benefits that could be expected from this new technique. As a result, new and more ambitious applications started to develop in 1981, this time on motorways.

The technique has been developed well beyond the experimental stage, and about 70 jobs have been conducted. At the end of 1988, the total surface area of porous asphalt laid in Belgium was about 2 million m². This puts Belgium and the Netherlands in the lead in Europe, especially when considering the relatively small areas of the two countries.

PRINCIPLE

Porous asphalts are bituminous road mixes designed so that after laying and compaction, they form a surface with a voids ratio of about 22 percent. They are used for wearing courses and are always laid on an impervious base (Figure 1).

With such a percentage of voids, a network of channels is created in the layer, which is capable of conveying the water that has fallen on the pavement during a rain shower and penetrated the surface.

Of course, the design of the road structure itself must enable this water to be drained off through the porous layer to the lateral collecting devices or the shoulders. This makes it necessary to have an impervious underlying layer with some crossfall to prevent the water from reaching the subbase and stagnating in the porous layer.

That is also why the lateral collecting devices or the shoulders must not be situated higher than the top of the underlying layer. This may seem quite obvious, but already design engineers have been found to overlook this essential requirement.

PROPERTIES OF POROUS ASPHALT

As just explained, porous asphalts are designed to allow free passage of rainwater. Furthermore they make it possible for the vehicle tires to maintain contact with the pavement surface under any circumstances, and thus to avoid the aquaplaning that may occur on conventional pavements at high speeds under wet conditions.

Porous asphalt also eliminates splash and spray behind vehicles (especially trucks) (Figure 2) and avoids reflections from the surface of the pavement at both day and night (Figure 3), thus making road marks more visible.

The draining capacity of porous asphalt surface, of course, depends on the percentage of voids. It is, therefore, important that this percentage be high when the pavement is opened to traffic. This is also necessary to prevent rapid clogging by dust or mud entering the layer.

Another important property of porous asphalt, which accounts for a great part of the success of the technique, is that it considerably reduces rolling noise both inside and outside vehicles (Figure 4). As demonstrated by research carried out at the BRRC, this reduction in noise levels results from:

- Sound absorption in the voids of the layer,
- Elimination of air pumping at the tire-pavement interface, and
- The good surface evenness of this type of wearing course.

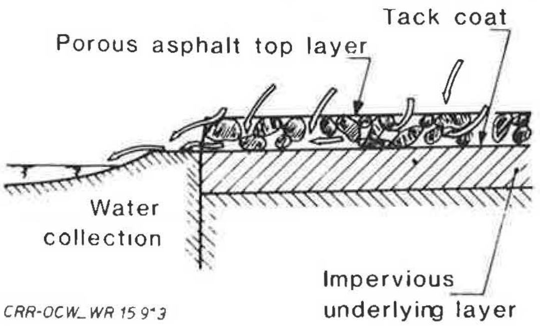

FIGURE 1 Example of a road structure with porous asphalt.

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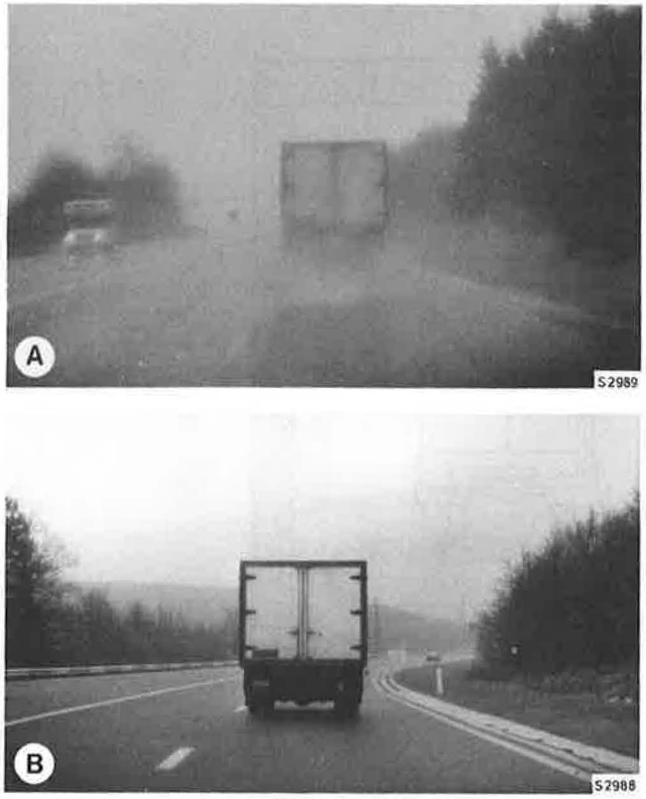

FIGURE 2 Splash and spray behind a vehicle under identical weather conditions on dense asphalt concrete (A) and on porous asphalt (B).

FIGURE 3 Difference in reflection of the headlights of a car on a wet road surface. In front, dense asphalt; behind, porous asphalt.

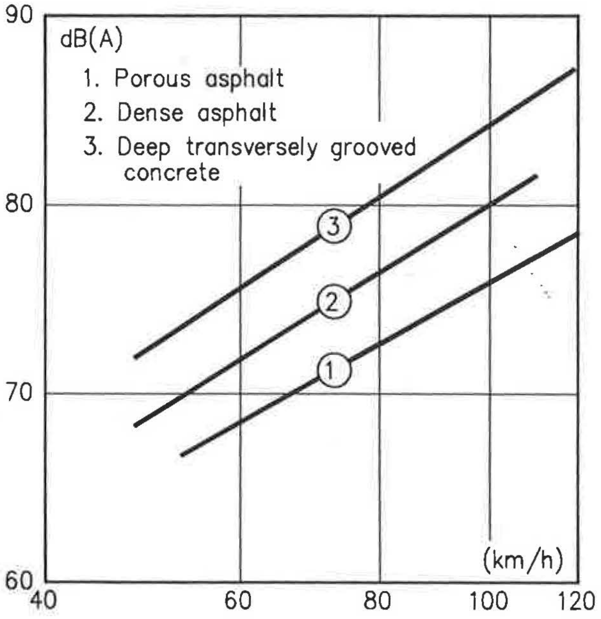

FIGURE 4 Rolling noise versus speed on three types of surfaces.

These findings were made with a standard vehicle traveling with its engine off at 80 km/hr over a measuring test section.

In real traffic, however, engine noise also plays a part. Porous asphalt partly absorbs this noise in the voids of the layer.

When considering the various applications of porous asphalt in Belgium, it can be seen that two different designs have been used: either 2.5-cm-thick layers or 4-cm-thick layers. It has become clear that, to ensure high draining capacity and a substantial reduction in rolling noise and to preserve these properties over a longer period, the 4-cm thickness must be recommended.

WHERE TO USE POROUS ASPHALT

Porous asphalt is most commonly used in areas where water tends to stagnate, such as changes of superelevation, wide pavements (motorways and airfield runways), and sags in the longitudinal profiles of roads in hilly regions.

Another interesting application is in tunnels whose invert is situated below the phreatic surface. Water accidentally rising through cracks in this invert will damage the asphalt pavement and lead to water stagnancy in the tunnel. An overlay of porous asphalt can cause this unwanted water to be drained off to the sides of the pavement (Figure 5).

Other applications are made to solve problems with rolling noise. A frequent case is that of crosstown express roads or motorway links with a transversely grooved concrete surfacing. Overlaying such concretes with porous asphalt has remarkable effects: under the measuring conditions described earlier, a noise reduction of 6 to 10 dB(A) was observed 7.5 m from the measuring vehicle and 1.2 m above the pavement.

The use of porous asphalt in tunnels also leads to considerable reduction of rolling noise not only for vehicle passengers, but also—and especially—in the vicinity of the approaches.

A more frequent application of porous asphalt is on particularly noisy arterials in urban areas. Because the pavement is generally boxed in between two curbs, lateral drainage must be correctly designed.

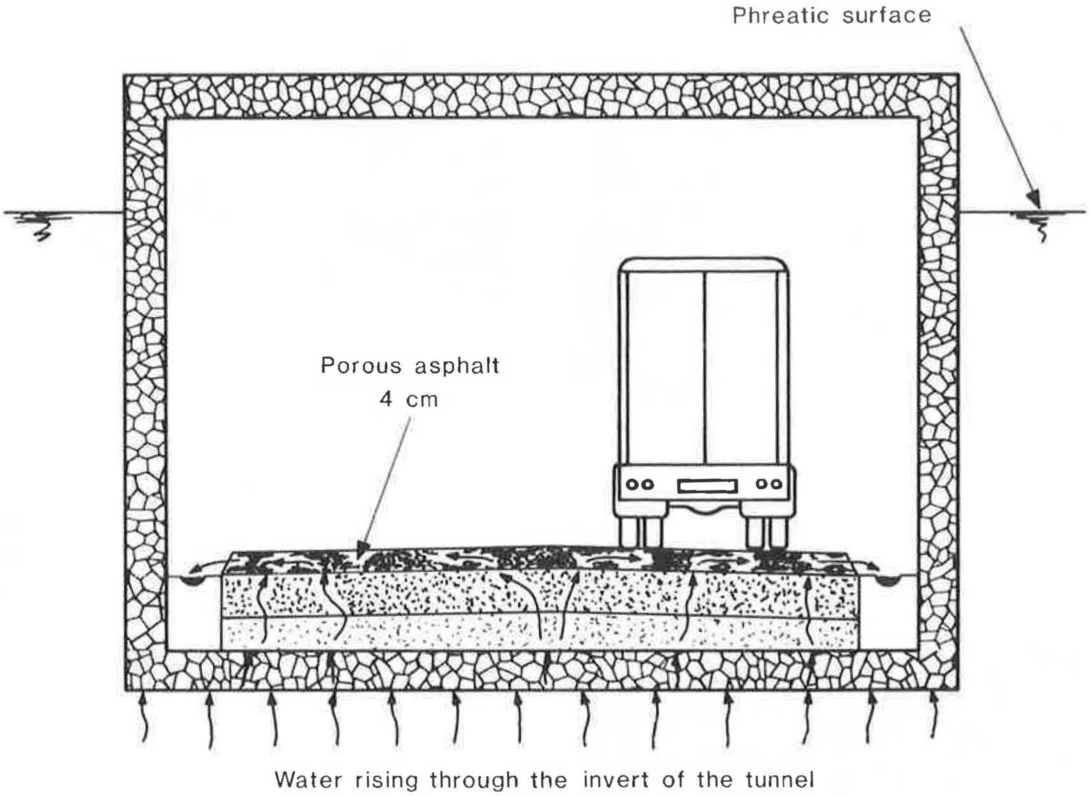

FIGURE 5 Overlaying an existing pavement in a tunnel with porous asphalt.

When the porous asphalt layer is placed on top of the existing pavement, a drainage channel may be left between the porous asphalt and the curb, but this solution may cause pedestrians or cyclists to fall and may be very inconvenient for the disabled; moreover, the curb is no longer sufficiently effective as an obstacle to stop slipping vehicles.

Another solution is to extend the porous asphalt layer to the curb and level the grids of the gulleys with the surface of the pavement. Holes (25-mm diameter) must then be drilled in the upper part of the side wall of each gulley to allow gradual disposal of the water caught in the porous layer. Simple saw cuts in the upper part (Figure 6) are generally inadequate because they will be blocked rapidly. When carried out as an overlay, this design reduces the protection provided by the curb for pedestrians; the best way to proceed, therefore, is to remove 4 cm of the existing pavement by milling before laying the porous asphalt.

Another technique, already used but applicable only when the pavement must be fully reconstructed, is to provide, along the curb at the lower side of the crossfall, a trench fitted with a longitudinal drain at the bottom and backfilled with porous asphalt. This drainage trench constitutes a buffer store in which surface water is allowed to accumulate until it can be carried off by the drain (Figure 7).

Finally, to facilitate lateral drainage in areas with zero crossfall, a solution has been tried consisting of making grooves in the layer to be covered by porous asphalt. These grooves become deeper as they approach the side of the pavement where lateral drainage is to be provided and are also filled with porous asphalt.

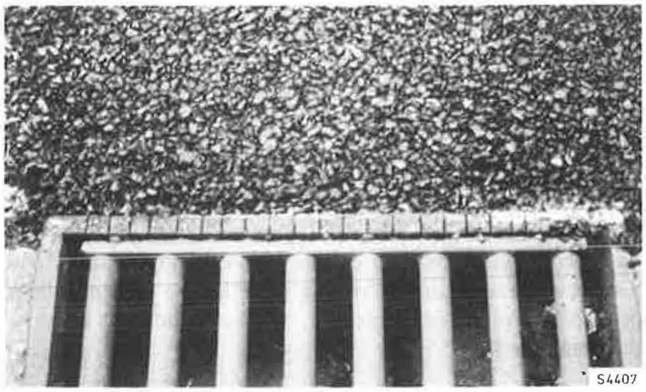

FIGURE 6 Saw cuts in the upper part of a gulley.

WHERE NOT TO USE POROUS ASPHALT

Although applications in urban areas require special care—as indicated—in designing the project, there are other sites where the use of porous asphalt should be avoided.

One example is roads that are frequently soiled with a variety of wastes. This is the case with roads in farming areas, where so much mud is left by tractors that a porous asphalt surface could be rapidly clogged.

Another example is low-volume or slow-traffic roads. This is because traffic ensures some self-cleaning of the surface of porous asphalt courses. Dust, which inevitably accumulates in the voids at the surface, can be swept only by the suction

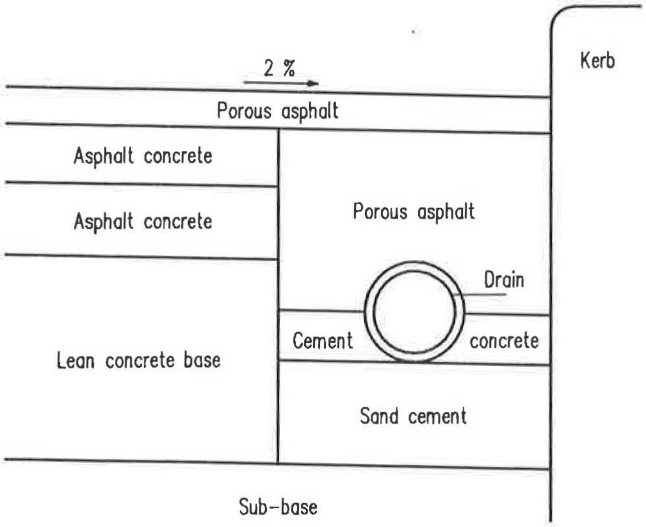

FIGURE 7 Application of porous asphalt in built-up areas involving the use of a collector drain.

effect of the tires of numerous vehicles traveling at fast speeds over the pavement.

Finally, it is preferable not to use porous asphalt in areas where the surface of the pavement is subjected to very high tangential loads, because relatively little is known about the resistance of porous asphalt to this type of loading.

COMPOSITION AND MIX DESIGN

Several principles must be respected to obtain the high percentage of voids required:

- A Sufficient quantity of "stones"—experience has shown that the aggregates should contain more than 80 percent of particles ≥ 2 mm;
- A gap grading, to be obtained, for example, by omitting the 2/7 or 2/10 mm fraction from a 0/14 mm mixture; and
- A limited quantity of binder, in order not to fill the voids yet ensure cohesion.

The Belgian specifications for the composition of porous asphalt are summarized in Table 1 (*1*). They relate to a 0/14 gap-graded mix to be laid in courses 4 cm thick, with a voids ratio that is to lie between 16 and 28 percent in each individual core sample and average between 19 and 25 percent over the various samples. This means that the mixture sought has an initial voids content of 22 percent. In addition, draining capacity is checked in situ by means of an outflow meter (Figure 8).

The mix design method proposed by the BRRC consists of first determining the voids in the coarse aggregate ("the stones") and then measuring, on Marshall samples with various binder contents, the voids and the percentage of wear after rotation in a Los Angeles cylinder without abrasive charge.

Binder content should be such that the granular materials are coated correctly but not excessively, because this would reduce the percentage of voids to below the desired minimum and lead to segregation during transport and laying. Moreover, there would be a risk that the porous asphalt would become postcompacted by traffic.

Except for lower-volume roads—for which porous asphalt is not recommended—Belgian specifications require an elastomer-bitumen type of binder. Two alternatives exist:

- Bitumens with newly manufactured elastomers (mainly SBS), for which the required binder content is 4.0 to 5.0 percent, and
- Bitumens with recycled elastomers (bitumen admixed with powdered rubber and an aromatic oil), with binder contents between 5.5 and 6.5 percent.

The possibility of using higher contents with recycled elastomers derives from the higher viscosity of the binder. This has the advantage of enabling the aggregates to be coated with a thicker film of binder which, in principle, should be less sensitive to aging. A disadvantage, however, is the risk of reducing the initial percentage of voids in the layer or of facilitating clogging by postcompaction.

The share of each of these various types of binder in the total surface area covered with porous asphalt in Belgium is currently 10 percent for bitumen 80/100, 30 percent for bitumen with new elastomers, and 60 percent for bitumen with recycled elastomers ("rubber-bitumen").

FIGURE 8 In situ measurement of the draining capacity of porous asphalt.

TABLE 1 BELGIAN SPECIFICATIONS FOR THE COMPOSITION OF POROUS ASPHALT

Property	Specification
Grading	0/14 mm gap
Stones (≥ 2 mm)	83 %
Crushed sand (0.080 mm - 2 mm)	12 %
Filler (< 0.080 mm)	5 %
Binder	
- bitumen 80/100	4 to 5 %
- modified bitumen	4 to 5 %
- rubber-bitumen	5.5 to 6.5 %
Thickness	4 cm
Voids ratio	
- average	19 to 25 %
- individual	16 to 28 %
Draining capacity (for 1,4 l water)	
- average	≤ 60 s
- individual	≤ 180 s

The various jobs were completed too recently to allow firm conclusions about the service lives achieved with the three types. Two experimental jobs done in 1983 and 1985 on the Philippeville-Couvin highway should yield important information on this subject within a few years.

MANUFACTURE AND LAYING

The manufacture of porous asphalt in conventional batch plants raises no particular problems compared with dense bituminous mixes. More attention must be paid, however, to the temperature of the mineral aggregates, which must not exceed 170°C to avoid dripping of the binder from the crushed stone particles and consequent segregation.

The order of entry into the mixer is generally the same as usual: sand, crushed stone, filler, and, finally bitumen. Nevertheless, good results have also been obtained with an alternative procedure, which consists of first introducing and mixing the sand, the filler, and the bitumen, and then adding the coarse aggregate and mixing again.

The risk of segregation during transport increases with the distance of travel, especially with excessive binder contents. This segregation results in materials sliding in large lumps from the trucks, which makes laying more difficult, and in the presence of fat spots in the surface after spreading.

Mechanical laying is normally not more difficult with porous asphalt than dense mixes. Static smooth-wheeled rollers are recommended for compaction. Vibrating rollers are to be excluded, mainly because of the risk of crushing stones; with pneumatic-tired rollers, there is a problem of porous asphalt sticking to the tires.

As do other types of mix, porous asphalt requires particular care as far as longitudinal construction joints are concerned, especially because coating these joints is not allowed here so that drainage is not obstructed.

Finished porous asphalt tends to stick to car tires when first opened to traffic, which may lead to stripping of aggregate in areas where severe tangential loads are applied (for example, in bends and at traffic lights). To prevent this stripping, it is advisable to spread about 50 g/m^2 of filler (fines < 0.080 mm) on the surface before opening it to traffic (Figure 9).

RESEARCH WORK

The BRRC has been conducting laboratory and field research into various particular aspects of this type wearing course (*2*), some of which are briefly discussed here.

Development of Binder Characteristics

Because porous asphalts are by definition rich in voids, the introduction of oxygen and ultraviolet rays into the bituminous layer and the continuing presence of water will lead to a rapid development of the binder's characteristics. Under site conditions, the penetration of pure bitumens has been

FIGURE 9 Spreading filler on a newly laid porous asphalt surface.

found to drop sharply in the first months. It can be said that after 3 years, all bitumens 80/100 have a penetration value below 25/10 mm and a ring and ball softening point exceeding 60°C. Beyond that period, the process appears to stabilize comparatively and it is remarkable that porous asphalt surfacings containing such aged bitumens still hold after 8 years of service.

With bitumens containing recycled elastomers, or "rubber-bitumens," the process is much slower; bitumens containing new elastomers stand midway between pure bitumens and bitumens with recycled elastomers as far as aging is concerned. But observations on test roads have not yet permitted researchers to establish whether improving the characteristics of the binder extends service life.

Acoustic Properties

The noise reduction is related to the high sound absorption coefficient (α) of the material. The coefficient varies with sound frequency and is most favorable at about 1000 Hz (Figure 10), which happens to be the frequency at which tire noise or the rolling noise of traffic has the highest intensity. The absorption coefficient increases with the percentage of voids and the thickness of the layer. Compared with conventional or chipped asphalt, the reduction in noise level at 80 km/hr is generally 2 to 3 dB(A). For transversely grooved cement concrete, the reduction is generally 6 to 10 dB(A).

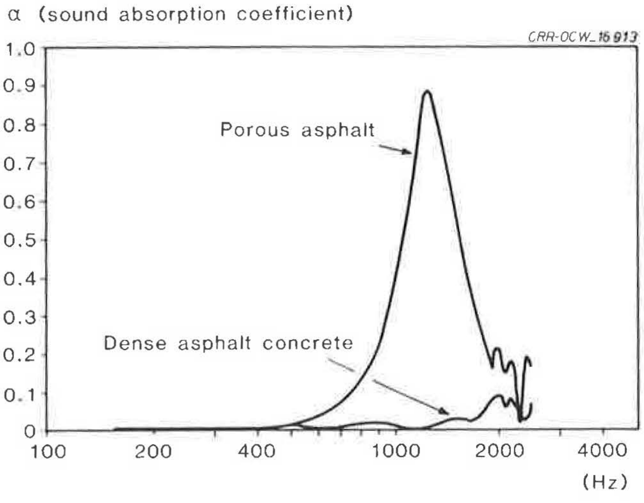

FIGURE 10 High sound absorption coefficient of porous asphalt, primarily at sound frequencies of about 1000 Hz.

Structural Contribution

By determining the moduli, it has been possible to quantify the structural contribution of porous asphalt manufactured with bitumen 80/100; this contribution lies between 73 and 79 percent of that of a wearing course in conventional asphalt concrete.

Winter Serviceability

Studies and observations made by the BRRC have made it possible to draw the following conclusions about the much-debated behavior or porous asphalt. Briefly, it can be said that porous asphalt and dense bituminous concrete do not behave differently in snowy weather when spread intensively with deicing salts. If such is not the case, snow may remain longer on porous asphalt because the brine that is formed under traffic can penetrate the voids in this material. However, this difference in snow-clearing behavior has never been the underlying cause of any accidents recorded in Belgium.

On the other hand, accidents have happened in icy weather on porous asphalt surfaces while the adjacent pavements were not icy, and vice versa. Ice simulation tests have shown that the comparison for skid resistance is sometimes favorable to porous asphalt and sometimes to dense surfacings, depending on ice conditions.

Clogging

It is well known that porous asphalt slowly silts up in places where traffic is not intense. This problem, therefore, does not occur in the traffic lanes of a highway or a motorway, and certainly not with an initial voids content of 22 percent and a 4-cm-thick layer.

The problem is raised by the hard shoulders for emergency stops, which silt up quite rapidly and, as a result, block water drainage from the traffic lanes. To avoid this situation, it is thought useful to provide the porous asphalt surface of the hard shoulder with a waterproofing surface dressing at the time of construction (Figure 11).

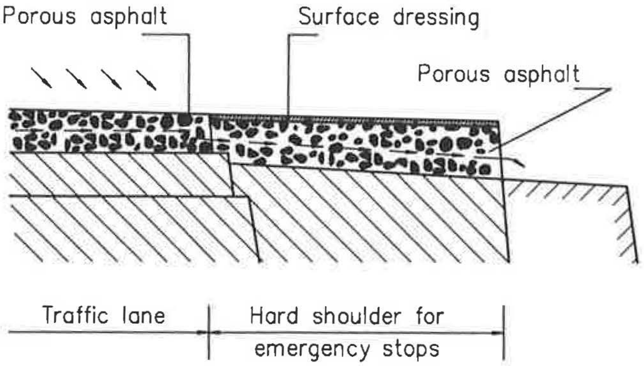

FIGURE 11 To avoid clogging, the surface of the hard shoulder is provided with a surface dressing.

FIGURE 12 Cleaning the surface with an appropriate suction sweeper using a water jet.

Maintenance

Studies have also been conducted into the behavior of porous asphalt courses and their deterioration with time. A joint Dutch and Belgian working group is investigating the specific maintenance problems with this type of surface. This effort has led to the development of cold-laid porous asphalt mixes for filling potholes or for durable local repairs. In addition, trials have been made with overlays in porous asphalt, in situ recycling of old porous asphalt, fog seal sprays, and the cleaning of partially clogged pavement surfaces (Figure 12).

CONCLUSIONS

Porous asphalt makes it possible to improve road safety in a number of critical cases and, by reducing rolling noise, contributes to the comfort of both road users and frontagers. It is not the universal remedy, however, and it should not be forgotten that porous asphalt is only one of the techniques available to contract awarders for designing their road pavements.

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Experiences with Porous Asphalt in Switzerland

THOMAS ISENRING, HARALD KÖSTER, AND IVAN SCAZZIGA

Since 1982 a research program observing the long-term behavior of porous asphalts under normal traffic conditions has been carried out at the Institute for Transportation, Traffic, Highway and Railway Engineering IVT of the Swiss Federal Institute of Technology in Zurich. In a first phase, an observation program measured skid resistance, permeability, rolling tire noise, and deformation once or twice a year on a selection of porous asphalt pavements already in service. The general appearance and behavior under winter conditions were also recorded. In a second phase, the research was extended to include the study of material properties such as aging of the binder, performance of the mix, and so forth. The emphasis in this paper is given to results from the first phase of the research program. Particular attention is devoted to the problems of skid resistance, permeability, noise reduction, and behavior under winter road conditions of porous asphalt pavements. For these parameters, the methods of measurement, results, and general conclusions are presented. Conclusions are provided separately for two potential areas of application of porous asphalt: motorways and other roads with fast traffic, and urban roads with slower traffic. Taking into account the different advantages and disadvantages of porous asphalt, experiences obtained so far are generally very positive about the application of porous asphalt to roads with high-speed traffic. When applied in urban areas, different problems appear and initial advantages may be lost within a short time. Also applications in an urban environment cannot take full advantage of the noise-reducing potential when traffic travels at lower speeds. Results from this research project also indicate that a number of conventional surface layers can have favorable acoustic properties; in this field there is potential for further development. Under winter road conditions, porous asphalt surfaces can present the same range of variation of skidding properties as conventional surface layers. However, at a particular moment, there is a difference in the behavior of the two pavement types along the road at the site where the type of surface changes.

The first porous asphalt in Switzerland was placed on an airport runway in 1972. On road pavements, porous asphalts have been used since the late 1970s and early 1980s. Since 1982 a research program has been carried out at the Institute for Transportation, Traffic, Highway and Railway Engineering IVT of the Swiss Federal Institute of Technology in Zurich to observe the long-term behavior of porous asphalts under normal traffic conditions. Using these observations, it should be possible to collect data on all material properties of porous asphalt concrete with a view to its future use. The work described here is mainly limited to experiences in Switzerland. Some studies from other countries were also considered in certain cases; otherwise they cannot be compared because of different conditions such as climate, winter maintenance, type of bitumen, test procedures, and so forth.

In a first phase, porous asphalt pavements already in service in 1982 were selected and an observation program measured skid resistance, permeability, rolling tire noise, and deformation once or twice a year. The pavement's general appearance and the behavior under winter conditions were also recorded. The research program was enlarged in a second phase and now also includes material properties such as aging of the binder, performance of the mix, and so forth. Results from the first phase of the research program are emphasized here.

TEST PAVEMENTS

The research program now comprises 17 sections located on motorways, interurban, and urban roads with a section length between 150 m and 2.2 km. The oldest section was placed in 1979; the majority were constructed in 1985 and 1986. Reasons for choosing porous asphalt on these sections were general material testing, traffic safety, or traffic noise reduction. (A polymer-modified bitumen is generally used as a binder for the porous asphalt.) General data on the materials used are given in Figure 1 and as follows:

	Porous Asphalt (0/10)	*Porous Asphalt (0/16)*
Max. aggregate size (mm) (round sieve)	10	16
Layer thickness (mm)	28–42	43–50
Binder content (% by mass)	4.65–5.82	4.23–4.99
Void content (%) (Marshall specimens)	10.9–22.5	14.9–17.0
Void content (%) (cores)	14.6–21.1	14.6–19.6

SKID PROPERTIES

Test Procedures

Skidding properties were measured once or twice a year with the Skiddometer BV8. This skid trailer makes it possible to determine the coefficient of friction with either a locked wheel or a braked wheel (slip ratio of 14 percent, normally on a theoretical water film of 0.5 mm thickness). Measurements were carried out with the PIARC skid test tire of dimension 165 R15 with four longitudinal grooves. Tire pressure is 1.5 bar and tire load 3.5 kN. The initial conditions of each section were measured within two months of the opening to traffic, in any case before the first winter.

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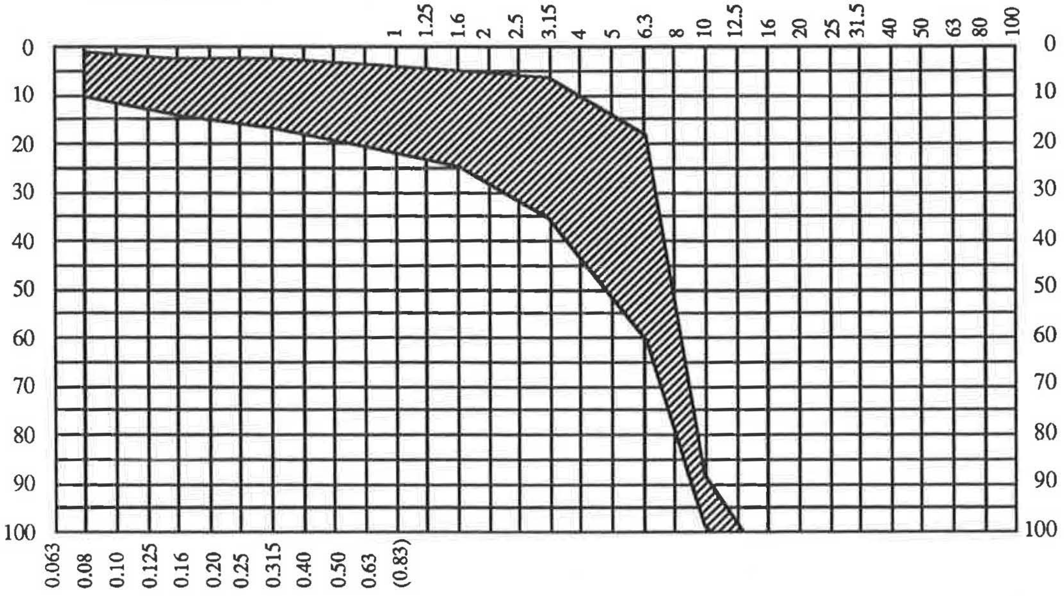
Porous asphalt 0/10



Porous asphalt 0/16

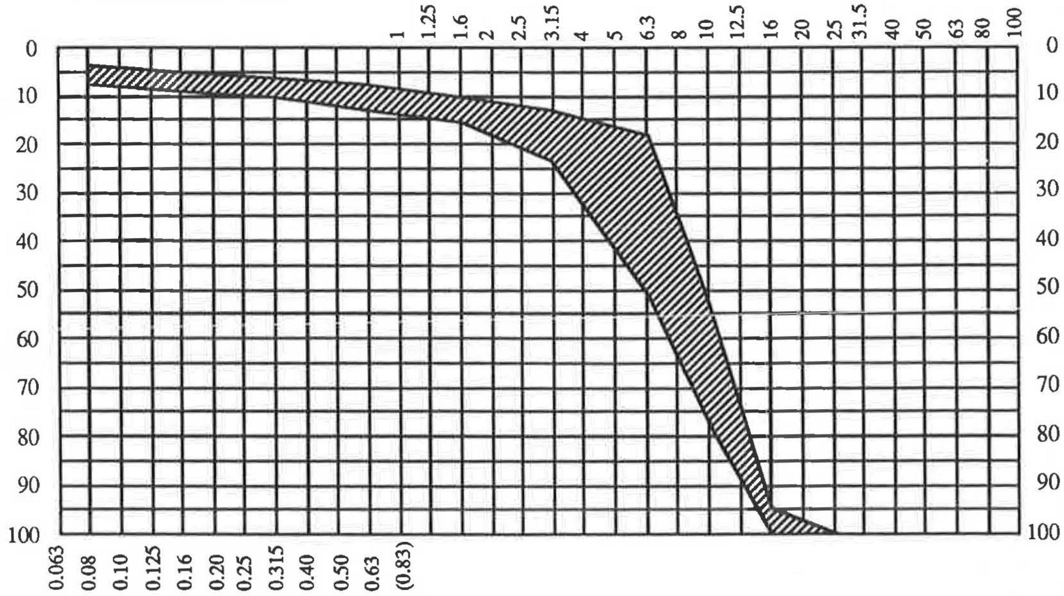


FIGURE 1 Gradation curves for porous asphalt (size in mm).

Other measurements of skid properties such as the SRT pendulum or the sand patch method were not considered suitable for this type of material. Also the Moore outflow meter (SN 640 510b) cannot be used for porous asphalt, where water outflow occurs through the pavement. Therefore, it is not possible to characterize of the pavement texture.

Results

Skidding properties of porous asphalt pavements (measured with the locked wheel) are usually in the range of values measured on conventional asphalt mixes. However, values for porous asphalt are hardly speed dependent. The curves in Figure 2 are flatter than the general shape of the frequency distribution used as the evaluation background. This means that porous asphalt has exceptionally good skidding properties at higher speeds where macro-texture is very important. At lower speeds, where micro-texture is more relevant, porous asphalt has, on the contrary, rather poorer skid properties than a conventional mix, as can also be seen in particular in Figure 3 with the results of the measurements with the braked wheel (slip ratio of 14 percent).

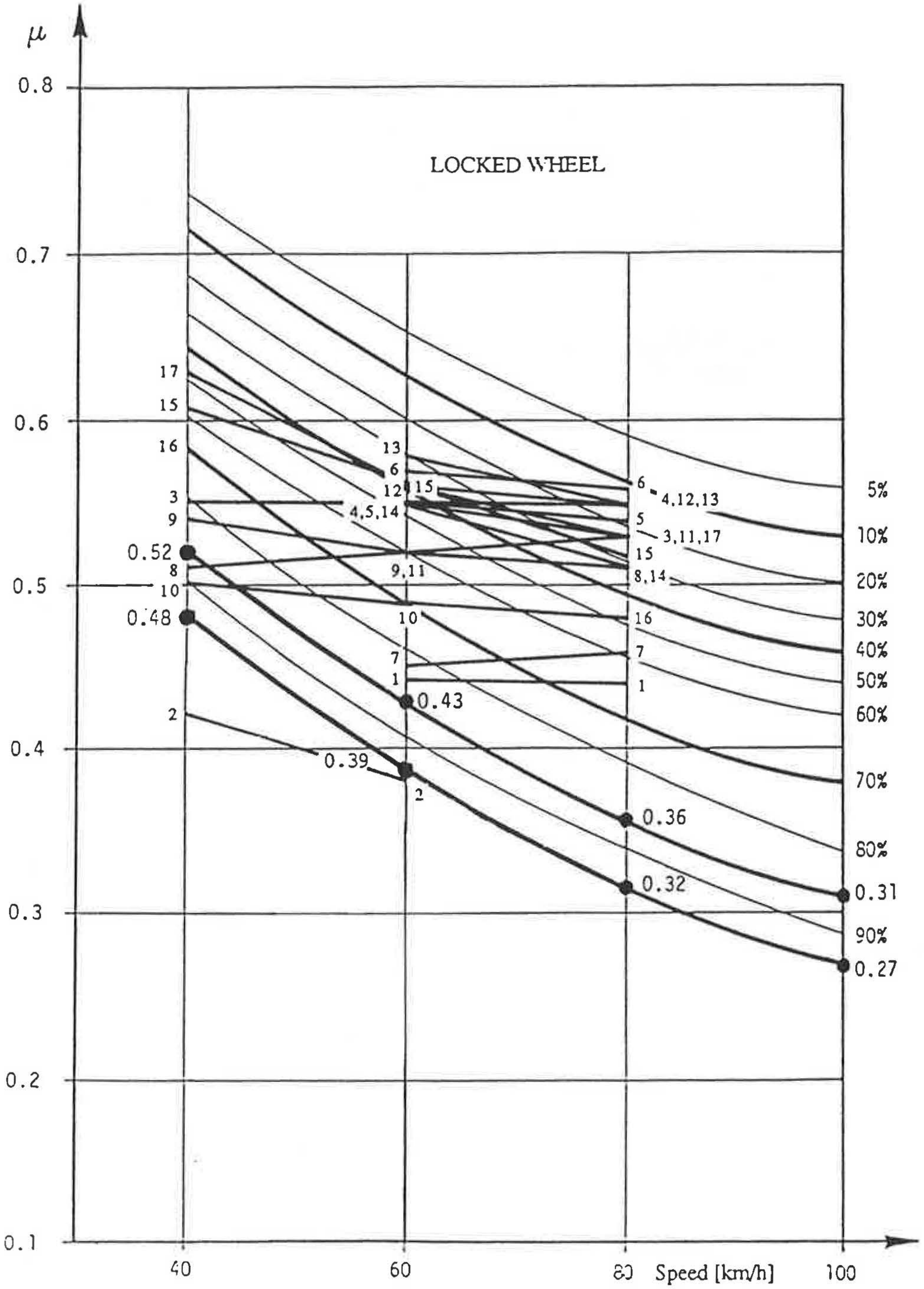


FIGURE 2 Skid measurements with locked wheel for porous asphalts compared with the general evaluation backround.

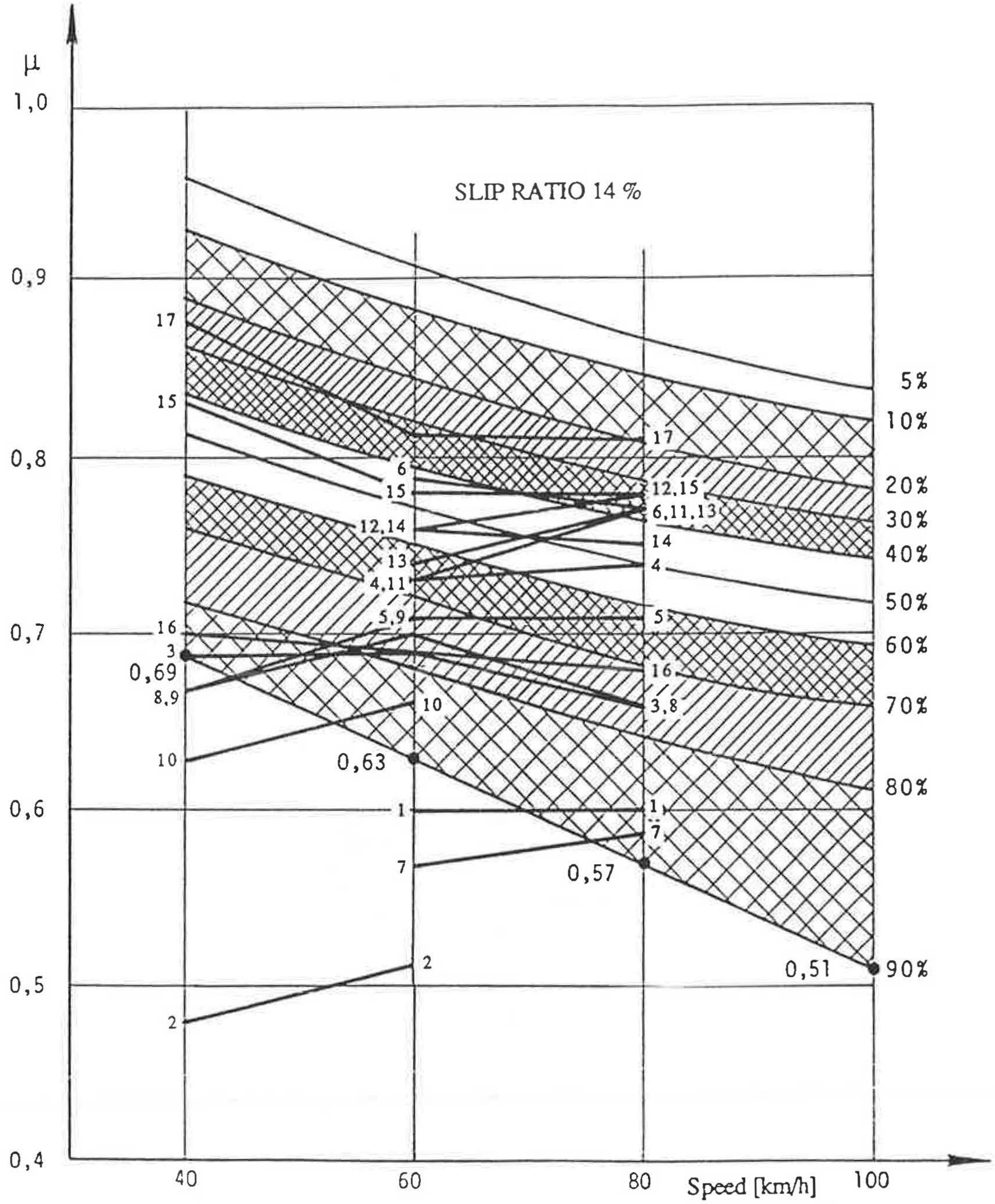


FIGURE 3 Skid measurements with braked wheel (14 percent slip ratio) for porous asphalts compared with the general evaluation background.

Skidding properties of porous asphalt in the initial stage after construction (Figure 4) are frequently lower than the values obtained on the same pavement after a certain usage time. This can best be seen in the results with the locked wheel, where skid values normally clearly increased after the first winter.

Skid Resistance: Conclusions

Skidding properties of porous asphalt are generally in the same range as conventional pavement mixes. Because of the high macro-texture, results for porous asphalt are generally above average at higher speed. However, a lack of microtexture can often be observed. This leads to lower skid values with the locked wheel at low speeds.

Because of the particular surface structure of porous asphalt, the aggregates used must meet more severe requirements. In particular, it is important for skid properties to use high quality aggregates with good resistance to polishing and with sharp edges. In fact, in the case of porous asphalt, all the contacts between tire and pavement occur on the single surface aggregates, which also by themselves alone contribute to the surface "sharpness." Normally good skid properties may be obtained

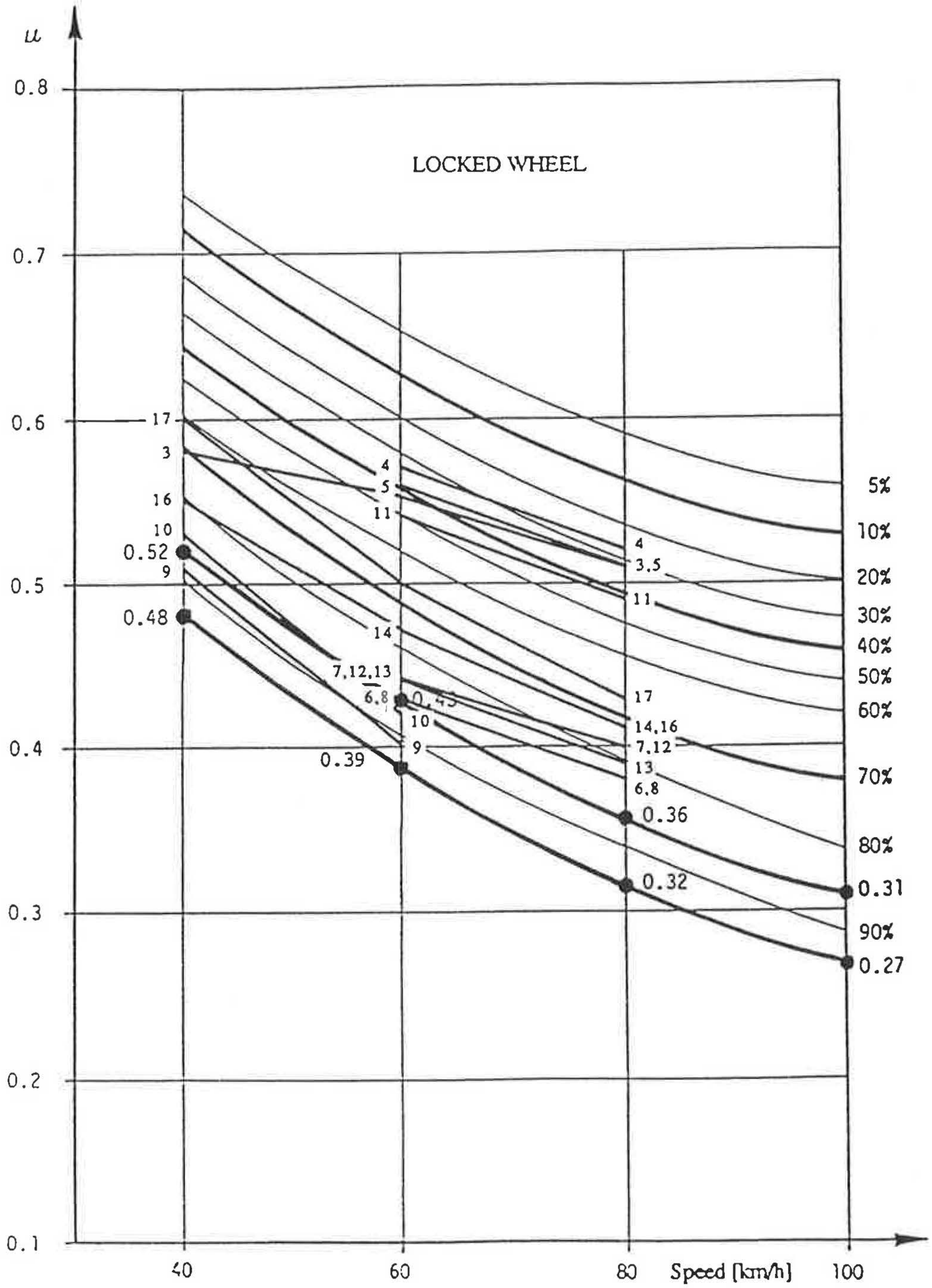


FIGURE 4 Initial skid values with locked wheel for porous asphalts compared with the general evaluation background.

with the available aggregates. However, the general shortcomings at lower speed must be considered when using porous asphalt in urban areas or in critical curves.

The occurrence of reduced skid properties shortly after construction is similar to the experience with conventional mixes. But with porous asphalt, there is a bigger problem because generally microtexture is poorer and normal repair methods (such as spreading of chippings) cannot be used. The situation improves after a certain time when the binder coating of the single surface aggregates has worn off.

PERMEABILITY

Permeability to water is one of the characteristic properties of porous asphalt. This is also the main difference with conventional asphalt mixes and the reason for the great advantages of porous asphalt (e.g., strong reduction in the risk of hydroplaning). New solutions had to be developed for measuring drainage potential. An objective methods to quantify this property is essential for evaluating these mixes.

Test Procedure

Within the research project, one of the first tasks involved the search for an appropriate methodology to measure permeability. Devices such as Moore's outflow meter could not be considered, as already mentioned. Other devices developed for this purpose were considered to be either insufficiently precise or too complicated for practical use. Therefore, the Institute chose to develop a new methodology which has now been used successfully in practice in Switzerland for about seven years.

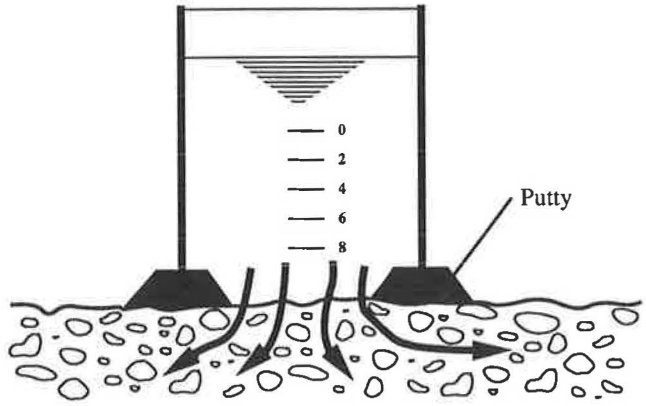


FIGURE 5 IVT permeameter (schematic, not to scale).

The IVT permeameter shown in Figure 5, is made of a plexiglass cylinder with an interior diameter of 190 mm and a height of 250 mm. The cylinder has five engraved markings 20 mm apart from each other, with the "zero-marking" 120 mm above the bottom of the cylinder. A special putty is placed as a 30 mm wide ring on the pavement surface in order to cover the highest aggregates and fill voids at the surface. Thus the contact zone between the cylinder and the pavement is sealed, and the water is forced to flow through the interior voids of the porous asphalt layer. Permeability of the layer is expressed by the time elapsed between the 0 and the 80 mm line. This downward movement of the water surface corresponds to an outflow quantity of 2.27 L. In cases when the time needed to pass the 40 mm line is greater than 300 sec, the permeability and thus also the functional quality of the porous asphalt is considered to be insufficient.

This method, a "single point measurement," is a disadvantage, recognizing the inhomogeneity of the porous mixes. A sufficient number of measuring points must be considered for a good characterization of the layer. Three sampling areas were therefore selected on each section, and in each sampling area, two measurements were made in the wheel track and two others outside of it. In order to follow with precision the development of permeability, measurements were always repeated at the same spots. measured values for a water level decrease of 80 mm range between 10 sec for a very permeable mix to almost ∞ for a dense mix (conventional mix or a porous asphalt with filled voids). Measurements within the research program had two purposes: to determine the permeability of new mixes and develop permeability with the increasing age of the porous asphalt.

Permeability of New Porous Asphalt Mixes

Initial permeability values for a water level decrease of 80 mm on new porous asphalt layers ranged between about 23 and 105 sec. These are the mean values for the different sections (determined on the sampling basis mentioned earlier). Single values can be outside of this range. The mean value for the initial permeability of all the observed pavements is 3.4 L/min, corresponding to an outflow time of about 40 sec. An influence of the maximum aggregate size on the initial permeability has not been observed with certainty.

Large differences can be observed not only between different mixes but also within the same section, already in an initial stage after construction. Standard deviations on the order of magnitude of 30 to 50 percent of the mean value are not rare, demonstrating the problems of getting good homogeneity during construction. Results from laboratory tests on material specimens (cores) also show this tendency. Under the assumption that a porous asphalt layer can be qualified as being homogeneous when the standard deviation of the permeability values is below 30 percent, about one half of the pavements observed fell in this category.

Development of Permeability

Permeability of porous asphalt layers decreases with higher or lower progression with the age of the mix (Figure 6). All kinds of dirt on the pavement and the consequent filling of the voids in the layer account for this progression. In single cases postcompaction of the layer can also lead to reduced permeability. Normally conditions remain better in the wheel tracks than in the center of a lane or on emergency lanes because of the "cleaning" suction effect of rolling tires. Therefore, postcompaction cannot be considered a major cause of reduced permeability.

The rate of reduction of permeability depends on a number of factors such as the environment, traffic loadings, type of mix, construction, and so forth. Some sections still show satisfactory values of permeability even after 5 years of traffic; others have become almost completely dense within 1 year

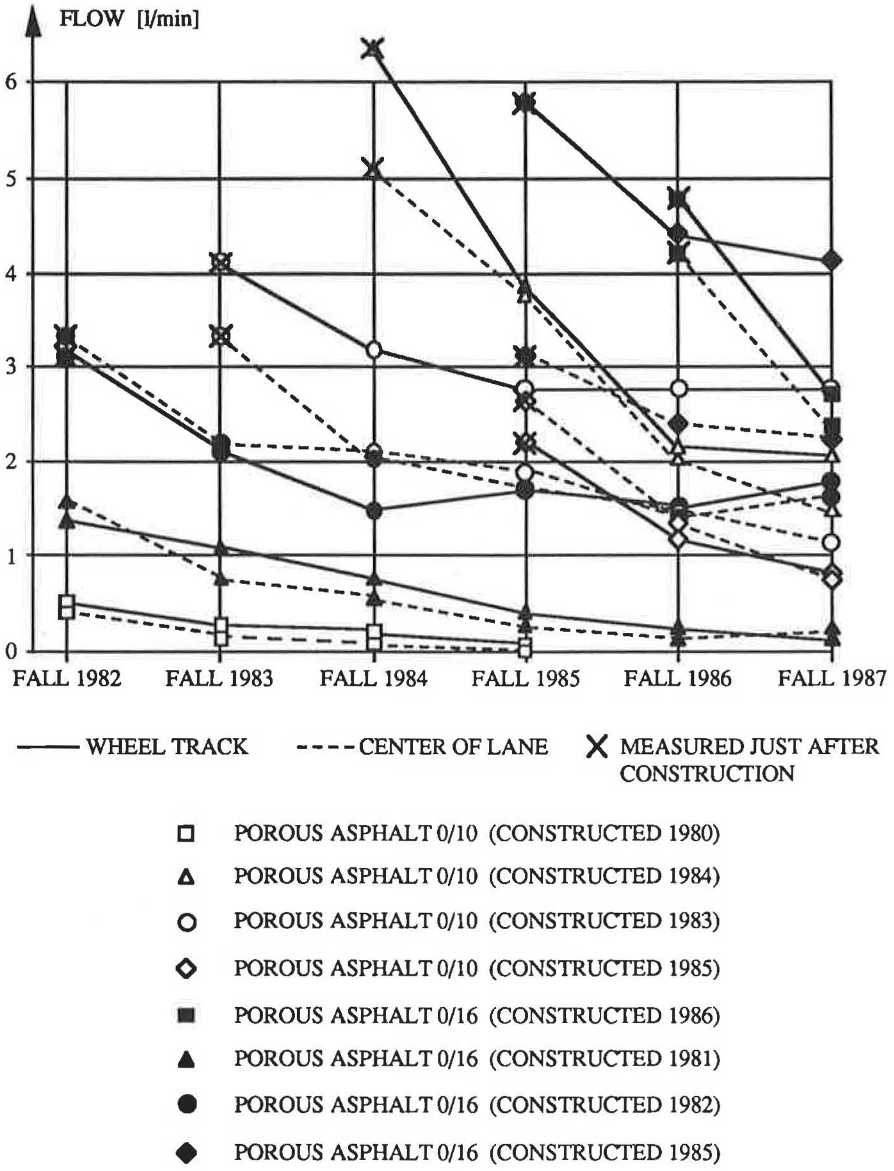


FIGURE 6 **Development of permeability with time.**

(Figure 6). Although just after construction no significant differences were measured for mixes with maximum aggregate sizes of 16 and 10 mm, those with 16 mm maximum aggregate generally show a much more favorable situation in the last series of measurements considered for this paper (fall 1987) than the mixes with 10 mm maximum aggregate. However, this result may not stem from the difference in maximum aggregate size but from generally more favorable service conditions for the sections having the 16 mm mixes (mostly on motorways).

Favorable conditions for maintaining a sufficient permeability are: reduced amount of dirt, good drainage (in particular, free water outflow at the edge of the layer and sufficient crossfall of the supporting layer), a layer structure with large voids and high void content, and finally the cleaning action of rapid and intense traffic. The use of porous asphalt layers on motorways can be seen very positively from the viewpoint of the developing permeability. On the contrary, more dirt and a reduced cleaning action by traffic are not favorable to an intense use of these materials in agricultural areas, nearby stone and aggregate pits, or urban areas. In the latter case generally, the influence of poorer drainage conditions for the layer must be considered. Porous asphalt overlays with a free edge usually are not recommended in urban areas for traffic safety reasons (cyclists and pedestrians). Ramps for lateral access also limit the lateral flow of the water from the porous layer. This leads, as experience shows, to deposits of dirt in the layer that tend to increase with time, which can considerably reduce the permeability of the layer.

Cleaning porous asphalt layers with filled voids could be very difficult if not completely impossible. First tests with water under high pressure and subsequent suction of the dirt have shown the capability of clearly cleaning the surface. However, permeability of the layer was not improved by this measure. Periodic cleaning of pavements with still sufficient permeability might have a positive influence on its development.

Effects of Permeability

The use of porous asphalt layers on motorway sections that had a concentration of hydroplaning accidents considerably reduced the number of accidents, even on sections deficient in surface drainage. Moreover, poorly drained porous asphalt layers can accumulate large quantities of water within the layer. Porous asphalt layers remain wet longer after rain than conventional, dense pavement layers because the water within the layer is pressured out by the tires. As long as the surface remains wet, this will also have an unfavorable influence on rolling tire noise.

Reducing permeability, except with very heavy rain, generally will have less influence on traffic safety than on the acoustical properties of the porous asphalt layer. In fact, a porous asphalt layer with filled voids can also be considered to be favorable from the viewpoint of safety on a wet surface because of its high macrotexture, if skidding properties are satisfactory. However, acoustical properties of these coarse, but unpermeable mixes are usually no longer positive, because the surface is no longer capable of noise absorption.

TRAFFIC NOISE

Methodology for Measurement

A 1986 environmental law fixed limit values for noise emission in order to reduce the nuisance to the population based on the general principle that noise should be reduced at the source. In view of this law, there is great interest in porous asphalt, because traffic noise derives from engine noise and, at higher speeds, from rolling tire noise.

For evaluating road pavements, three different measurement methods can be adopted:

- Measurement of rolling tire noise with a special trailer (LMA),
- Measurement with a microphone at the roadside (coasting or traffic noise) or sound level L_{eq}, and
- Measurement of the absorption qualities of a pavement surface.

Measurements on fixed facilities, such as the drums used for tire testing, are not suitable for investigating pavement surfaces under realistic conditions. Because the problem is complex, the three methodologies just mentioned have been used in this research project. The following values have been used to characterize the noise:

- Degree of reflection: the amount of sound reflected by the pavement surface and the quantity of sound absorbed by the pavement respectively,
- LMA-value: determinant of rolling tire noise level in the noise-measuring trailer LMA,
- Coasting noise: maximum sound level of a passenger car rolling by with engine turned off,
- Traffic noise: maximum sound level of a passenger car passing at constant speed, and
- Traffic noise (L_{eq}): the energy-equivalent continuous sound level for total "normal" traffic (including trucks).

Measurement of Absorption

Measurement of the absorption or reflection of sound can be done either in the laboratory on cores or other suitable samples with the impedance tube, or in the field with special instrumentation. The principle is the measurement of a known emitted sound and the sound signal reflected by the pavement. The degree of reflection of sound is determined by comparing the signals; it is then possible to calculate die absorption (1 − degree of reflection). Conventional, dense-graded asphalt pavements are very hard and lead to almost total noise reflection. Porous asphalt layers, however, can absorb part of the sound. A porous asphalt layer in good functional condition can therefore reduce the nuisance deriving from traffic noise. Because it can be assumed that the absorption potential depends on the permeability of a porous asphalt, the IVT permeameter was also used in conjunction with all noise measurements. The program of measurements was carried out only on select pavements, because the primary purpose was only to study general relationships.

The study of absorption characteristics has shown porous asphalt pavements in good functional condition capable to absorb sound. Figure 7 shows some typical curves for different pavement materials. However, on the basis of acoustical theory, high absorption effects are not expected for the layer thickness (30 to 50 mm) used today for porous asphalt. The lowest mean reflection value measured in this study was 0.79 (corresponding to an absorption factor of 0.21). This means that a maximum of about 20 percent of the sound was absorbed.

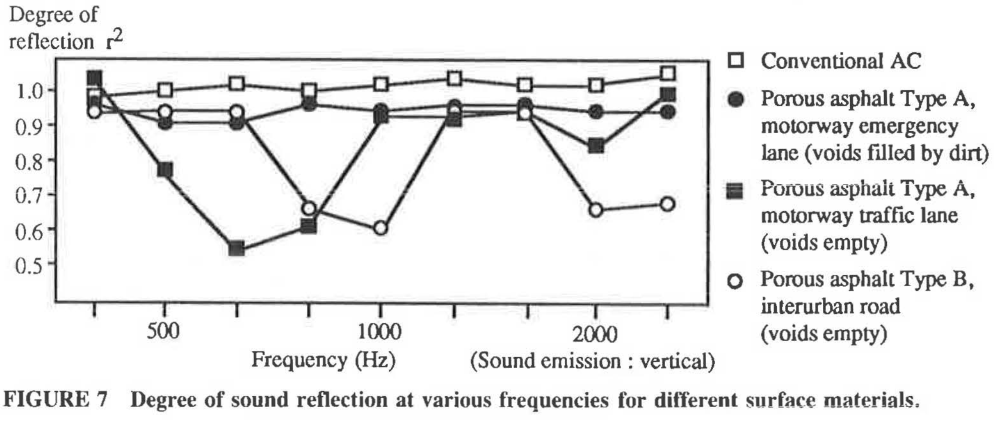


FIGURE 7 Degree of sound reflection at various frequencies for different surface materials.

Analyzing some parts of the spectrum of frequencies, one can find absorption factors of up to about 40 percent.

A correlation between reflection and absorption has been determined (Figure 8). (Figure was based on 21 pairs of values for 4 porous asphalt sections. Permeability was determined by IVT permeameter. Measurement was of the degree of reflection on the road. Mean value of reflection values in the octave volumes 500 Hz, 1,000 Hz, and 2,000 Hz. Sound absorption, $\alpha = 1 - r^2$.) In order to obtain a noticeable absorption of at least 10 percent, permeability should not be above 130 to 140 seconds, or the flow value not below 1 L/min. Mean flow quantities for many of the sections with porous asphalt are below this limit.

Rolling Tire Noise Measurement with the Measurement Trailer LMA

The trailer for noise measurement (LMA) has been developed and built by the Institute based on a scheme adopted by the Technical University of Stuttgart. It is a one-wheel trailer meant to determine the rolling noise of tires on different road surfaces at different speeds. Two microphones are used to register the sound immediately adjacent to the wheel. The body is fitted with sound insulation that prevents almost any outside influence. Therefore it is possible to obtain a precision of ±1 dB on homogeneous surfaces and without larger disturbing effects from the outside.

The two microphones register two parts of the noise creation and diffusion mechanism. A laterally placed microphone registers sound emitted from the tire side due to the vibrations of the rolling wheel. A microphone on the rear side of the tire is used to determine the sound-increasing influence of the "funnel-effect" between tire and surface or the absence of this effect on porous asphalt surfaces. The mean value from both microphones is used as the determinant value. Frequency analysis was carried out by the acoustics department of the Swiss Federal Laboratory for Testing of Materials (EMPA). The results are shown in Figure 9 and are discussed next.

Standard conditions of measurement include the use of the European PIARC test tire 165 R15 with 4 longitudinal grooves, which is normally used for skid testing. Earlier comparisons of different tires have shown that the PIARC tire is in the same range as modern standard production tires as far as rolling noise is concerned, but has the advantage that it best differentiates among road surfaces. The use of the noise measurement trailer has proven to be a simple method, which under normal traffic conditions precludes disturbances from other noise sources. This method is therefore particularly well suited for comparing pavement surfaces.

The use of two microphones in the trailer allows differentiating between sound propagation from the tire and from the texture of the pavement surface. Values measured from the recordings on the rear microphone are usually greater than for the lateral position on conventional, dense asphalts because of the "funnel effect." In the case of porous asphalt, both recordings lead generally to the same values and in certain cases the higher value is even recorded for the lateral microphone, because of the high absorption behind the tire. The lateral microphone is not influenced by the absorption characteristics of the surface and, moreover, the coarse surface may even increase lateral reflection.

For porous asphalt layers in good functional condition, values recorded on the rear microphone are lower than for conventional pavement surface layers at speeds above 50 to 60 km/hr. The difference increases with higher speed. At speeds below 60 km/hr, it is possible to measure the same level of rolling noise at the rear microphone for certain "acoustically favorable" conventional materials.

Values obtained from the lateral microphone for porous asphalt are in the range of values obtained with other surfacings. This could happen because of the generally coarse

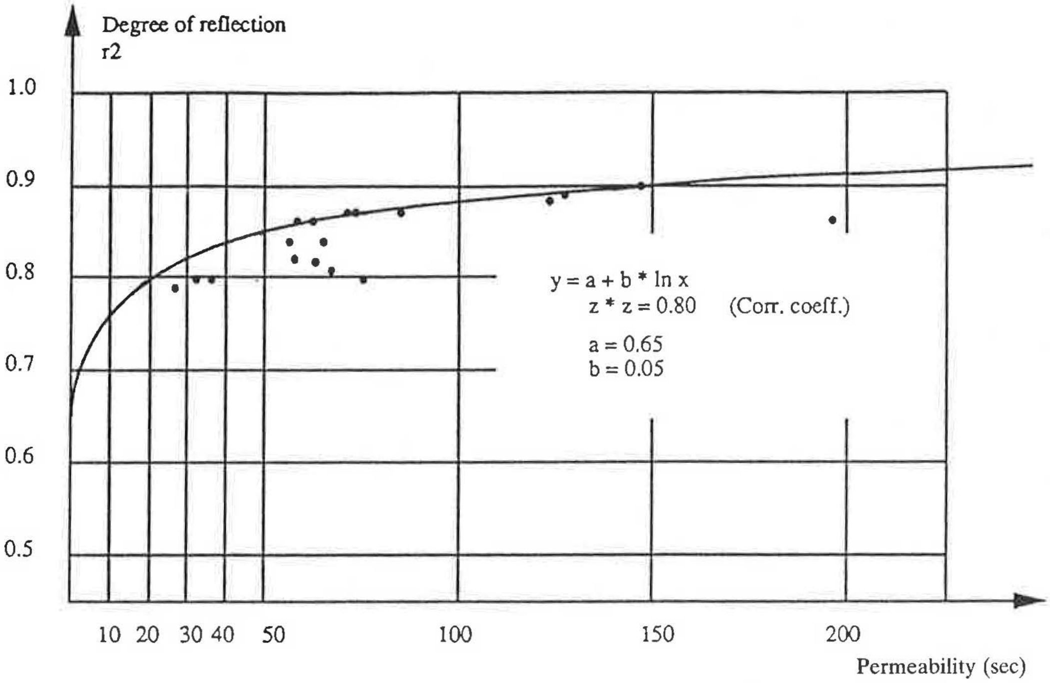


FIGURE 8 Relation between permeability and degree of sound reflection.

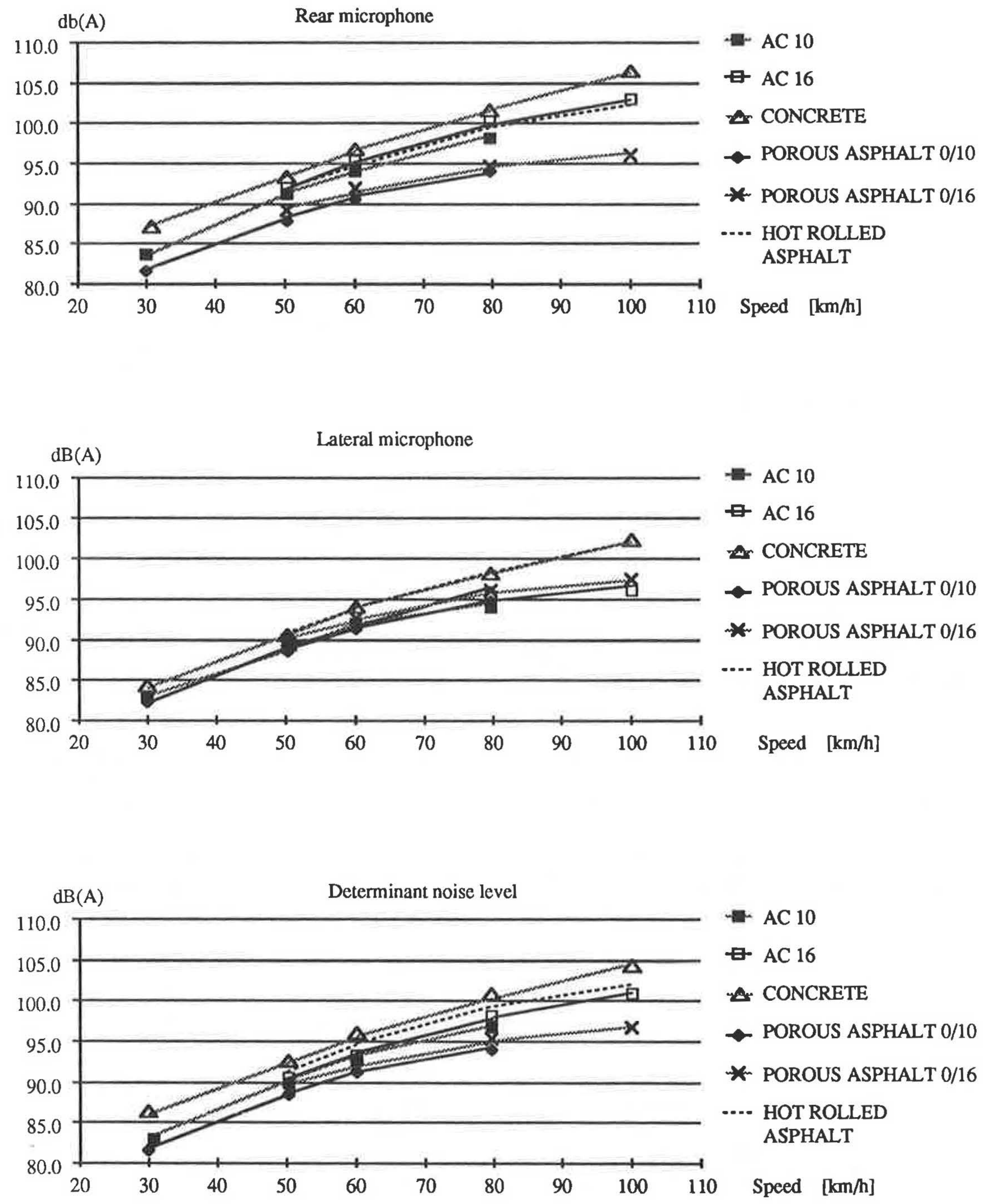


FIGURE 9 Mean values for rolling tire noise (LMA trailer) for selected pavement surfaces.

texture of porous asphalts used in Switzerland. The "acoustical optimization" or a porous asphalt leads to a finer texture of the surface.

The determinant LMA value gives an overall characterization of acoustical conditions. The difference in sound level for the porous asphalt with the lowest value and the corresponding conventional surface depends on the speed. Based on the results obtained so far, this difference is 1.5 dB(A) at 50 km/hr, 3.5 dB(A) at 60 km/hr, and 5.0 dB(A) at 80 km/hr. This shows that a reduction of rolling noise by the use of porous asphalt can be obtained primarily at a higher speed level. Similar results should be obtained in the comparison between porous asphalt and conventional materials when the mean values of rolling noise are considered.

A low noise level is not necessarily typical for all porous asphalts. The difference in noise level between all sections lies between 7 and 9 dB(A), a value corresponding to the difference between porous asphalts and dense-graded layers. A binder film at the surface seems to have a noise-reducing effect. Indeed, also on dense-graded asphalts, noise measurements carried out immediately after construction of the pavement had lower noise levels than for the same pavement at a later time. No influence was found in relation to the material (concrete or asphalt) of the pavement layer beneath the porous asphalt.

The noise level is influenced by aggregate size, size distribution, permeability, and the condition of the layer. Porous asphalts with smaller maximum aggregate size or a more continuous gradation have a lower noise level than coarse porous asphalt layers. Permeability also has a positive effect on the noise. However, the influence of texture seems to be more important because some pavements in the study still had low noise levels despite having filled voids and very reduced permeability. This again is particularly true for fine-textured porous asphalts, whereas coarse layers are generally noisy when their voids have been filled completely with dirt.

The observation that some porous asphalts still exhibit low noise volumes, even when the voids are filled, leads to the conclusion that the comparatively low noise level, of fine-textured porous asphalt layers in particular, is caused by a reduced rolling noise emission rather than the absorption effect of the pavement surface. Therefore, it should be possible, in attempting to achieve an "acoustical optimization" of conventional pavement surface layers, to obtain equal or even better rolling noise values than with porous asphalts, in particular when their permeability is reduced. A dense asphalt layer with a surface similar to that of a fine-textured porous asphalt therefore should perform quite will in respect to rolling tire noise.

Measurements with Roadside Microphone

Measurements with a roadside microphone were used to directly determine the effects of the construction of a porous asphalt on the noise nuisance at the roadside and to verify a possible relationship between values measured with the noise trailer LMA and roadside noise levels. This type of measurement involves considerable effort and gives valid results only in an acoustically appropriate environment (including traffic conditions). Therefore, such measurements were conducted only on selected sections.

Measurements would usually be carried out in the zone of a change in pavement type. A microphone was installed at a distance of about 30 m on both sides of the surface change at a distance of 6 m from the road edge and at a height of 1.7 m. Normally, the traffic noise of individual passenger cars driving at constant speed was measured and also the general traffic noise (L_{eq}). The value for traffic noise of individual cars was determined taking the mean value of 60 to 80 recordings of cars driving by at constant speed. Traffic noise, L_{eq} was determined from a number of short-time recordings of the total traffic (including trucks).

For traffic noise (maximum value) of individual cars, a level reduction between 1 and 5 dB(A) was measured for porous asphalt in good functional condition compared to conventional, dense layers. The magnitude of the reduction depends on the acoustical properties of the porous asphalt and the compared material. Traffic noise levels L_{eq} could be reduced with a porous asphalt in good functional condition between 0 and 3.5 dB(A) compared to the conventional material, depending on the type of porous asphalt, the compared material, and the traffic. In the case of two "before and after" comparisons with a microphone at a longer distance from the road edge (25 m, 75 m, and 140 m) on roads which previously had a concrete pavement traffic noise (L_{eq}), reductions of 3 to 5 dB(A) have been measured. But on older, coarse porous asphalts with filled voids, too, the noise values measured were higher than on the adjacent, conventional surface.

Noise Frequencies

Besides generally reducing noise level, porous asphalt often can also lead to a reduction of particularly disturbing higher sound frequencies. The remaining noise is then comparatively acceptable to human perception. For this reason, it has been possible to register positive reactions from road neighbors, even if the measurable difference in noise level would not justify such a reaction.

Traffic Noise: Conclusions

The noise-reducing effect of porous asphalt results from the following factors:

- Lower rolling noise at the source, particularly on fine-textured surfaces and at higher speeds,
- Absorption effect of the pavement surface. However, the absorption effect is rather limited on today's thin porous asphalt layers. In addition, this quality is not permanent because porous asphalts with a reduced or disturbed permeability show few or no signs of absorption, and
- "Pleasant" noise from a change in frequencies stemming from a rolling noise of lower sound frequency and the absorption "cutting off" higher frequencies.

Porous asphalts in good functional condition can potentially reduce the traffic noise level (L_{eq}) by 0 to 4 dB(A), compared to dense-graded asphalt layers and by 3 to 7 dB(A) compared to old concrete pavements. Porous asphalts with fine-textured surface generally are acoustically more favorable than coarse-graded ones.

Regarding the relatively low reduction in rolling noise compared to the more "silent" characteristics of the conventional dense-graded layers and the fact that the absorption effect is often limited in time, it would not seem appropriate generally to consider porous asphalt as the real alternative to other noise-reducing means such as noise barriers (walls) or sound-insulated windows, and so forth. This is particularly true in urban areas, where direct accumulation and the drainability of porous asphalt layers are a more serious problem and where engine noise is generally more relevant than rolling tire noise.

BEHAVIOR UNDER WINTER CONDITIONS

Problem Description

Despite the advantages mentioned so far, generally unfavorable behavior under winter road conditions is said to be a major disadvantage of porous asphalt. To investigate this problem in more detail, it was decided to run a series of skid measurements with the Skiddometer under winter road conditions on some sections, in addition to visual inspections and contacts with the road maintenance departments. Measurements were carried out with the test wheel brake only (slip ratio of 14 percent at a speed of 60 km/hr on motorways and of 40 km/hr on other roads). This choice was made because of very inhomogenous road surface conditions on one side and of the possible formation of a snow or slush wedge in front of a blocked wheel. The purpose of these measurements was to determine relative values as the basis for comparing porous asphalt and other surface materials. More than 160 measurement runs were made under winter road conditions in the winters 1981 to 1982, 1983 to 1984, 1984 to 1985, and 1985 to 1986.

Results of Skid Resistance Measurements for Winter Road Conditions

Road conditions in winter are very variable and can change rapidly with time. Therefore the results of skid measurements also show a large degree of variation. Generally, it can be said that skid values on porous asphalt are in the same range as those measured on conventional, dense asphalt layers. In the winters 1981 to 1982 and 1984 to 1985, porous asphalts were rather better, and in the winters 1983 to 1984 and 1985 to 1986, rather below compared materials, but this depended on the situation at the moment the measurements were carried out (Table 1).

It also was found that the influence of other factors is generally more important than the type of pavement surface. Such other factor are microclimate, side vegetation, wind exposure, width of the roadway, and so forth. In comparing different sections under winter road conditions, differences concerning the factors mentioned above must be considered. It also was observed that porous asphalt with filled voids and a permeability of less than 1 L/min behaved in almost the same manner as conventional, dense asphalt layers with similar surface texture. Differences in the behavior of porous asphalt show up mainly on heavily trafficked roads in areas not directly covered by traffic (center of a lane, center, and edges of the road).

Winter Conditions: Conclusions

Porous asphalt surfaces generally do not behave worse than conventional pavement materials under winter road conditions. The differences in behavior could, in areas of the change of surface material, lead to increased traffic hazards due to inhomogeneity. However, it should not be forgotten that road surface conditions are very inhomogeneous in winter. Their variability depends strongly on time and location (shaded areas, altitude, wind, winter maintenance, etc.). Variations in skid values for porous asphalt layers lie overall within the variations observed for conventional pavement materials.

The main differences in behavior of porous asphalt under winter road conditions can be summarized as follows:

- Advantages of porous asphalt: Ice formation on a wet surface is generally prevented because of good surface drainage and a good macrotexture. This good macrotexture is also an advantage for porous asphalt on snow and slush. The tendency for ice formation in the wheel tracks on roads covered with snow is reduced again by macrotexture, water absorption within the layer, and limited thaw.
- Disadvantages of porous asphalt: Winter maintenance on porous asphalt surfaces requires the use of deicing salts and other thawing products. The use of sand and small aggregates is not possible because of the negative effect on the void structure. Snow has a tendency to stick sooner on a porous asphalt surface because of its generally colder surface (about 0.5°C). Snow and icing rain can also form earlier on porous asphalts because deicing salts do not remain on the surface. Preventive salting does not make great sense, because the salt sinks into the voids or is blown away. If the drainage within the porous asphalt layer is bad, ice can build up within the layer and expand later on the surface. In this case, preventive salting may be appropriate. The absence of a salt solution on the surface outside the wheel tracks can also keep the snow on the surface longer. With reduced traffic and winter maintenance, this problem can also appear in the wheel tracks. It also has been observed that some icing problems can occur in the initial part of the following road section with a conventional surface, which does not receive salt, by transportation through road traffic from the preceding porous asphalt section.

TABLE 1 GENERAL DATA ON POROUS ASPHALTS IN SWITZERLAND

	1981/82	1983/84	1984/85	1985/86	
AC 1	0.67	0.57	0.36	0.58	
Porous asphalt 1	0.62	0.48	0.48	0.58	voids filled since 1984/85
Surface treatment	0.63	0.64	0.58	0.65	
Hot rolled asphalt			0.51	0.61	
Porous asphalt 2			0.52	0.54	
AC 2			0.51	0.57	
Mean value	0.63	0.56	0.49	0.59	

Measurements carried out with braked wheel (slip ratio 14%), speed = 40 km/h

The disadvantages of porous asphalt in winter can be controlled by intensive winter maintenance. The reduced effect of salting porous asphalt surfaces must be compensated by more intensive salting. Critical times are the beginning of snowfall and, in certain cases, the thaw period.

SUMMARY AND CONCLUSIONS

The experiences so far with porous asphalt layers on motorways and similar roads can be qualified as good. Their excellent quality in surface drainage reduces the risk of hydroplaning and sight-disturbing spray. Porous asphalt layers can also be used for dealing with drainage deficiencies in zones of change in crossfall, even if this use of porous asphalt is not optimal in view of the accumulation of water within the pavement and its consequences for the qualities of the layer. Skid properties of porous asphalt are adequate for motorway requirements.

On motorways, too, the durability of a good permeability can be expected. Drainage at the edges of the layer normally does not cause any problems and winter maintenance can be controlled. At higher speeds, traffic noise is also significantly reduced and the remaining noise is experienced as more pleasant.

Results are not quite so positive in urban areas. Major problems are the drainage of the layer at the edge and frequently a rapid reduction in permeability. Skid properties of porous asphalt are often inadequate for the needs of urban traffic. The use of deicing salts, generally tending to be used increasingly less often in residential areas, is imperative for porous asphalt. Pavement repair work, frequently in conjunction with the utility work in the roadway, is also a specific problem for urban conditions. At lower speeds, the measurable effects in noise reduction are well below certain expectations. And many porous asphalts soon lose their noise advantage with decreasing permeability. At lower traffic speeds, then, porous asphalts are not different from conventional pavement materials. Thus, the noise problem in urban areas generally cannot be solved with the use of porous asphalt. Rather, this problem might be solved by developments in vehicle technology, traffic management, passive means of noise protection, and eventually by the development of new noise-reducing road surfaces.

Advantages and Disadvantages of Porous Asphalt

Advantages

- Reduction of hydroplaning on motorways,
- Spray reduction generally, particularly on motorways,
- Good skid properties at higher speeds on motorways,
- Noise reduction, generally, particularly on motorways,
- Reduced glare at night and on wet surfaces generally, and
- Good resistance to permanent deformation generally, particularly on motorways.

Disadvantages

- Poor durability of good qualities by loss of permeability, generally, particularly in urban areas,
- Unknown durability (oldest porous asphalts of the new generation only 5 to 6 years old) generally, particularly on motorways,
- Special requirements for (lateral) drainage in urban areas,
- Unfavorable skid properties at low speed in urban areas,
- Different behavior for winter road conditions, use of salt, generally, particularly in urban areas,
- Repairs, utilities in urban areas, and
- Costs, particularly in urban areas (special drainage).

Before using porous asphalt layers on a large scale, some open questions should be answered. The principal problem is durability; others include quality requirements and control, the study of possible ways to improve the development of permeability, and more experiences are needed. Research on the acoustic properties of road surfaces should also be intensified. In the future, it might be useful to differentiate between porous asphalts used as a safe surface with good drainage on the one hand and those used as noise-reducing surfaces on the other hand. In this second group, porous asphalts are not necessarily the only surface. Optimal texture can already reduce rolling tire noise; in addition, a porous structure can also produce a sound absorption effect. Today's porous asphalts are not yet satisfactory for urban situations. The use of porous asphalts is very interesting on motorways and other roads with constant, fast traffic and little dirt accumulation, where they improve traffic safety and also contribute to reducing traffic noise.

Experiments with Porous Asphalt on the Nantes Fatigue Test Track

M. HUET, A. DE BOISSOUDY, J.-C. GRAMSAMMER, A. BAUDUIN, AND J. SAMANOS

Within the framework of an agreement between the French Public Works National Research Institute, SCREG Routes et Travaux Publics, and its regional subsidiary SCREG Ouest, comparative experiments were carried out on several porous asphalts using the Nantes circular fatigue test track. This facility is designed to accelerate the effect of heavy traffic, making it possible to compare different pavement structures. Although this has never been done before, SCREG Routes et Travaux Publics and French highway authorities decided to use this equipment to follow the evolution of porous asphalts under traffic. Four mixes were selected, differentiated by the nature of the binder and the grading curve. One had a base of pure asphalt cement, two of elastomer (SBS) modified binder, and the last, developed by SCREG Routes et Travaux Publics, was pure bitumen and fiber based. After a short description of the test facility, the methodology developed for investigating the on-site properties of porous asphalts and presenting the results is defined. It is concluded that the experiments made it possible to observe trends in porous bituminous mixes under traffic, demonstrate the influence of mix design parameters on the stability of properties, and confirm the excellent performance of fiber-based porous asphalt.

Porous asphalts have been developing rapidly in France. Their high void content (about 20 percent) gives them hydraulic and acoustic characteristics that provide user safety and comfort. Several variants are available, provided by both government departments and industry. They differ by their grading curve, binder content, or binder specification, as well as in some cases by their additives. Whatever the mix design, however, the aim is to obtain sufficiently good initial draining performance that can withstand traffic use.

The Public Works National Research Institute (LCPC) fatigue test track accelerates the effects of heavy traffic so that structures can be compared. Although the test track had never been used for testing wearing courses, SCREG Routes and the French highway authorities thought it would be interesting to try it out to observe porous asphalts in heavy traffic conditions. Four different mixes were selected and an agreement drawn up between LCPC, SCREG Routes, and its subsidiary, SCREG Ouest.

NANTES FATIGUE TEST TRACK

The LCPC fatigue test track, situated on the Nantes–Bouguenais site of the Central Laboratory, was designed to study the mechanical performance of road structures under accelerated heavy traffic loads. This means in practice that the equivalent of 15 or 20 years of normal traffic can be simulated in a few months.

The units consist of four arms rotated by a central hydroelectric 1,000 hp motor. Loads are attached to the ends of the arms by single or double couplings. The rotation radius of loads can be varied between 15.5 m and 19.5 m by half-meter steps. When working, the loads go around the track and also zigzag to simulate real conditions. Each load can therefore use a surface up to 1.6 m wide.

With a single configuration, the test track simulates axle loads adjustable from 9 to 15 tons. Maximum speed in this configuration is 100 km/hr. A novel suspension device controls load weight at high speeds and on uneven or damaged surfaces. With this device, the load applied to the surface remains near the nominal calculated load at all times.

TEST SITE

The test track is a circular road whose average radius is 17.5 m. It is 6 m wide and can be divided into two concentric tracks each 3 m wide with average radii of 16 and 19 m. The porous asphalts were applied to the inner part of the track, which has an average radius of 16 m and a width of 3 m. This is shown in Figure 1.

MIX DESIGNS

Of the four mixes selected, two were developed by LCPC; the others are the results of the following SCREG ROUTES techniques under development:

- Section 1—grading curve, 0/14 mm; gap grading, 2/10 mm; binder, pure asphalt cement.
- Section 2—grading curve, 0/14 mm; gap grading, 2/10 mm; binder, SBS modified asphalt.
- Section 3—grading curve, 0/14 mm; gap grading, 2/6 mm; binder, SBS modified asphalt cement.
- Section 4—grading curve, 0/14 mm; gap grading, 2/6 mm; binder, pure asphalt cement with mineral fibers.

The SBS modified asphalt cement contains 4.5 percent of SBS. Its penetration at 25°C is 130 (0.1 mm) and its ring and ball softening point is above 65°C. The mixes put forward by the LCPC were designed using a gyratory shearing press. The binder contents are given in Figure 2.

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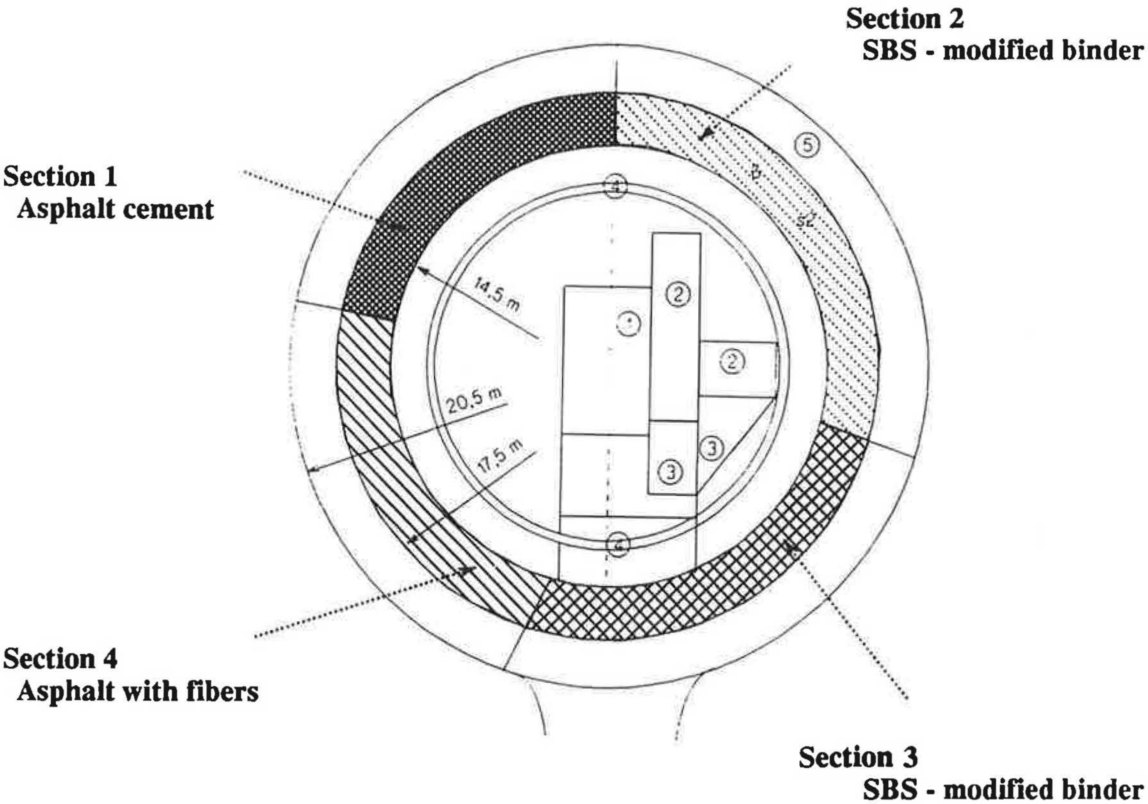

FIGURE 1 Test setup showing the different types of binders used in porous asphalts.

Section		1	2	3	4
Binder type		Pure Asphalt Cement	SBS-Asphalt Cement	SBS-Asphalt Cement	Pure Asphalt Cement
Binder content	pha	4.5	4.5	4.5	6.0
Fibers	%	-	-	-	1
Material		Diorite	Diorite	Diorite	Diorite
Origin		La Noubleau	La Noubleau	La Noubleau	La Noubleau
Grading curve		0/14	0/14	0/14	0/14
Gap		2/10	2/10	2/6	2/6
Quality Control					
Binder content	pha	4.1	4.8	4.2	5.6
Filler Content	%	5.4	5.6	5.6	9.5
Grading curve					
Passing at 2 mm	%	13	15	16	14
Passing at 6 mm	%	17	17	24	23
Passing at 10 mm	%	24	24	57	55
On-site					
Thickness	cm	4.2	3.4	3.8	4.2

FIGURE 2 Details of the trial sections.

MANUFACTURING AND APPLICATION

Manufacturing and application were carried out by Screg Ouest in July 1987. Section-by-section control results are shown in Figure 2.

RESULTS

The experiment took place between August 17 and October 22, 1987. It was thus started three weeks after the asphalt was laid. The total number of loads was 1,100,000.

Visual Appearance

From the beginning, differences in appearance were visible and continued to be so throughout the experiment. These differences were related to different grading curves. The two asphalts with a 2/10 gap had a seemingly more porous appearance than those with a 2/6 gap. At the end of the experiments, after 1,100,000 cycles, the four asphalts showed no surface deterioration.

Void Content

The initial values and their changes were calculated using apparent density from three or four core samples. The results are given in Figure 3 and the corresponding graph in Figure 4. It appears that highly discontinuous 0/14 formulations lead to a considerable reduction in void content (reduced by 28 percent and 21 percent in relative value, respectively, for the pure asphalt mix and for SBS asphalt). On the other hand, asphalt, with fibers that had a high void content at the start, remained at its initial level throughout the experiment. Section asphalt based on SBS-modified binder and a 2/6 gap provided an intermediate result.

Number of loads	Section 1	Section 2	Section 3	Section 4
4,000	17.1	21.3	19.4	23.2
24,000	17.3	18.3	18.8	23.2
100,000	16.9	17.5	19.8	23.9
600,000	13.3	18.7	16.8	22.0
1,100,000	12.4	16.7	16.4	23.8

FIGURE 3 Void content of core samples.

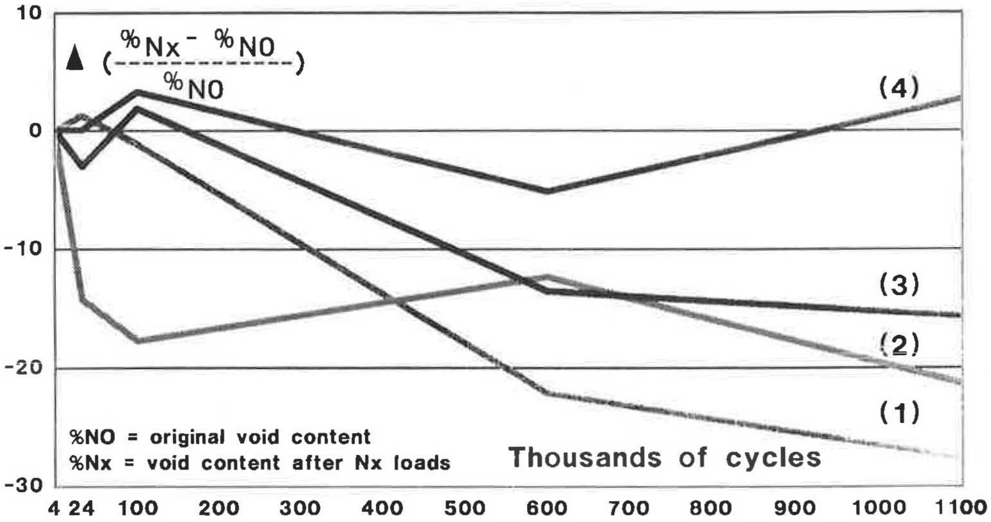

FIGURE 4 Relative change of void content during the experiment.

Rut Depth

Measurements taken by "transversoprofilograph" at various stages of the experiment led to the calculation of the average rutting for each section. The graph in Figure 5 shows the results obtained and points out greater speed of deformation at the beginning of the experiment. Beyond 600,000 cycles, stabilization can be seen for all the asphalts. This could have been influenced by the ambient temperature during the experiment. With time, rut depth divides the asphalts into two distinct groups. The first includes the asphalts based on pure asphalt cement and SBS modified binder (2 and 3). Overall rut depth is about 5 mm with a slight advantage going to the SBS modified binders sections. This could result from the high ring and ball softening point of this binder. The second consists only fiber-based asphalt which had a very slight deformation of 2 mm after 1,100,000 cycles.

These results are consistent with the change in void content, thus tending to prove that the rutting observed partially corresponds to the increasing density of the asphalt, probably related to postcompacting. Calculations indicate, however, that this phenomenon is not the only reason for deformation.

Hydraulic Properties

Effective Porosity and Horizontal Permeability

Figure 6 illustrates how the results evolve under traffic conditions. A clear advantage of between 5 and 7 percent can again be noted in favor of fiber-based asphalt. The other three mixes perform similarly. After swift change at the beginning, porosity, as with rutting, stabilizes; in this case, after 100,000 passages.

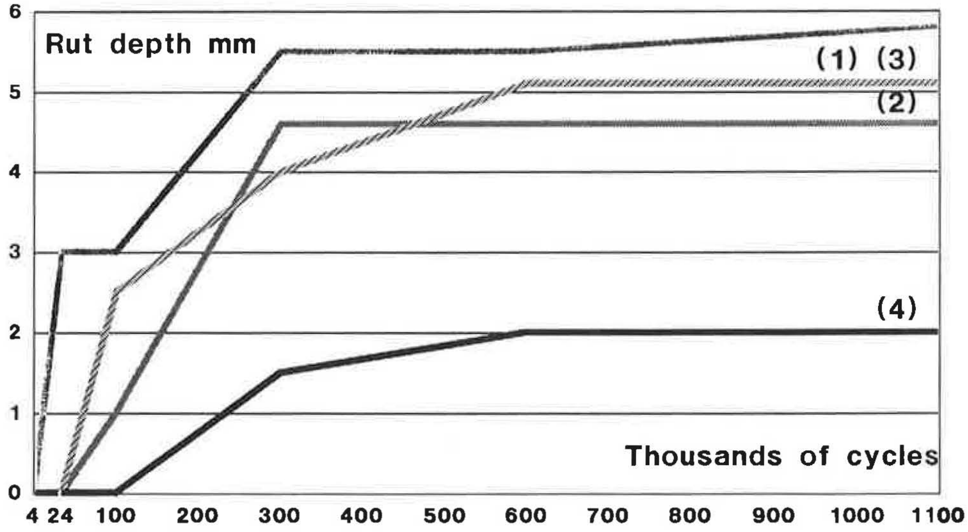

FIGURE 5 Rutting.

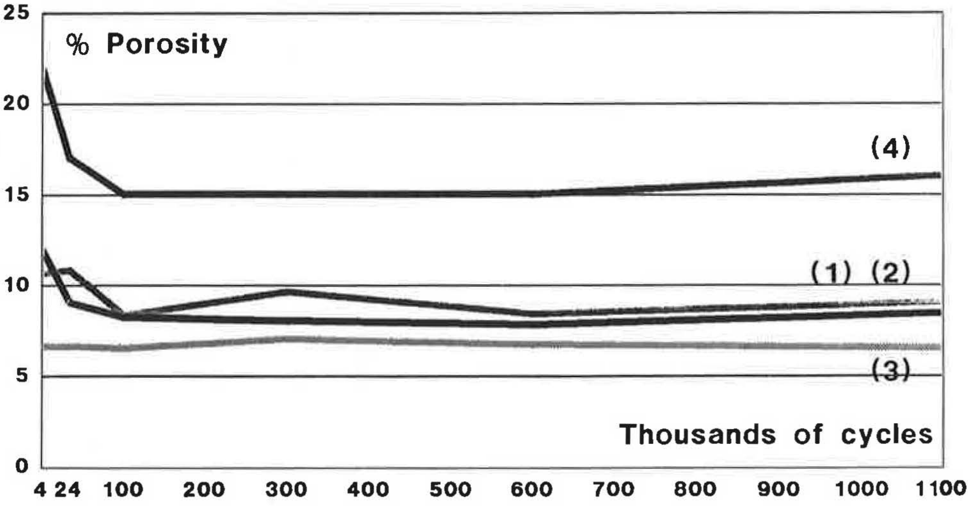

FIGURE 6 Porosity.

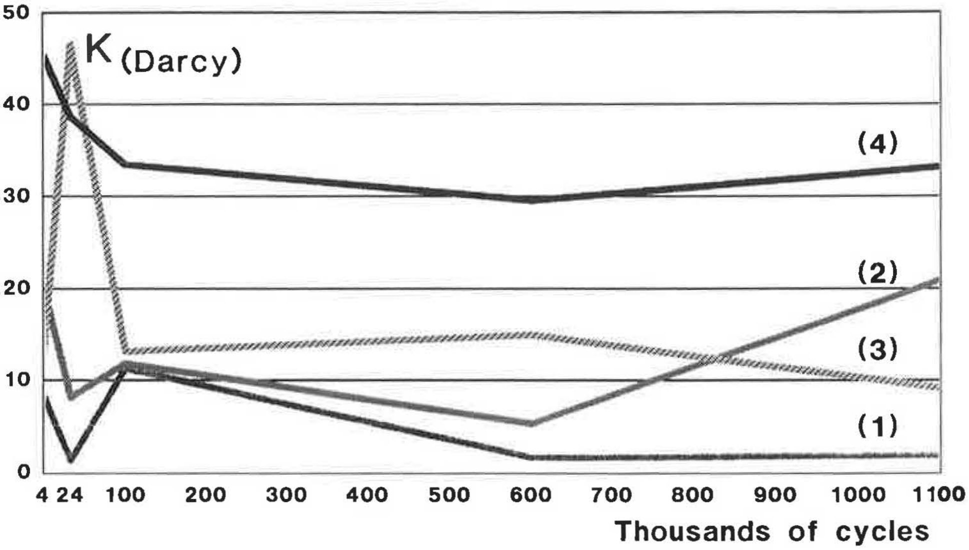

FIGURE 7 Permeability of core samples.

Permeability measurements made in permanent water flow conditions gave tightly grouped results varying over the whole experiment between 2 and 3×10^{-2} m/sec. These results are all satisfactory because it is generally recognized that permeability is adequate when lateral water evacuation exceeds 10^{-4} m/sec.

Vertical Permeability

Whatever the pressure used in laboratory measuring, the results are scattered for cores of Sections 1–3 unlike Section 4. Therefore, they are not easy to interpret. Comparison between the mixes, however, indicates, as in the previous test, a clear advantage in favor of asphalt with fibers, and on the other hand a low level for the highly discontinuous pure asphalt cement formula (Figure 7).

Surface Characteristics

Macrotexture by sand patch test and macroprofilograph: The values obtained are high for all tested porous asphalts, regardless of the number of cycles. It should be noted, however, that the highly gap-graded formulas give better results at the beginning of the experiment as well as after 1,100,000 cycles.

CONCLUSION

This experiment carried out on the LCPC's fatigue test track is innovative for several reasons. The track was designed to assess the fatigue behavior of road structures, and this was the first time wearing courses were studied.

In this series of tests, four porous asphalts were compared. One was based on pure asphalt cement, two were based on modified binders (differing from each other by the gap of the grading curve), and the last was based on asphalt cement with fibers.

Now that the experiment, which took place over 1,100,000 cycles, is finished, a number of conclusions can be drawn:

- Despite their lower mechanical properties compared with dense asphaltic mixes based on identical binders, porous asphalts underwent no surface deterioration during the tests.
- Under traffic conditions, the void content of the porous asphalts generally tends to diminish. As this increased density occurs, there is also slight surface rutting and a reduction in hydraulic properties. Surface characteristics also undergo modifications.
- At the end of the experiment, it clearly appeared that the fiber-based porous asphalt had undergone no reduction in void content; its drainage properties were practically unchanged and rutting was minimal.
- The other three asphalts had lost a considerable proportion of their void content: −28 percent in related value for the porous asphalt based on pure asphalt cement, −21 percent and −16 percent, respectively, for Section 2 and Section 3 asphalt based on SBS modified binders. This change appears to be related to, on the one hand, the size of gap of the grading curve (the void content of the asphalt with a larger gap in the grading curve underwent an even greater change), and on the other hand, the nature of the binder (with the same grading curve, the change in void for SBS modified binder is less than that of pure asphalt cement). This void content drop is accompanied by slight rutting and a reduction in drainage properties. From these two latter standpoints, the differences between the three asphalts are very small.
- Porous asphalts with a large gap in the grading curve have significantly better macrotexture both at the beginning and the end of the trial than those of a smaller gap (2/6).

Although such an experiment cannot simulate all conditions such as the filling-in effect of dust, binder aging, and weather conditions, the operation nevertheless proved useful. The precise test methodology allowed the modification of porous asphalt to be observed under traffic conditions and SBS modified binder-based porous asphalts to be improved. The superior performance of porous asphalt with fibers has been confirmed.

Optimization of Porous Mixes Through the Use of Special Binders

F. E. PÉREZ-JIMÉNEZ AND J. GORDILLO

The studies carried out in the laboratory to value the effect of the use of special binders in the manufacturing of porous mixes are covered in this article. The results obtained from the use of polymeric bitumens and conventional binders are compared. These studies were conducted in the Road Laboratory of the University of Cantabria and in the E.S.M. Research Center. It also reflects the performance of some sections constructed with polymeric bituments as compared to the response of porous pavements fabricated with conventional binders.

In recent years, the use of porous mixes as a wearing course has demonstrated enormous advantages and many road technicians, especially in Spain, are selecting them. This use has made evident the properties to be emphasized in these mixes in order to achieve good medium- and long-term performance: on the one hand, resistance to disintegration and, on the other, porosity.

The basic mechanical characteristic to be taken into account in the design of these mixes is the resistance to disintegration. An observation of sections in service reveals that scabbing, potholes, and aggregate losses appear very frequently in this type of pavement. These deficiencies stem from a drop in the cohesion of the mix, making it unable to adequately resist the abrasive effect of traffic.

In addition, these mixes must have a high degree of porosity if their beneficial effect on the circulation of vehicles is to be appreciable and maintained on a medium- and long-term basis. The advantages that these mixes offer for improvements in traffic circulation in wet conditions are directly related to their permeability. The greater the permeability, the greater the pavement's drainage capacity and the more difficult it will be to encounter splashes or vehicle skidding.

The acoustics of these mixes also depend on their porosity. The greater the porosity and the thicker the draining course, the greater the pavement's capacity to reduce traffic noise and improve the quality of life of those living near the road.

The initial porosity achieved also functions to maintain these properties over a long term. With a low initial percentage of porous, (16 to 18 percent, the filling of these mixes usually takes place in a short period, and they lose a large part of their initial properties. One can deduce from the experience of the pavements in service that it is convenient to design these mixes with a high percentage of porous (more than 21 to 22 percent), in order to maintain a high degree of their permeable characteristics during their active life.

A problem arises because the two properties considered are in opposition. An increase in porosity always represents a loss of cohesion and less resistance to disintegration in the manufactured mix. In fact, it is sometimes difficult to reach a satisfactory solution with the use of conventional materials and binders, and it becomes necessary to resort to special binders in order to improve their properties and, at the same time, achieve elevated porosity and adequate cohesion.

Moreover, utilization of these special binders has other effects which must be considered when using this type of mix. They increase the film thickness of the binder and reduce the risk of binder runoff when the mix is transported. They also improve the mix's adhesion and its resistance in the action of atmospheric agents.

The studies carried out in the laboratory to evaluate the effect of the use of special binders on the manufacturing of porous mixes are covered in this article. The results obtained, from the use of polymeric bitumens and the use of conventional binders, are compared. These studies were carried out in the Road Laboratory of the University of Cantabria and in the E.S.M. Research Center. The performance of certain sections constructed with polymeric bitumens compared with the response of porous pavements constructed with conventional binders are also discussed.

LABORATORY STUDY

The laboratory study centered on the effect produced by the incorporation of polymeric bitumen on the following properties of the mix:

- Resistance to plastic deformations,
- Resistance to indirect traction,
- Resistance to disintegration,
- Adhesiveness, and
- Runoff.

The grading of the mix studied is that of a continuous open type, ophite aggregate, with the following characteristics: maximum size, 10 mm; percentages passing through the sieves of 5, 2.5, and 0.080 mm, 30, 10, and 4 percent, respectively.

Two bitumens of a similar penetration are used with this grading, one having been modified by the incorporation of a mix of polymers.

These two binders were chosen prior to laboratory analysis of different types of polymers and their effect on bituminous binder. For this study, an 80/100 bitumen was chosen, modified by the incorporation of an EVA type polymer, whose

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characteristics are given in Table 1. (Toughness and tenacity are measured by pulling a hemispherical screw-head out of binder specimen at 25°C.) The same table also includes the characteristics of the B-60/70 bitumen used. The differences between the binders are notable, especially with respect to their toughness and thermal susceptibility.

Resistance to Plastic Deformations

The study of the resistance to plastic deformations was carried out with the use of the wheel tracking test at a temperature of 60°C. The percentage of binders over aggregates tested ranged from 4.0 to 4.5 percent for both mixes.

In Figure 1, it can be observed that with the use of polymeric bitumen, there is greater resistance to plastic deformations than with the mix fabricated with ordinary bitumen, which is itself resistant and displays good performance in practice, and represents greater security in the face of this type of deficiency.

The use of polymeric bitumens can diminish the effect of postcompacting by traffic, which is sometimes observed in porous mixes.

Resistance to Indirect Traction

The effect of the binder on improving resistance to traction of this mix was studied through the rupture of Marshall test samples at a diametrical compression.

The tests were carried out at two temperatures: 5 and 45°C, and for a charge application velocity of 50.8 mm/min. The Marshall test samples were compacted with an energy of 50 blows per face, in accordance with the compacting energy employed in the sections and the densities reached.

The test results, as can be seen in Table 2 and Figure 2, show a better performance of the mix made with polymeric bitumen compared with that made with ordinary bitumen. This difference is more significant at 45°C than at 5°C, which leads to the belief that the use of a lower rupture velocity would have made manifest the difference with respect to flexibility and toughness presented by these two binders in use.

Nevertheless, the results obtained show an increase in the traction resistance of 20 to 30 percent for polymeric bitumen with respect to ordinary bitumen at 45°C.

Resistance to Disintegration

This is perhaps the most valuable property in these mixes and it is here that the effect of the bitumens modified with polymers becomes more evident.

Disintegration resistance is tested in the laboratory through the Cantabro test of wear loss, consisting of introducing Marshall samples into the Los Angeles machine (without balls) to obtain their weight loss after 300 drum revolutions. This test has been used as a basis for Spanish standards for establishing design criteria for these mixes. In accordance with this test, Spanish design criteria are the following:

- The voids in mixes should be more than 18 percent and, preferably, not less than 20 percent, and
- The test loss will be no more than 35 percent and, generally, no more than 30 percent, if the test is carried out at 18°C.

These values refer to Marshall test samples compacted by 50 blows per face.

The final results clearly show the advantages of using polymeric bitumens over traditional ones. For the same binder

TABLE 1 CHARACTERISTICS OF THE BINDERS TESTED

	B - 60/70	Polymeric bitumen
Penetration at 25 °C (0,1 mm)	65	70
Softening Point (°C)	50	68
Penetration Index	- 0,5	+ 1,9
Fraass Point (°C)	- 8	- 13
Plasticity Index (°C)	58	81
Toughness (Kg.cm)	4	157
Tenacity (Kg.cm)	95	229

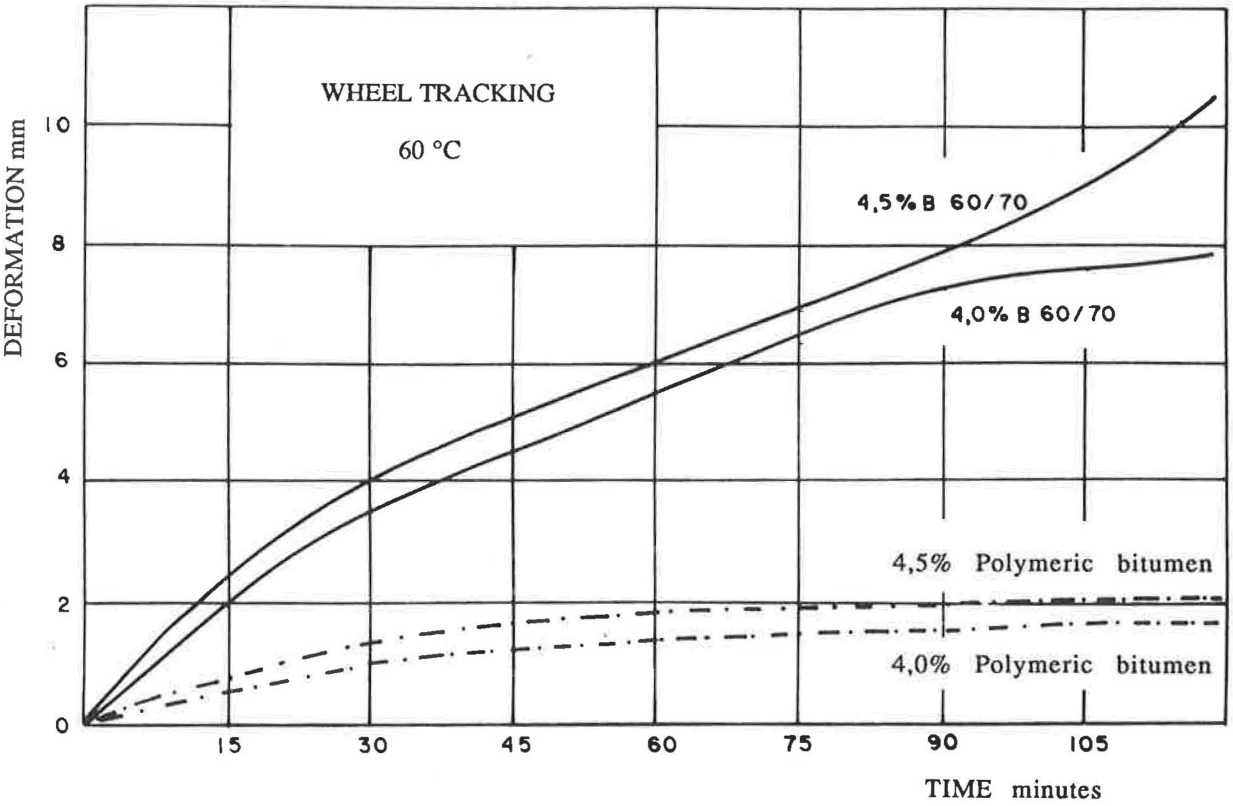


FIGURE 1 **Resistance to plastic deformation.**

TABLE 2 EFFECT OF TEST TEMPERATURES AND PERCENTAGE OF BINDER ON ULTIMATE TENSILE STRENGTH.

	Ultimate tensile strength (Kp/cm2)					
	3,5% binder		4,5 % binder		5,5% binder	
Test temp. °C / Binder type	5	45	5	45	5	45
Polymeric bitumen	71,5	3,8	72,5	3,5	70,1	3,1
B - 60/70	65,4	2,9	69,6	2,9	71,0	2,7

content and with similar void percentages, the use of polymeric bitumens reduces the losses by 15 to 20 units, as can be seen in Table 3 and Figure 3. Thus, the non-utilization of polymeric bitumen would result in the rejection of the selected mix according to Spanish standards, except for the use of 5.5 percent of binder with the consequent loss of voids in the mix and the possible problem of binder runoff.

Adhesiveness

Another important property to be considered in these mixes is their resistance to the stripping effect caused by water. Their high porosity favors this water action, which can cause rapid disintegration of the mix in cases using aggregates and binders with a deficient adhesiveness factor.

In this study, the resistance to this stripping action was evaluated in the Cantabro wear test be determining the loss in the test sample that was submerged in water at 49°C for four days.

The results, given in Table 3 and Figure 4, show that the mix manufactured with elastomeric bitumen maintains a high resistance to disintegration after the period of water immersion, even higher than that displayed when dry by the mix manufactured with B-60/70 bitumen. On the other hand, the mix fabricated with ordinary bitumen loses a large part of its

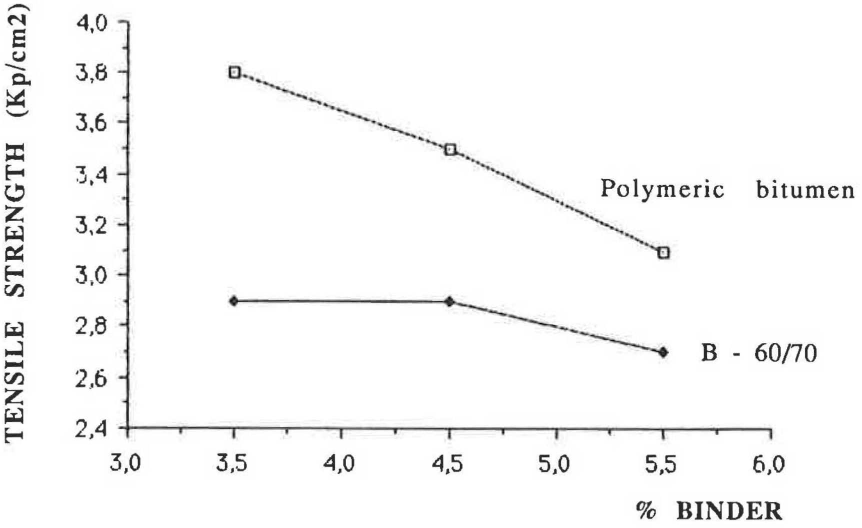


FIGURE 2 Influence of binder type on tensile strength (indirect traction test at 45°C).

TABLE 3 VOIDS AND LOSSES IN THE TWO MIXES TESTED IN THE CANTABRO WEAR TEST

	B - 60/70			Polymeric bitumen		
% binder s. a.	3,5	4,5	5,5	3,5	4,5	5,5
Voids (%)	24,1	22,2	20,2	24,1	22,1	19,9
Dry losses	46	40	33	30	20	15
After immersion (%)	86	65	50	52	32	24

cohesion, resulting in very high losses in the tests, even for the 5.5 percent binder.

These results emphasize the greater adhesiveness of the polymeric bitumen compared with ordinary bitumen, which can also be seen in the increase in losses in the tests after the immersion period. Thus, although the increase in test losses for the polymeric bitumen after the immersion period ranges from 9 to 22 points, this gain varies from 18 to 40 points for ordinary bitumen.

Runoff

This problem sometimes occurs in these mixes, especially when they are manufactured with a low fines content and a high percentage of binder. In such cases, it is possible that a runoff of the binder to the bottom of the truck layer may occur during transport. This represents a weakening of the bitumen and a loss of the mix's cohesiveness, which may rapidly become evident by its quick disintegration by traffic.

The tests carried out in the laboratory to ascertain the influence of the binder type on runoff showed, as can be observed in Table 4, that the use of a polymeric bitumen can notably reduce runoff, especially when vibration exists, as normally occurs in the transport of this mix.

The test consisted of putting 1,000 g of mixture into a capsule and introducing it for 1 hour into an oven at the test temperature of 140 or 160°C. After the time had elapsed, the capsule's contents are emptied and the parts that adhered to the walls are weighed. When the test is conducted with vibration, the test continues, after taking the capsule out of the oven and before pouring its contents, with a series of shakings on the table for 15 minutes for compacting test samples of cement mortar.

The results demonstrate that, at 140°C and with vibration, a runoff of ordinary bitumen is clearly produced while for the polymeric bitumen it remains at very low values, barely staining the bottom of the capsule.

POROSITY VERSUS RESISTANCE TO DISINTEGRATION

The design of porous mixes must compromise between porosity and resistance to disintegration. The porosity is necessary

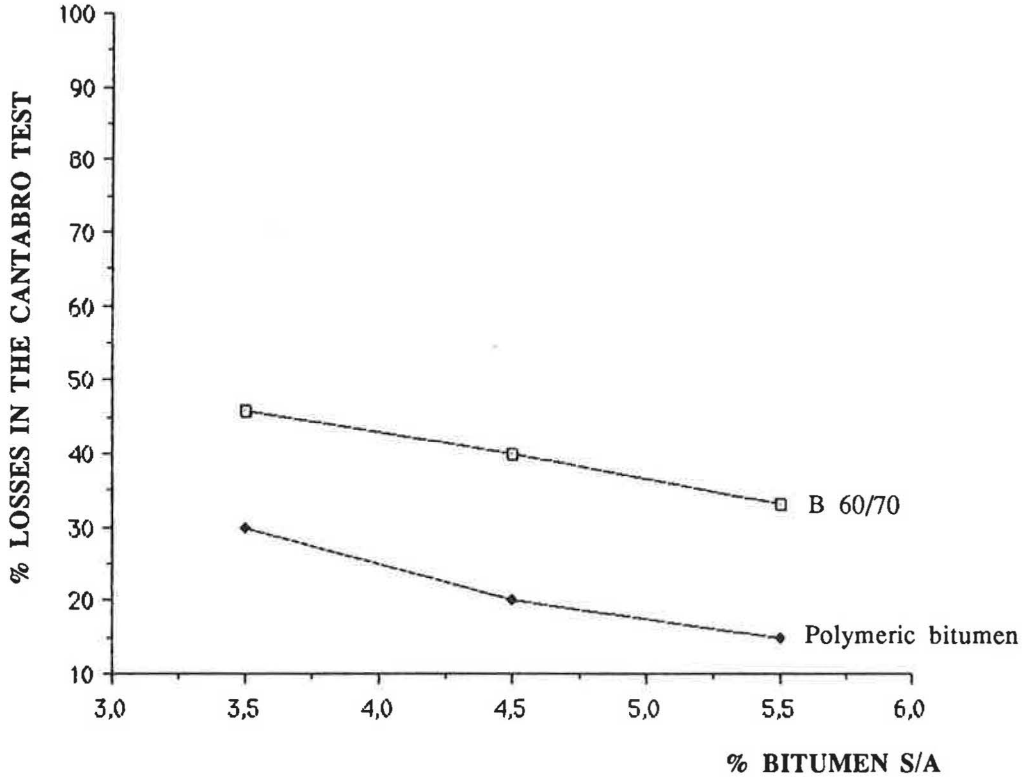


FIGURE 3 Effect of the type of binder on losses in the Cantabro test.

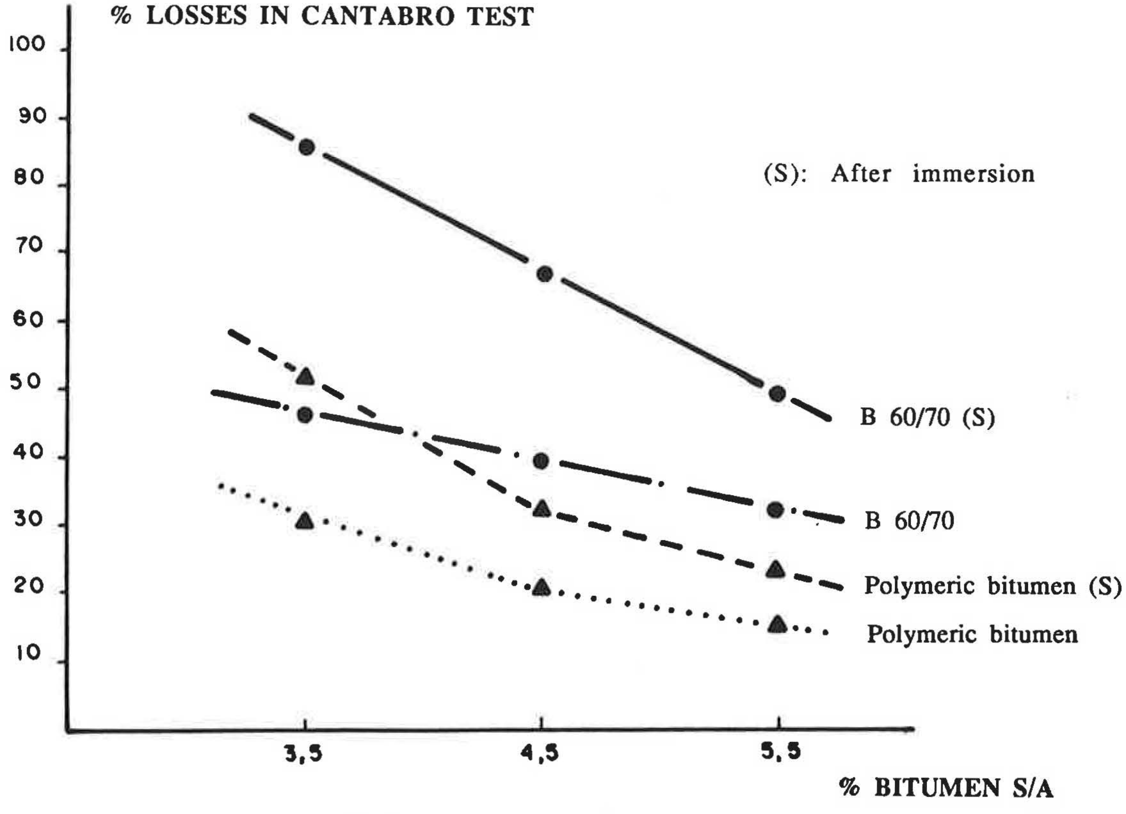
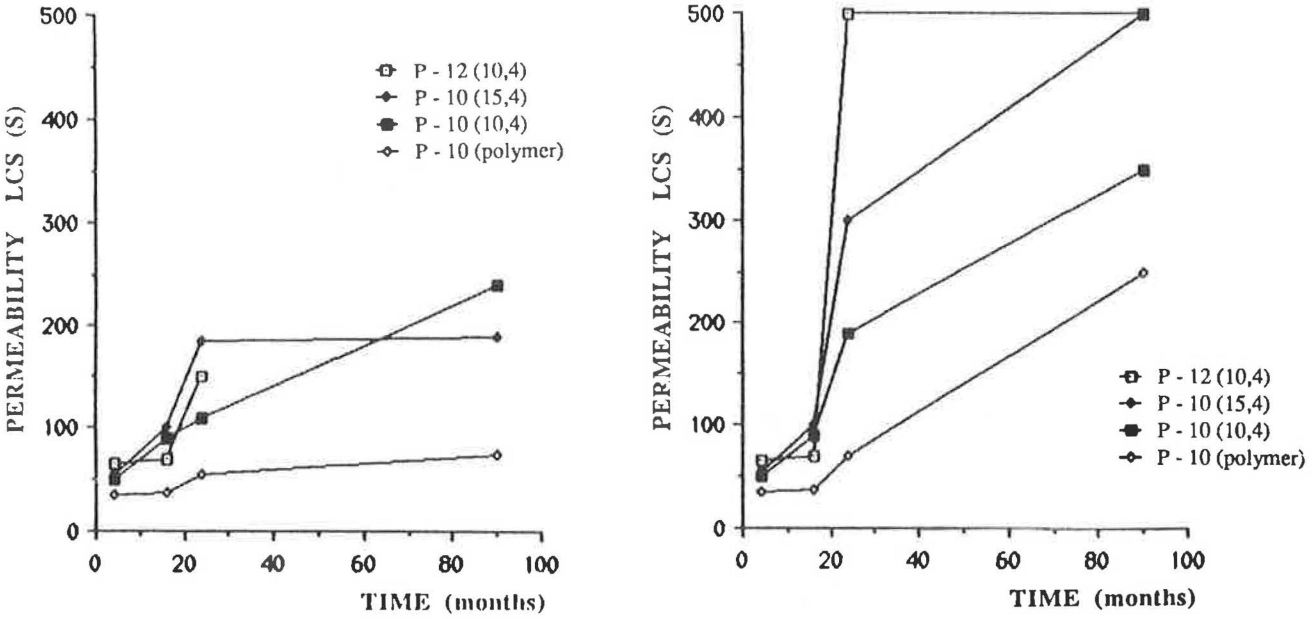


FIGURE 4 Effect of binder on adhesiveness.

TABLE 4 INFLUENCE OF BINDER TYPE ON PERCENTAGE OF DRAINED WEIGHT

	Without vibration		With vibration	
	5% of binder		5 % of binder	
Test temp. °C / Binder type	140	160	140	160
Polymeric bitumen	1,4	1,9	1,8	4,0
B - 60/70	1,6	2,0	5,1	5,3



a.-Track

b.- Between the edges

FIGURE 5 Evolution of permeability with time.

to appreciate to a high degree the qualities that these mixes possess and maintain these qualities over a certain period. The resistance to disintegration is necessary for the mixes to resist the tangential stress and suction of traffic without disintegrating.

One frequent problem is that sometimes it is not possible to manufacture mixes that are highly permeable and, at the same time, resistant to the abrasive stress of traffic with conventional materials.

Available experience points to the fact that it is easy for the filling-up to occur in these mixes if one does not start from a high percentage of voids (more than 20 to 21 percent). It is necessary to surpass this porosity if these mixes are to be genuinely permeable and maintain their porosity over time.

The graph of Figure 5 shows the evolution of the permeability measurement on a test section of porous mix (N-634 road) over 7½ years. The following defects can be observed:

1. There is differential filling up caused in the lane, (Table 5. In the wheel track zones, the vehicles' suction force has a cleansing effect, helping to maintain the permeability of the mix, and
2. When using low porosities, filling up may easily result.

Only the P-10 mix, which contains polymeric bitumen, maintains an appreciable permeability after 7½ years.

The void-loss ratios of the two mixes tested in the laboratory, graphed in Figure 6, show that only by using a modified

TABLE 5 EVOLUTION OF PERMEABILITY WITH TIME

	Solares-Beranga sections							
	Evacuation time (s). LCS permeameter							
Mix type and void	P-12 (10,4)		P-10 (15,4)		P-10 (10,4)		P-10 (polymer)	
Track zone	Track	Between edges	Track	Between edges	Track	Between edges	Track	Between edges
4 mths. (1)	65		55		50		35	
16 mths. (1)	70		100		90		38	
2 years	150	500	185	300	110	190	55	70
7,5 yrs.		500	190	500	240	350	74	250

(1): Average value.

P - a (b,c): a.- maximum aggregate size
b.- % pass 2.5 mm UNE
c.- % pass 0.080 mm UNE

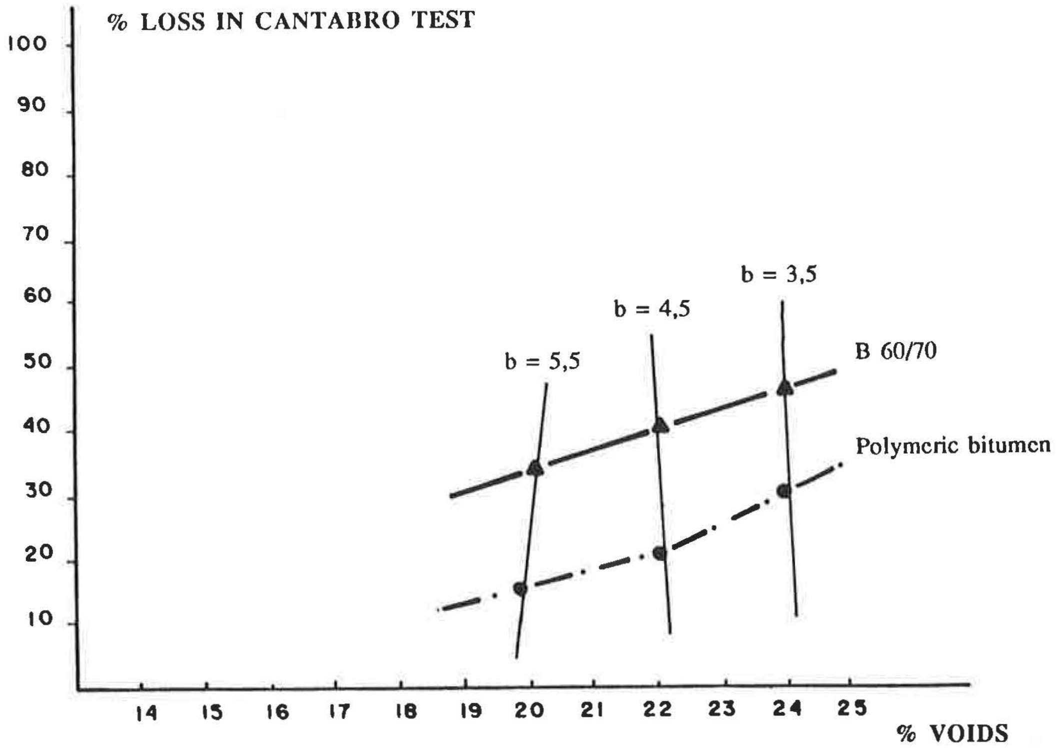


FIGURE 6 Ratio of voids to losses.

binder can highly porous mixes (> 20 percent for the percentage of voids) be achieved that are simultaneously resistant to disintegration (< 30 percent for losses).

BEHAVIOR OF SECTION IN USE

The results obtained for the different roadways in which polymeric bitumens are used are almost the same. As can be seen in Table 6, mixes of similar gradings and binder content have been employed in these. For example, the results corresponding to the A-8 freeway from Bilbao to Bohobia are included, where the aforementioned characteristics are being wholly and continuously measured.

Permeability

After more than two-and-a-half years of service, a slight filling up of the mix employed has occurred. The water evacuation time, measured with the LCS permeameter, has gone from 16 to 35 seconds. [See Table 7. Measurement of permeability: time (in sec) of evacuation of water in the LCS (Laboratorio de Caminos de Santander) permeameter.]

This slight reduction (a predictable one, in any case), has no appreciable effects on the efficiency of water drainage and the avoidance of its projection and splashing. It should be kept in mind that, after this type of service, the mix still remains a coefficient of permeability of 20 × 10^{-2} cm/sec, higher than that of a permeable sand.

Macrotexture

By using a sand circle procedure, the tests carried out a year after its installation give values ranging from 1.8 to 2.2 mm, indicating an excellent superficial macrotexture.

Coefficient of Longitudinal and Transversal Friction

The measurement of the longitudinal friction coefficient with the Road Research Laboratory friction pendulum showed an initial value of 0.49, increasing after opening to traffic, as a consequence of the disappearance of the binder film covering the surface of the aggregates. After one month, it was already 0.55 and after six months, 0.61.

TABLE 6 ROAD WORKS UNDERTAKEN

Date	Place	Grading UNE sieves % passing 12.5	10	5	2.5	0.08	bit. (%)	Voids (%)	Cantabro (%) Dry	Wet
4-80	Solares	100	85	36	18	5.5	4.5	20	12	-
12-80	Orense	100	87	25	16	3.5	4.5	20	12	-
2-82	Solares	100	82	32	14	3.5	4.8	20	14	-
4-82	Pamplona	100	87	36	15	4	4.6	21	13	-
3-86	A-8 (*)	100	85	35	13	3.5	4.5	21	12	-
85	Orense	100	87	25	16	4	4.5	20	15	-
3-86	A-8	100	94	31	11	4	4.5	22.5	13	29
7-86	A-6	98	82	24	12	4.1	4.3	22	8	-
87	Irurzun	100	87	28	13	4	4.5	21	18	35
9-87	Oviedo	100	86	28	16	4	4.4	20	16	37
10-87	Las Rozas	100	84	22	14	4	4.5	22.5	12	24
1-88	La Avanzada	100	85	27	13	4	4.3	23	14	-
3-88	Vigo	100	91	21	17	4	4.0	22	17	32
3-88	Lugo	100	86	19	12	4	4.5	21.6	10	-
6-88	La Coruña	96	59	20	14	4.7	4.5	21.4	12	22
9-88	Pontevedra	100	87	29	21	4.7	4.5	21.4	13	25
9-88	Palencia	84	77	21	17	4	4.5	22.3	11	22
12-88	Orense	100	82	28	16	4	4.5	22.5	11	22
12-88	Barcelona	100	87	28	15	3	4.5	21.7	16	28

(*): A-8, Bilbao-Behobia Freeway

TABLE 7 BILBAO-BEHOBIA FREEWAY. EVOLUTION OF THE INITIAL CHARACTERISTICS OF THE MIX

	Service time				
	Initial	1 month	6 months	1 year	2,5 yrs.
LCS permeability (s)	16	20	24	29	35
Coef Longitudinal Friction RRL pendulum	0,49	0,55	0,61	0,61	
Coef. Transversal Friction SCRIM		50-70		70-75	60-75

TABLE 8 EFFECT OF THE TYPE OF PAVEMENT ON VEHICLE NOISE

TYPE OF PAVEMENT	dB(A) sonority	
	Dry	Wet
Porous mix 0/12 mm	74,2	74,8
Dense mix 0/12 mm	76,8	78,5
Slurry seal 0/8 mm	77,8	80,2

The measurement of the transversal friction coefficient with SCRIM shows that, after an initial value ranging from 50 to 70, it increased and then established itself in a variation interval of 60 to 75.

Rolling Noise

The measurements carried out by the Industrial Testing and Research Laboratory of Bilbao in different sections and pavements of the highway indicate the following: for porous mix, cold microasphalt concrete (slurry seal 0/8 mm), and dense conventional hot mix, the draining agglomerate is shown to be quieter and the cold microasphalt concrete to be noisier, with level differences between them, at 5m, of 3 to 5 dB(A). (See Table 8)

The data recorded in rainy conditions show an increase of 2 dB(A) when driving in wet conditions on the slurry seal and the conventional dense hot mix, and only a slight increase for sections paved with porous mixes.

Noise Inside the Vehicle

Measurements carried out on this freeway by the SEAT Acoustics and Vibrations Laboratory on a SEAT Malaga vehicle, demonstrate a lower noise level on draining pavements. In the spectral analysis in octave thirds, for the driver's position as well as the passenger's position, a reduction of up to 5 dB(A) is observed in low and middle frequencies with respect to the slurry seal and of 2 to 3 dB(A) with respect to the conventional dense hot mix.

CONCLUSIONS

The test results make clear the advantages of using bitumen modified with polymers in the properties and characteristics of the porous mixes. These advantages can be summarized as follows:

- The use of polymeric bitumen makes it easier to obtain a greater thickness of the binder film, which improves the cohesion, resistance to aging, and durability of the mix.
- For a minimal value of the content in voids, the wear losses in the Cantabro test are spectacularly lower when using polymeric bitumen compared with pure binders of the same penetration.
- They lead to the obtention of mixes with a higher content of voids without their abrasion resistance being affected. The obtention of mixes with void content equal to or more than 20 percent and abrasion losses of less than 30 percent requires the use of modified binders.

- This ease in obtaining more open mixes results in greater endurance of the initial permeability.
- The tests after immersion show excellent performance of the binder modified with polymers. Its use produces half the losses caused by abrasion of a normal bitumen, which supports the excellent passive adhesiveness of the mentioned binder's properties, and is of great importance in this type of mix.
- Lower criticalness in the manufacture of draining agglomerates resulting from the null risk of under-dosification because of running off of the binder in the manufacturing or extending process.
- The track test results confirm the lower thermal susceptibility of the polymeric bitumen and its superior performance in the face of plastic deformation.

Advantages of Asphalt Rubber Binder for Porous Asphalt Concrete

ALAIN SAINTON

In France, after 10 years of scattered experiments, porous asphalt concrete mixes are expected to solve the problems of aquaplaning, water projection, noise reduction, and the mirror effect at night. There was some apprehension regarding the adaptability of the material to winter maintenance and the gradual reduction in draining properties with time on heavy traffic roads or turnpikes. In 1982, a French contractor specializing in road and turnpike construction carried out laboratory studies of a new modified binder composed of an asphalt–ground-rubber mix. This binder has remarkable rheological properties (viscosity at 200°C 10 times more than that of pure asphalt and elastomer properties with high elongation, even at low temperature) and good resistance to aging. The first use of asphalt rubber binder (ARB) was the stressed absorbing membrane and the stressed absorbing membrane interlayer. But ARB qualities led the engineers to formulate porous asphalt rubber concrete (PARC) and then compare it with other formulas using sophisticated laboratory tests. At the same time, on-site experiments have been conducted since 1983, particularly on the A26 turnpike in the north of France. The French Roads and Bridges Laboratory made rolling noise tests and completely assessed PARC characteristics (roughness, draining, and evenness properties) after 3 years of traffic. Laboratory test data indicate the advantages of ARB in porous mixes compared with those of pure asphalt and polymermodified asphalt. Moreover, all the work site tests made on PARC during the last 5 years on heavy traffic turnpikes confirm its excellent durability.

Asphalt rubber binders (ARBs) appeared in France in 1982 after exhaustive laboratory studies. The composition of the rubber powder, the choice of the extender oil, and the kind of asphalt were the subjects of lengthy research that led to the final adjustment of a high-performance binder with remarkable elastomeric properties, particularly at low temperatures.

The first use of ARB was the stress-absorbing membrane (SAM) or stress-absorbing membrane interlayer (SAMI). Within 6 years, more than 3 000 000 m² were used on different types of pavements: turnpikes, parkways, highways, and airport runways.

At the same time the idea emerged of making hot asphalt concrete with this new binder, in particular porous mixes and very thin overlays; rheological properties of ARB perfectly fitted those formulations.

CHARACTERISTICS OF ARB

ARB is obtained by mixing ground rubber powder (15 to 25 percent by weight) in asphalt with extender oil (2 to 10 percent by weight) at a high temperature (>200°C). The basic asphalt is usually an 80/100 grade with special chemical composition. The extender oil is a crude oil fraction with aromatic properties that extends unsaturated elastomers such as polybutadiene and polyisoprene, the main ingredients of ARB.

Ground rubber powder, which comes from old or retreaded scrap tires, is made primarily of one part natural and synthetic rubber and one part mainly stabilizing and antioxidizing filler. Its granular size is determined by laboratory tests.

The hot mix is followed by an important elevation of viscosity (swelling of rubber particles) then by a fall in viscosity that progressively slows down (devulcanization). After 1½ hr, the dynamic viscosity is stabilized below 10 poises and the binder is ready to use. See Figure 1.

The important physical characteristics of ARB are as follows:

- Penetration at 25°C in 1/10 mm, 50 to 80;
- Softening point, higher than 60°C;
- Penetration index [Laboratoire Central des Ponts et Chaussées (LCPC)], +1.5 to +5; and
- Density at 18°C, 1.03.

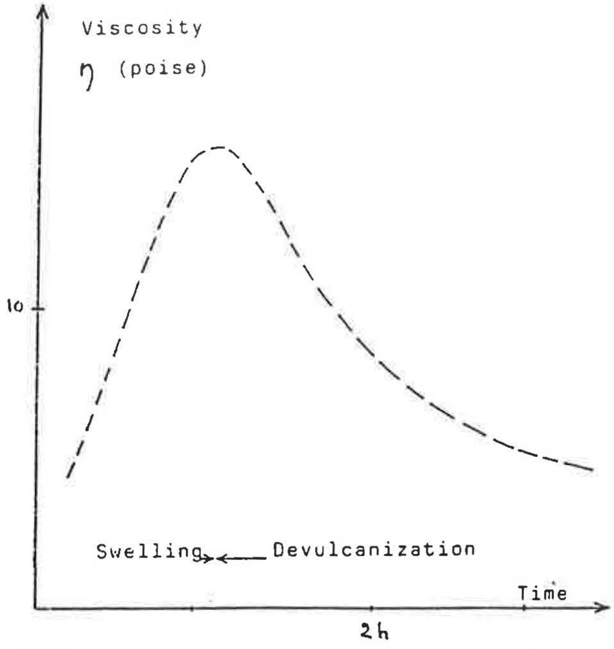


FIGURE 1 Viscosity evolution through rubber swelling.

Beugnet Group—France, 66, Avenue des Champs Elysées, Immeuble C, 75008 Paris, France.

Tensile tests indicate high elongation and good resilience even at low temperatures and after aging in a thin film (3 mm) at 50°C. See Figures 2 and 3.

The adhesion test inspired by the "Vialit test" at very low temperatures indicates that ARB has tacky properties with stones much better than pure asphalt 60/70. See Figure 4.

POROUS ASPHALT RUBBER CONCRETE (PARC)

The general advantages of porous mixes are as follows:

- High skid resistance at high speed and in rainfall (no aquaplaning),
- No spray or splash,
- No light reflection from wet pavement,
- Reduction of tire rolling noise, and
- Low cost due to low density.

Why PARC?

Pure asphalt cements have neither the cohesion nor the flexibility to give porous asphalt concrete (PAC) resistance to heavy traffic. Asphalt content must be limited to 4.5 to 5 percent; otherwise rutting occurs. With such content, the stones are bound firmly, but fatigue restance is weak and porous asphalt life is limited. Moreover, the thin asphalt film is sensitive to air aging.

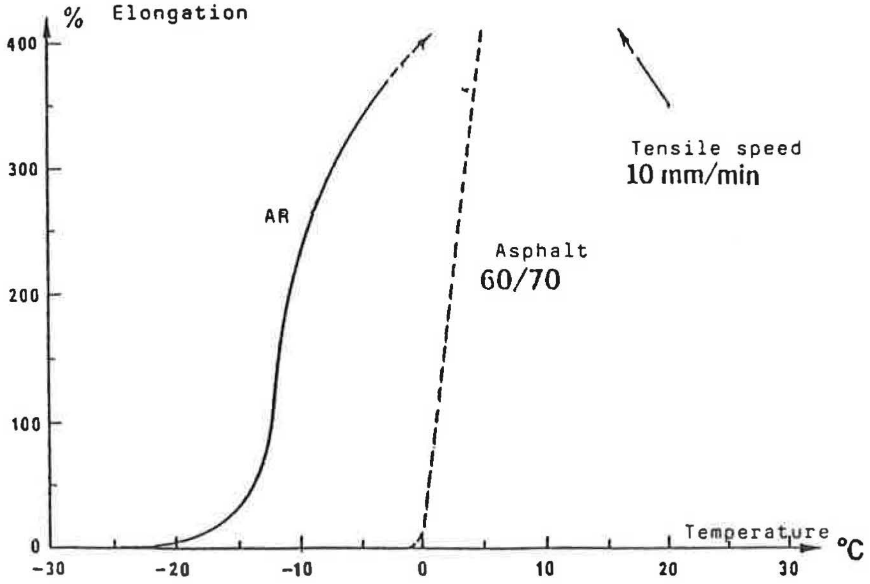


FIGURE 2 Elongation versus temperature.

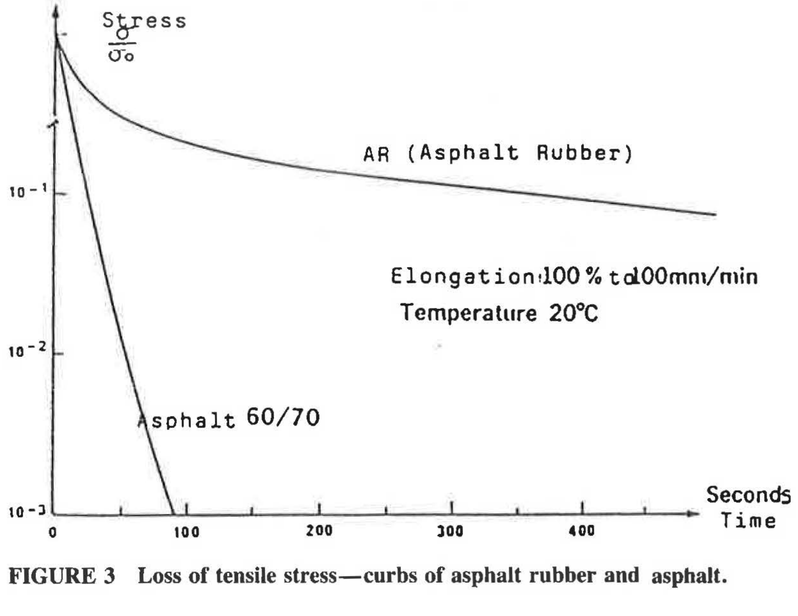


FIGURE 3 Loss of tensile stress—curbs of asphalt rubber and asphalt.

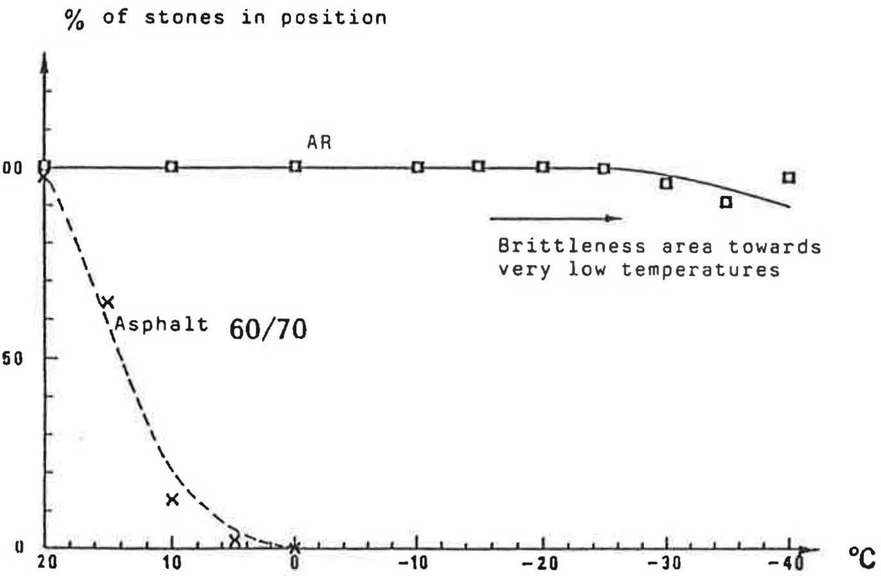


FIGURE 4 **Shock resistance of AR according to temperature.**

Polymer-modified asphalt (PMA) has good rheological mechanical properties at first, but these are not stable over time, and after aging by oxidation, PMA becomes brittle at low temperatures.

ARB has high cohesion, high flexibility at low temperature, strong creeping resistance (a softening point between 60°C and 75°C), and a remarkable aging resistance because there is no fluxing agent and because of an antioxidant in the rubber powder.

Because of the binder's high viscosity, it is possible to have a high binder content in porous asphalt mixes, which leads to binding strength, fatigue resistance, and aging resistance (thick film).

PARC Composition

The studies led to a 0/10 granular size; a voids content >20 percent (density about 2); and an ARB content from 6 to 7 percent, according to thickness, structural state of support, traffic, and weather.

For example, to use a PARC in a depth of 4 cm and under heavy traffic, the following formulation is needed (see Figure 5): 87 percent 6/10 crushed porphyry, 11 percent 0/2 crushed porphyry, and 2 percent filler. The ARB is 6.8 percent.

Laboratory Test Results

Duriez-LCPC Test

In the Duriez-LCPC test, the compaction ratio was 79.2 percent (20.8 percent voids); the percentage of efficient voids was 12; compressive strength^R (8 days at 18°C) was 410 psi; compressive strength^r (7 days immersion at 18°C) was 393 psi; $r/R = 0.96$. The water stripping resistance is remarkable (the same formula with 4.5 percent asphalt 60/70 given an r/R index of 0.8).

Gyratory Test

The compaction rate at n_i gyrations (C_i) was as follows [see Figure 6]:

$$C_1 = 65.4 \text{ percent}$$

$$C_{10} = 70.8 \text{ percent}$$

$$C_{30} = 73.4 \text{ percent}$$

$$C_{40} = 74 \text{ percent}$$

$$C_{200} = 77.8 \text{ percent}$$

$$K_1 = \frac{C - C_1}{\log n_i} = 2.34$$

Tests by the Exxon European Research Center in Mont-Saint-Aignan (France)

Laboratory Tests for Mechanical Properties Exxon Company, supplier of the asphalt and extender oil used to make ARB, conducted a comparative laboratory study on three porous mixes with the same granular size but with three different binders and three binder contents using the ESSO Road Design Technology (ERDT method) developed by Mont-Saint-Aignan Research Center engineers.

The granular size of each mix was as follows: 87 percent; 6/10 crushed porphyry, 11 percent; 0/2 crushed porphyry, 2 percent limestone filler.

Binder content was 4.7 percent for asphalt 60/70, 5.5 percent for PMA, and 6.8 for ARB.

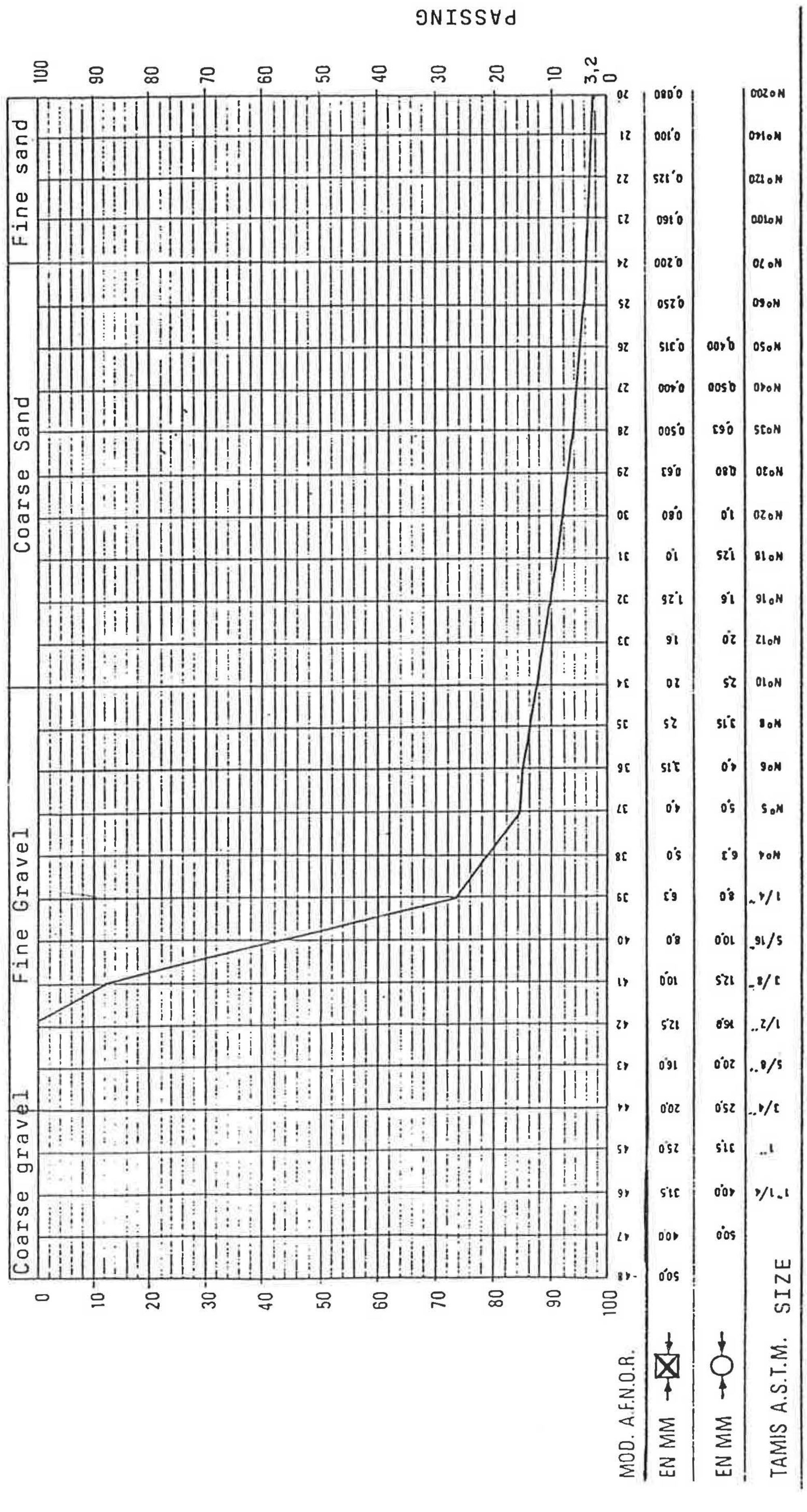
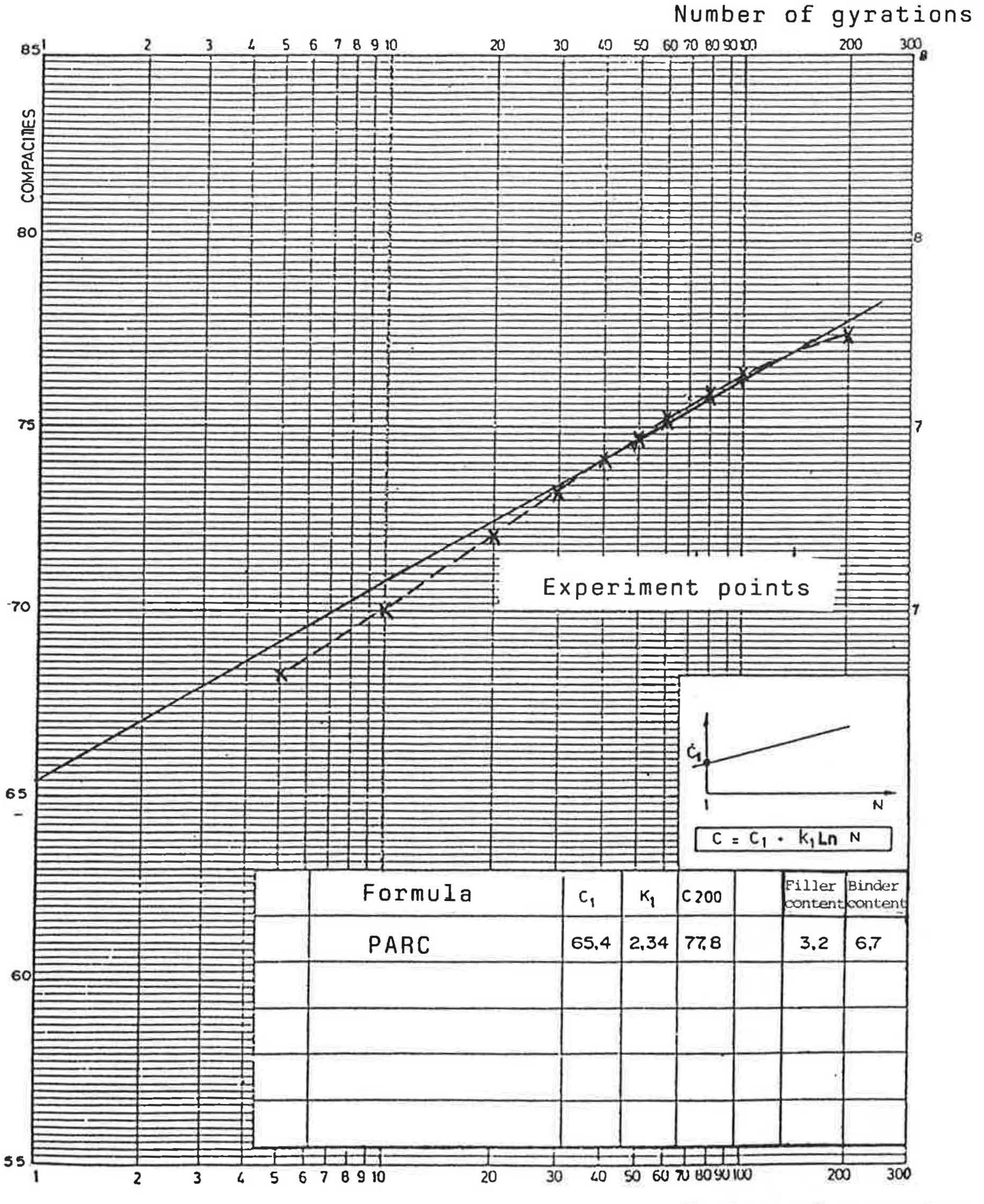


FIGURE 5 Granular size—0/10 PARC.



	Formula	C1	K1	C 200		Filler content	Binder content
	PARC	65.4	2.34	77.8		3.2	6.7

FIGURE 6 Gyratory test.

Binder properties appear in the following table.

	Asphalt 60/70	*PMA*	*ARB*
Density at 25°C	*1.030*	*1.01*	*1.030*
Penetration (1/10 mm)			
10°C	*15*	*18*	*22*
15°C	–	–	*32.5*
20°C	–	*52*	*46*
25°C	*61*	*97*	*68*
30°C	*96*	*135*	*105*
Softening point (°C)	*50.2*	*83*	*63.2*
Breaking point (°C)	*−12*	*−19*	–

Mixing temperature was 150°C with asphalt 60/70, 160°C with PMA, and 180°C with ARB.

Dynamic modulus of the hot mixes was determined at four temperatures (10°C, 20°C, 30°C, and 40°C) and six frequencies (20, 10, 3, 1, 0.3, and 0.1 Hz). See Figures 7–11. Note that porous mixes have a lower stiffness compared with that of dense mixes (the structural strengthening is approximately half for porous mixes). At low temperatures, PARC is more flexible, a great advantage in cold winter weather.

The dynamic creep test was conducted at 30°C under an axial compressive stress amplitude (σ_v) equal to 0.3 MPa (45 psi) by applying an isotropic stress (σ_v) equal to 0.1 MPa (15 psi) over the entire specimen. See Figures 12 and 13. Although less stiff, PARC behaved well against creep and rutting.

The specimen was prepared for the fatigue test in the same way as for the dynamic modulus test, but the central portion was reduced in diameter to ensure rupture in the part during the test. An alternating (push-pull) axial sine wave stress σ_v of amplitude σ_{2v} was applied without rest periods, until the specimen broke. The applied stress induced an axial sine wave strain of 2½ percent amplitude, which increased during the test. The number of cycles to failure (N_f) and the initial strain amplitude were recorded. The temperature was 10°C. (See Figures 14 and 15).

For an initial strain = 7 × 10^{-5}, PARC specimens have a lifetime 13 times superior to PAC and 23 times superior to PMAC.

Freeze-Thaw Cycle Tests and Resistance to Deicing Salts

Sensitivity to freeze-thaw cycles was compared for PARC and PAC for a dry specimen and a water–saturated specimen with fatigue tests as described earlier. (See Figures 16 and 17.) The tests were carried out at −20°C for 24 hr and at ambient temperature for 24 hr. They were carried out for an initial strain of 8 × 10^{-5} with PAC and 12 × 10^{-5} with PARC. The saturated specimen evolved faster than the dry specimen; PARC had better fatigue behavior than PAC.

The purpose of the deicing salts study was to assess the mechanical properties of PARC and PAC after immersion in water and two deicing salt solutions at 18°C and −5°C. The deicing salt solutions used were potassium salt and Nivacal ($CaCl_2$).

Fatigue tests were done on different PAC and PARC specimens before and after immersion during 8 days in water, potassium salt solution (0.25 kg/l), and Nivacal (0.8 percent calcium dichloride).

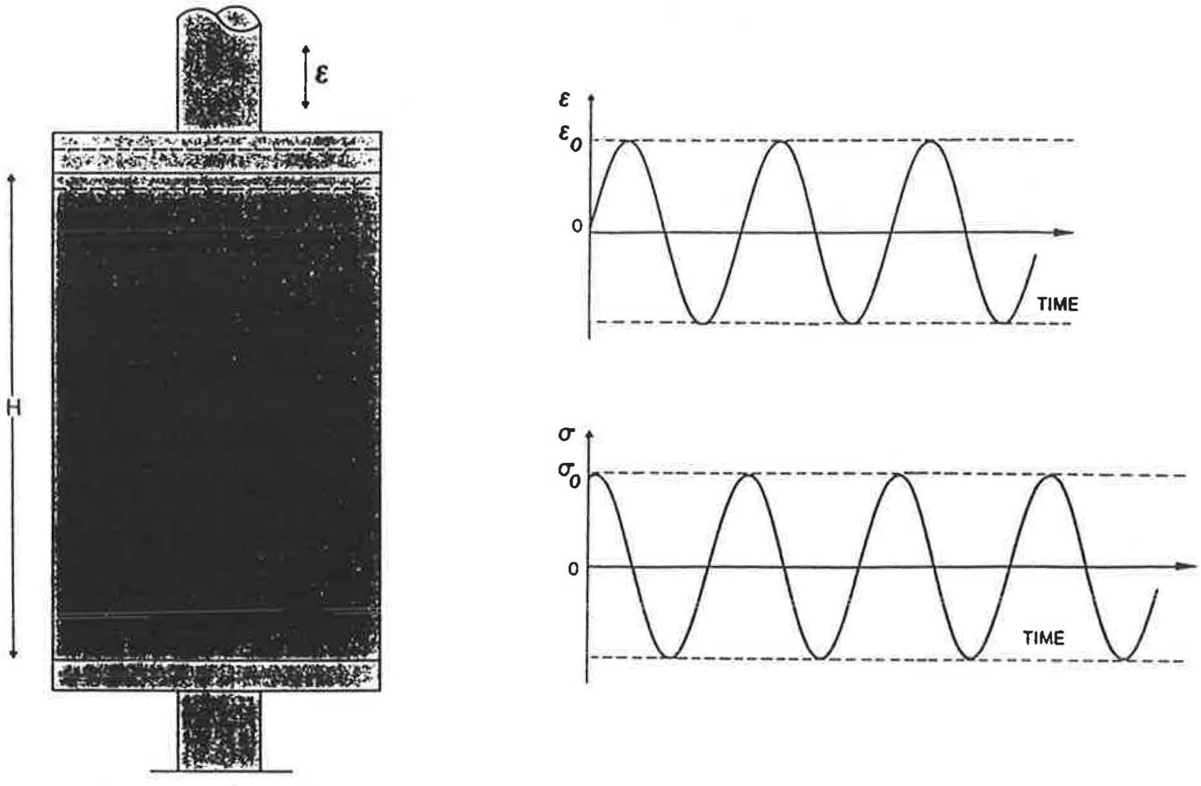


FIGURE 7 Dynamic modulus test.

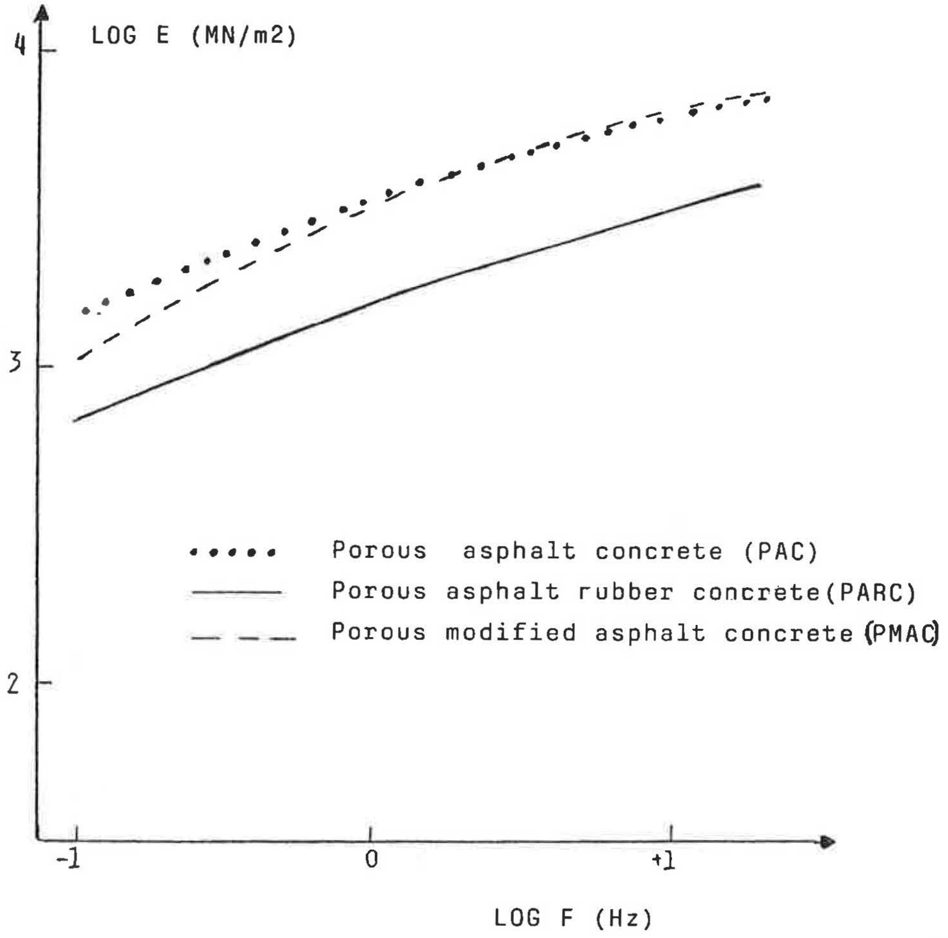


FIGURE 8 Dynamic modulus compared at 10°C.

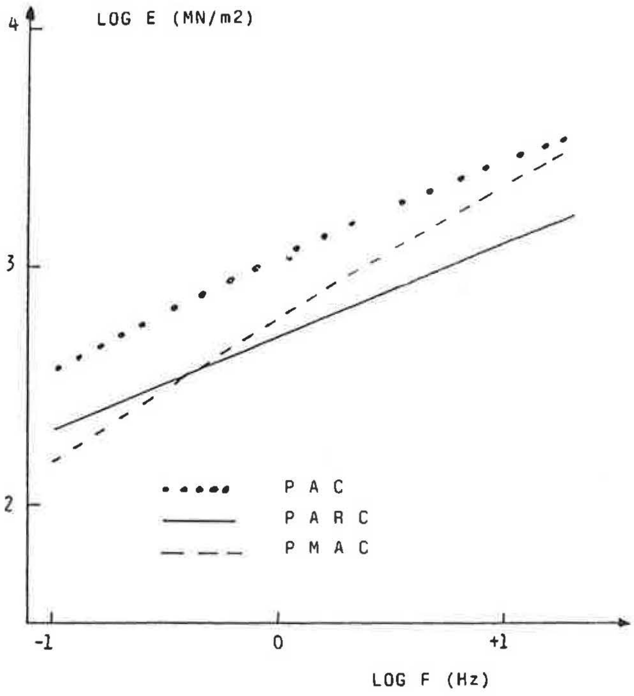


FIGURE 9 Dynamic modulus compared at 20°C.

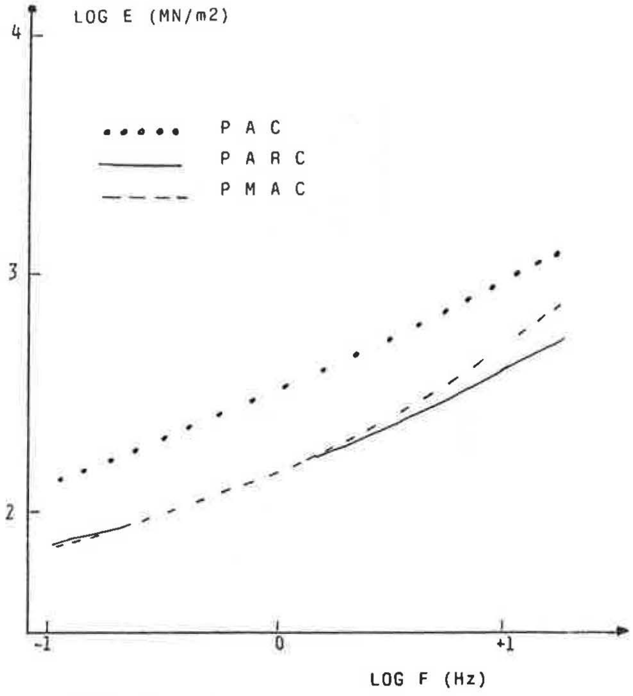


FIGURE 10 Dynamic modulus compared at 30°C.

The fatigue resistance of PARC was not sensitive to water or deicing salt solutions after 8 days' immersion, but the fatigue resistance of PAC (with asphalt 60/70) is reduced by 25 to 60 percent. See figures 18 and 19.

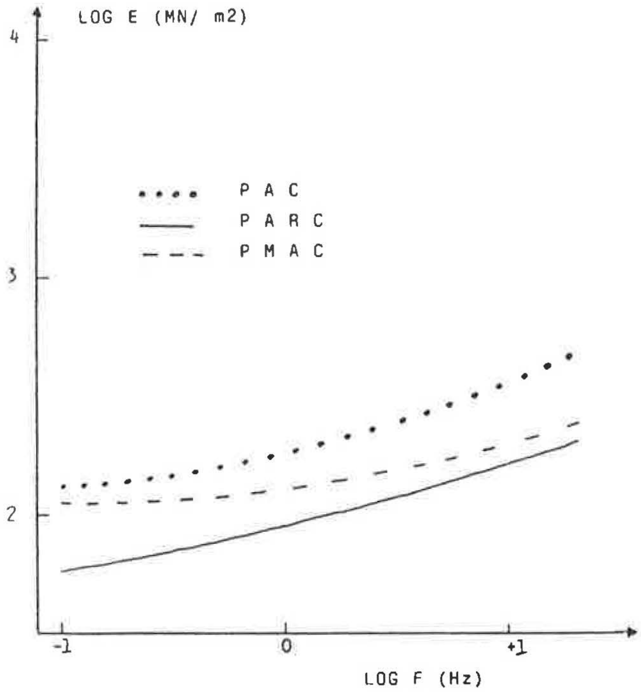


FIGURE 11 Dynamic modulus compared at 40°C.

Tire Rolling Noise

The goal of the tests was to compare sound levels of tire-pavement contact in city areas before and after the use of PARC. The method was the one given by the LCPC. Tests were done in situ near Lille in the north of France.

The tests gave the level noise pressure in weighted decibels dB(A) caused by a free-wheeled vehicle on the pavement with engine cut off. The microphone was 7.5 m from the axle path of the vehicle and 1.20 m above the pavement. Speed of the vehicle was 80 km/hr. See Table 1.

Compared with smooth portland cement concrete pavement, PARC improved the noise level by 3 dB(A). Compared with smooth dense asphalt concrete, PARC improved the noise level by 1 dB(A).

Spectrum examination in 1/3 octave indicates that the gain is mainly important [5 to 10 dB(A)] in 1/3 octave frequency bands above 1600 Hz corresponding to treble frequencies. See Table 2.

Tracking Results on PARC Implemented on A1 Turnpike in the North of France

More than 1,000,000 m^2 of PARC has been implemented on A1 turnpike in the north of France since 1984. A1 turnpike use is 40,000 vehicles per day; 35 percent of the vehicles are heavy trucks.

Evolution of roughness is shown in Figures 20 and 21.

Evolution of voids content is shown in Figure 22. After 2 years, the slow lane cross section does not show significant deformation at wheel track areas (no rutting).

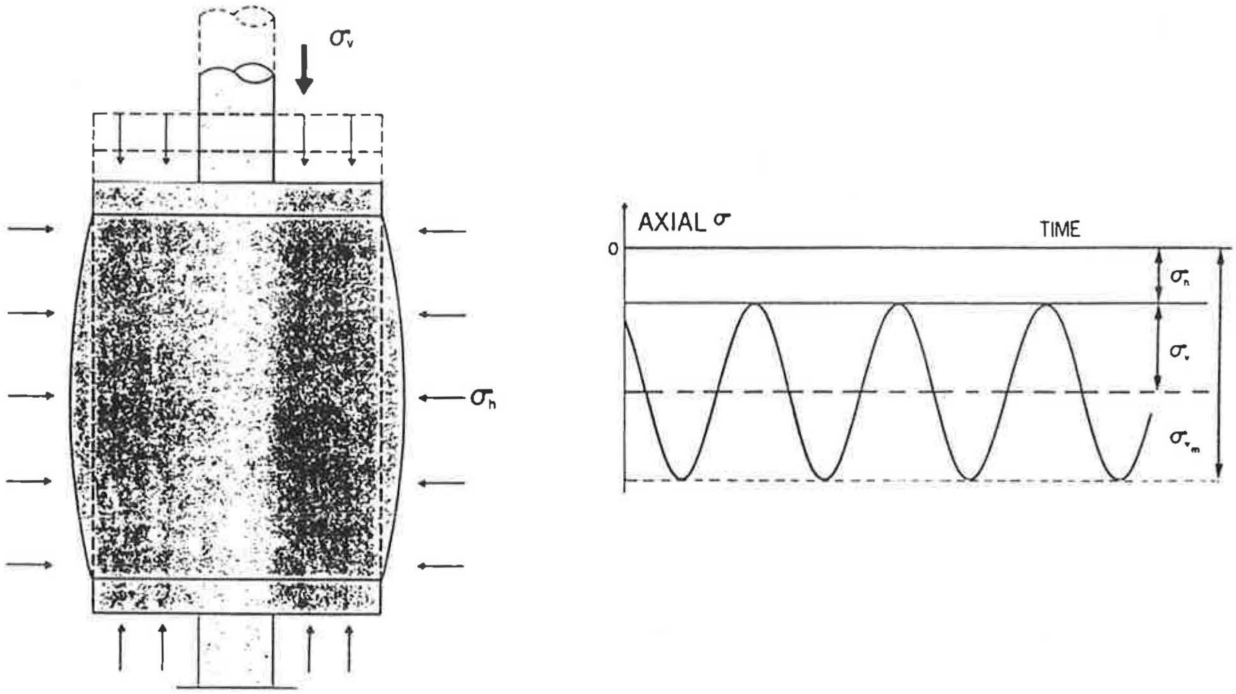


FIGURE 12 Dynamic creep test.

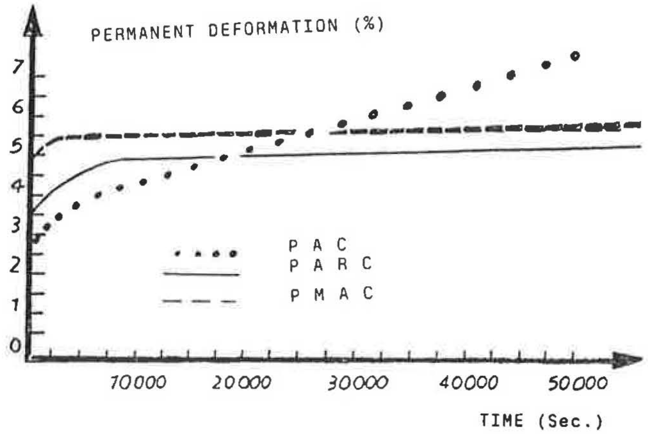


FIGURE 13 Dynamic creep.

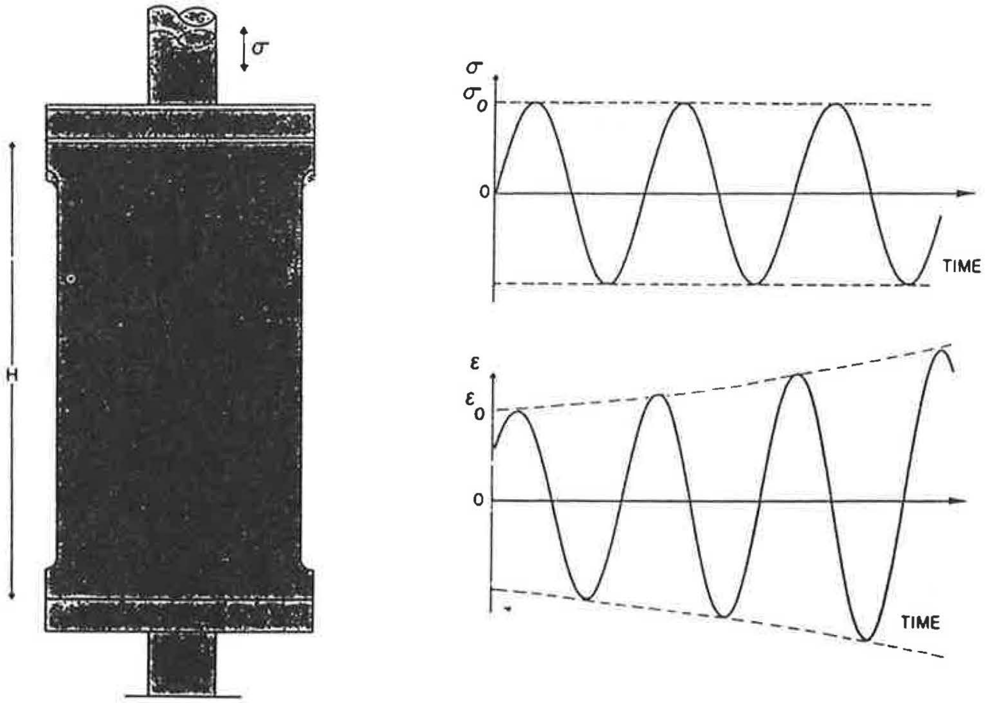


FIGURE 14 Fatigue test.

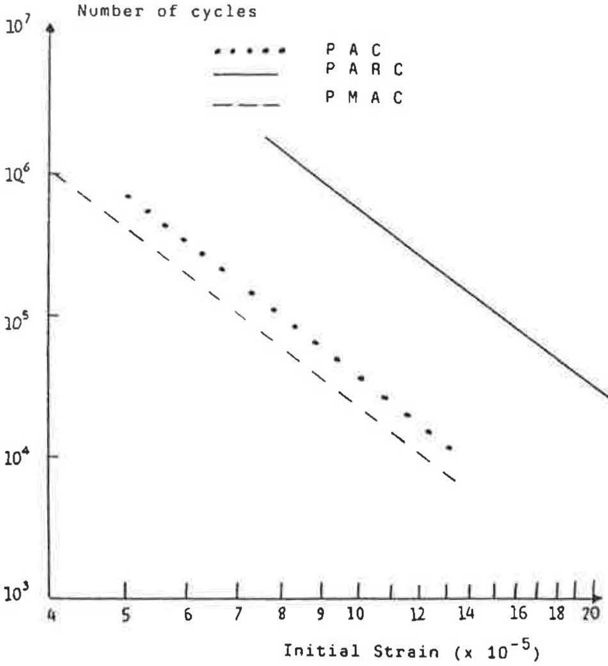


FIGURE 15 Fatigue damage laws.

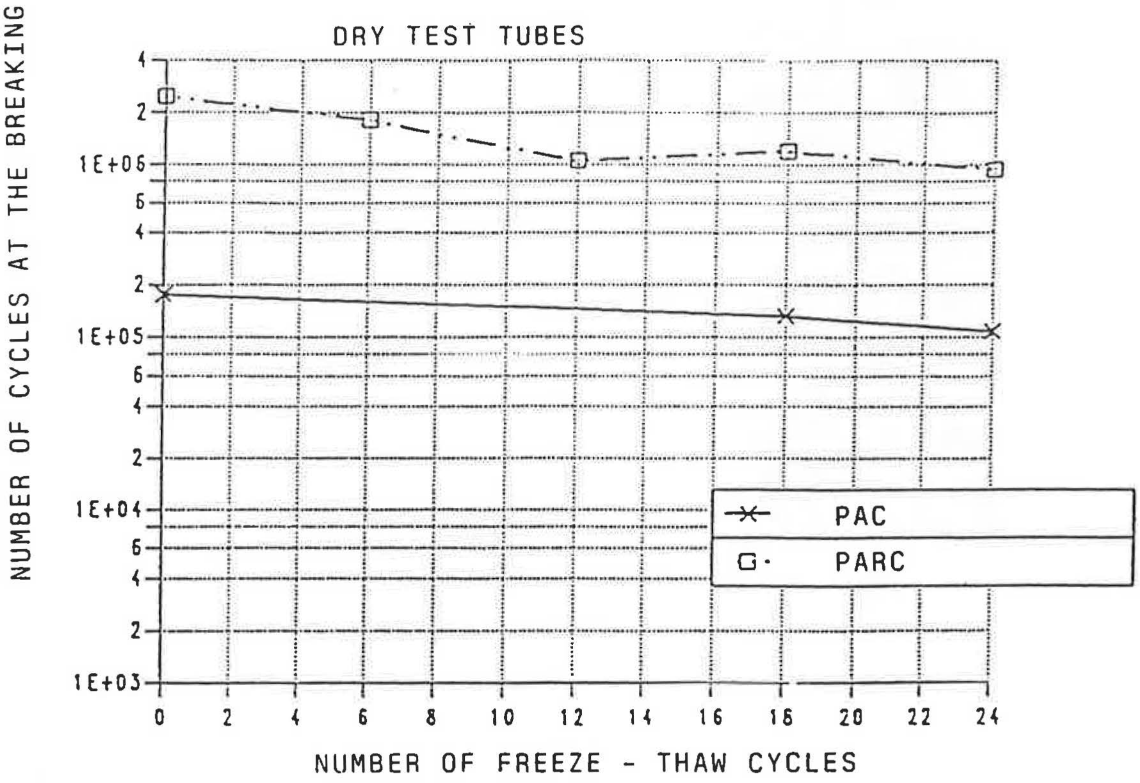


FIGURE 16 Freeze-thaw cycles: dry specimens.

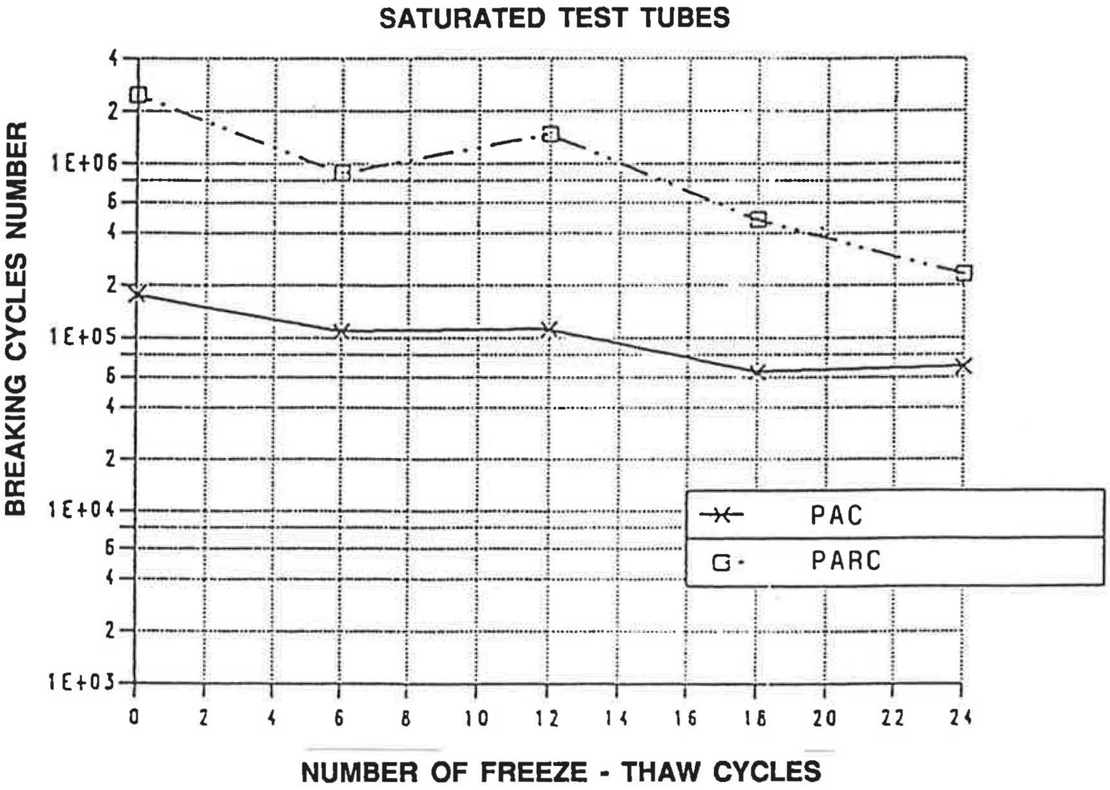


FIGURE 17 Freeze-thaw cycles: saturated specimens.

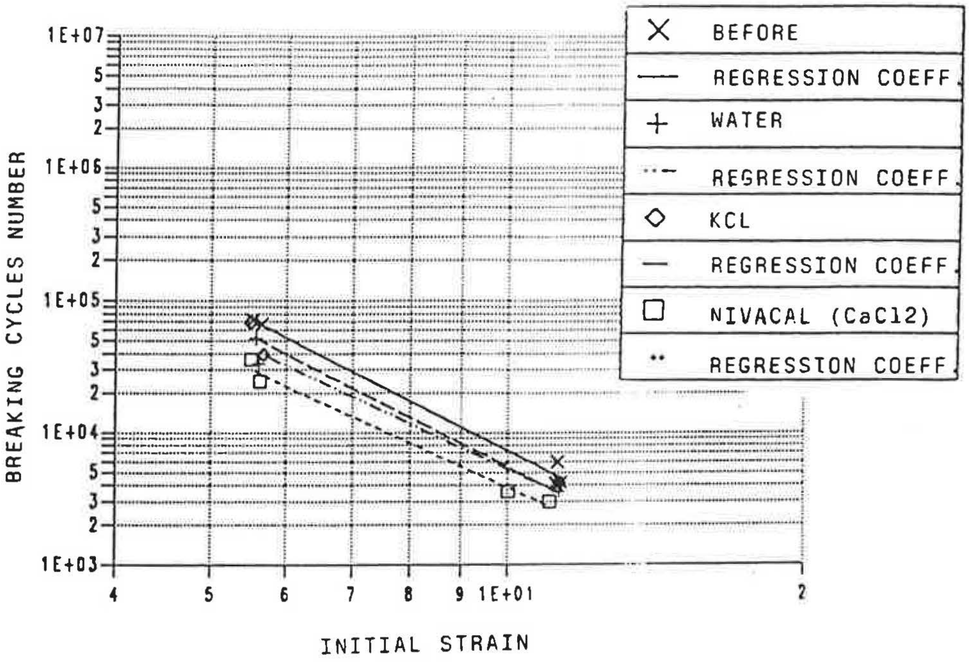


FIGURE 18 Fatigue resistance—PAC.

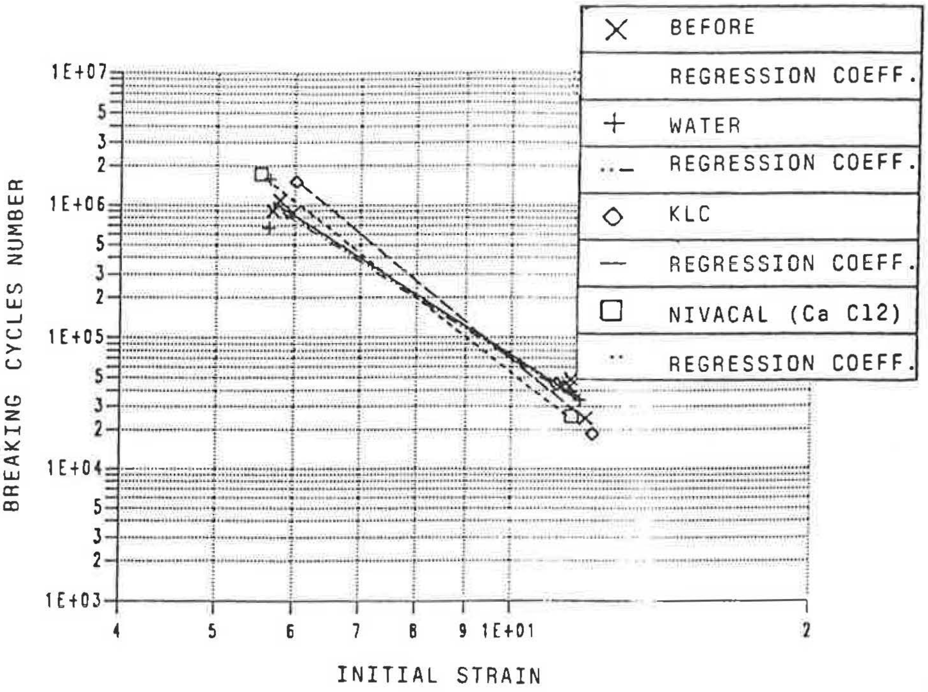


FIGURE 19 Fatigue resistance—PARC.

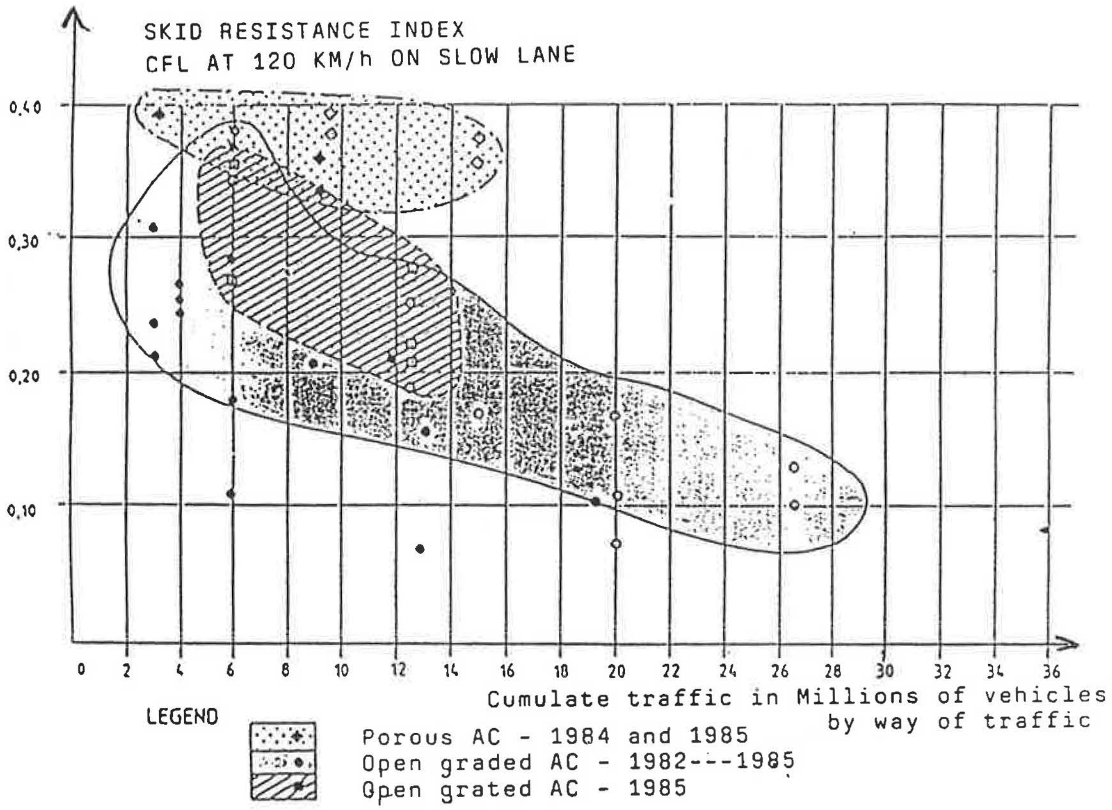


FIGURE 20 Hot-mix overlay performance analysis according to cumulative traffic on A1 turnpike, Paris-Lille.

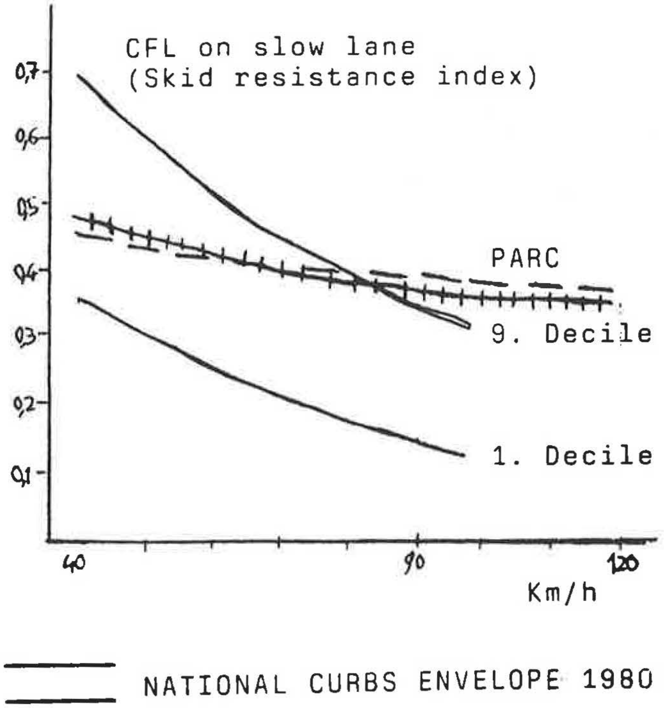


FIGURE 21 PARC on A1 turnpike, Paris-Lille, skid resistance index according to speed.

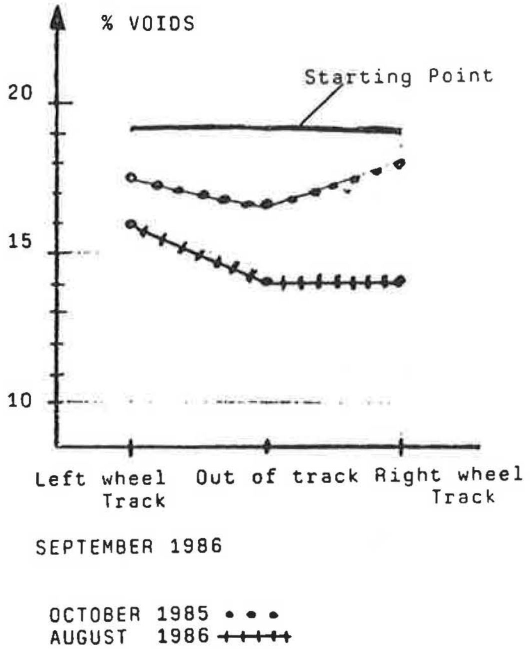


FIGURE 22 PARC on A1 turnpike, Paris-Lille, voids content after 2 years on slow lane.

TABLE 1 ROLLING TIRE NOISE

Experiment Test Area	Pavement	Sound Level [dB(A)]
1	Old: smooth portland cement concrete	75
	New: PARC	72
2	Old: dense asphalt concrete	72
	New: PARC	71

TABLE 2 SPECTRUM EXAMINATION OF NOISE LEVEL

Frequency Band on 1/3 Octave (Hz)	First Intervention[a] (3/7/85)	Second Intervention[b] (5/9/85)
100	74	70.5
125	74.5	74
160	68.5	66
200	65	69
250	66	64
315	63	62
400	63.5	61.5
500	62	59.5
630	62.5	63
800	66	66.5
1,000	70	69.5
1,250	68	68
1,600	66.5	63
2,000	65	58.5
2,500	63.5	53.5
3,150	60	51
4,000	59.5	48.0
5,000	56	48.0

[a] Initial state, smooth PCC.
[b] PARC 0/10.

CONCLUSION

Different experimental sections were made in France in the 1970s without significant results. The approach until then seemed too empirical to achieve a reliable solution that corresponded to a necessity (rain doubles the risk of accident on dense asphalt concrete pavement).

Since 1982, laboratory studies in France have clearly indicated the advantages of ARB in porous mixes; ARB offers the following advantages:

- Constant draining properties,
- Good behavior under heavy truck traffic (fatigue and rutting resistance),
- Shearing stress resistance, and
- Insensitivity to bad weather.

The excellent durability of PARC has been confirmed by work in France during the last 5 years.

Contribution of Cellulose Fibers to the Performance of Porous Asphalts

Y. DECOENE

Observations on Belgian roads have not yet demonstrated any significant effect on polymer additives on the peformance of porous asphalts, also known as open-graded asphaltic concrete or open-graded friction course. Nevertheless, they have shown that there may be local problems with pure bitumen draining by gravity through the bituminous material during mixing, transport, and laying. This occasionally happens. SCREG Belgium has developed porous asphalt mixes containing pure bitumen and organic fibers. Numerous test carried out on its initiative, both in the laboratory and on roads, have confirmed the anti-draining action of cellulose fibers, which makes it possible to lay low-cost, high performance porous asphalt with an eventual higher bitumen content, while solving the occasional problem of binder drainage.

The use of porous asphalt mixes in Belgium and other Western countries has greatly increased the past few years, mainly because of the well-known advantages they present regarding skid resistance, aquaplaning, splash and spray, visibility, rolling noise, and resistance to permanent deformation (*1*).

Observations made on Belgian roads have shown the good performance of those mixes, even with pure bitumens. With the latter, it is possible, although they are less expensive than polymer-modified bitumens, to obtain pervious and high performance surfacings. However, it has been found (*2*) that local problems may occur with pure bitumen draining by gravity through the material during mixing, transport, and laying. As a result, aggregates are worn away by traffic on local spots where the bitumen content is too low.

To solve this problem and enable porous asphalt mixes to be laid with higher contents of bituminous mastic, SCREG Routes has been successfully using (*3,4*) a small amount of asbestos fibers in its porous asphalts. Because the use of these mineral fibers is prohibited by law in Belgium, SCREG Belgium has been investigating the possibility of working with cellulose fibers in its porous asphalt mixes. This investigation, intended to determine whether those fibers prevent bitumen drainage and make it possible to work with higher bituminous mastic contents, is the subject of this paper.

ORGANIC FIBERS USED

The organic fibers used are gray fibers with a cellulose content of at least 75 percent and a pH of 6 to 8.5. The maximum length of the fibers used is 1.2 mm, and their density is about 1.5 g/cm^3. The fibers generally have a temperature-resistance of more than 180°C during 1 hr.

This type of fiber has already been used in chip mastic asphalt in the Federal Republic of Germany (*5*), The Netherlands (*6*), and elsewhere, and in the thin surfacings (*7*) of SCREG Routes and SCREG Belgium.

The celluose fibers are wrapped in sealed polyethylene packs with a sufficiently low melting point, to be dissolved in the hot mixture. There are also precoated fibers containing 50 percent fibers and 50 percent hard (20/30 or 40/50 penetration) bitumen. They are specially intended for drier drum mixers.

LABORATORY TESTS ON MIXES

Basket Drainage Tests

Seven porous asphalt mixes, with or without fibers (Table 1), were subjected to a basket drainage test. The operational procedure was as follows:

1. The mixes were manufactured and compacted in great Duriez molds (*8*) under a pressure of 30 bars,
2. These molds were laid on a grid and the set was then placed in an oven at 180°C for 7½ hr; these severe conditions were choosen to simulate occasional cases when the bitumen is draining through the aggregates, and
3. The bitumen drained through the mix to the grid was recovered and the loss of bitumen was calculated with respect to the initial binder content.

The bitumen used for these tests was an 80/100 pen bitumen doped with 3 ⁰/oo of adhesion agent.

The amounts of bitumen drainage obtained, as percentages, are given in Table 1 and represented in Figure 1. From these results, it can be concluded that:

- Porous asphalt without fibers lost 13.5 percent of its binder during the test, even at low binder content (4.7 percent),
- In the mixes composed with fibers, the latter play an important role as an anti-draining agent. Indeed, compared with the mixes without fibers, little bitumen is lost (maximum 4 percent), even at binder contents higher than 5.5 percent. It is thus possible to use a great deal of binder if organic fibers are added, and
- There is very little difference in drainage behavior between the porous asphalts with 0.3 and 0.5 percent of fibers. Consequently, it does not seem necessary to use more than 0.3 percent.

SCREG Belgium S.A., Rue du Commerce 20, 1040 Brussels, Belgium.

TABLE 1 BASKET DRAINAGE TESTS

Mix	A	B	C	D	E	F	G
Composition (%)							
Diorite 10/14	55.5	55.5	55.5	55.5	55.5	55.5	55.5
Diorite 6/10	30	30	30	30	30	30	30
Sand 0/2	13	12	12	12	12	12	12
Filler	1.5	2.2	2.2	2.2	2.0	2.0	2.0
Organic fibres	0	0.3	0.3	0.3	0.5	0.5	0.5
Bitumen 80/100	4.7	5.5	5.7	5.9	5.5	5.7	5.9
Loss of bitumen (%)	13.5	1.5	2.9	3.4	0.3	1.3	1.2

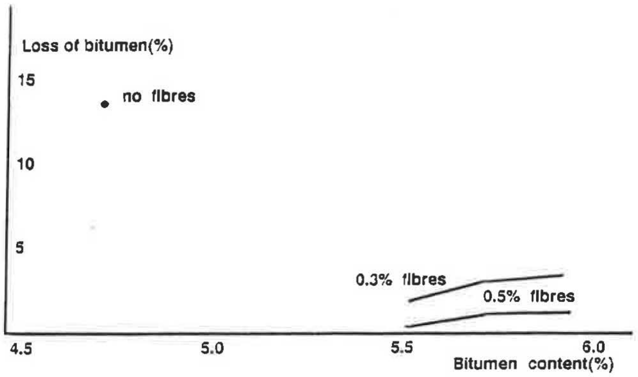


FIGURE 1 Influence of the bitumen and the fibers content on the loss of bitumen by the basket drainage tests.

Schellenberger Drainage Tests

Drainage tests done according to the Schellenberger method (*9*) were conducted on porous asphalts the composition of which is given in Table 2.

In short, 1,000- to 1,100-g samples of asphalt were put in 800 ml glass receivers and then placed in an oven at 170°C for 60 min. Here, too, the amount of binder drainage was determined with respect to the initial amount of bitumen during mixing. The bitumens used for these tests were not doped. The conclusions from the results of these tests (Table 2) are similar to those from the basket drainage tests: the mixes without fibers lost 15 to 21 percent of their binder and the fibers are effective in preventing bitumen drainage (Figures 2 and 3). Again, no significant difference was found between the results according to the amount of fibers (0.3 or 0.5 percent), so that the lowest of these contents should be sufficient.

Moreover, the loss of binder from the porous asphalts with fibers was found to be smaller than in the basket tests; on the other hand, it was slightly greater for the mixes without fibers. In making this comparison, one should nevertheless consider the difference between the bitumens used.

Finally, the cellulose fibers used all gave similar results.

Voids Content and Cantabrian Abrasion Test

For the mix design of porous asphalts, the Belgian Road Research Centre has suggested a procedure which consists of determining the voids ratio on Marshall samples and then performing the Cantabrian abrasion test on those samples, to determine the percentage of wear of the material after 300 revolutions in a Los Angeles cylinder without abrasive charge (*1,2*).

These tests, carried out on 4 porous asphalt mixes with or without fibers (Table 3) produced the following findings:

- A slight reduction (1 percent) of the voids in the porous asphalt without fibers with the 1 percent increase in bitumen content,

TABLE 2 SCHELLENBERGER DRAINAGE TESTS

MIX Composition (%)	A	B	C	D	E	F	G	H	I	J	K	L
Durite 10/14	55.5	55.5	55.5	55.5	55.5	55.5	55.5	55.5	55.5	55.5	55.5	55.5
Durite 6/10	30	30	30	30	30	30	30	30	30	30	30	30
Sand 0/2	12	12	12	12	12	12	12	12	12	12	12	12
Filler	2.5	2.5	2.5	2.5	2.2	2.2	2.2	2.0	2.2	2.2	2.5	2.2
Fibres a	0	0	0	0	0.3	0.3	0	0	0	0	0	0.3
Fibres b	0	0	0	0	0	0	0.3	0.5	0	0	0	0
Fibres c	0	0	0	0	0	0	0	0	0.3	0	0	0
Fibres d	0	0	0	0	0	0	0	0	0	0.3	0	0
Bitumen 60/70	4.5	4.7	4.9	4.9	5.9	6.1	5.9	5.9	5.9	5.9	0	0
Bitumen 80/100	0	0	0	0	0	0	0	0	0	0	4.7	5.9
Loss of bitumen (%)	15	16	21	17	0.1	1.1	1.1	0.3	0.6	1.1	18	0.5

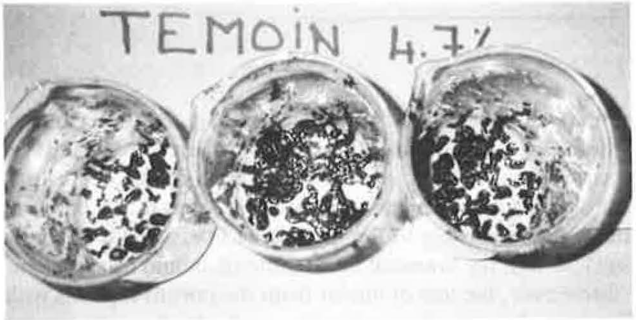


FIGURE 2 View of the glass receivers after the Schellenberger drainage test. (Porous asphalt with 4.7 percent bitumen and without fibers.)

FIGURE 3 View of the glass receivers after the Schellenberger drainage test. (Porous asphalt with 5.9 percent bitumen and 0.3 percent fibers.)

TABLE 3 VOIDS CONTENT AND CANTABRIAN ABRASION TEST

Mix	A	B	C	D
Composition (%)				
Porphyry 7/14	85	85	85	85
Sand 0/2	12	12	12	12
Filler	3.0	2.7	2.5	3.0
Fibres	0	0.3	0.5	0
Bitumen 80/100	4.5	5.5	5.5	5.5
Voids (%)	22.5	20.3	21.3	21.1
Wear of material (%)	15.9	16.6	18.0	20.0

- No significant difference in voids content between the porous asphalts with 5.5 percent of 80/100 pen bitumen, according to whether they contained fibers, and
- A very good resistance of all the porous asphalt mixes—with or without fibers—to attrition, whatever their binder content. There is little difference between the mixes tested, but the wear of their material is well below the maximum value of 30 percent which is generally suggested.

One of the conclusions to be made from all those tests is that the voids of porous asphalts with 5.5 percent of pure bitumen and with the addition of 0.3 or 0.5 percent of fibers is equivalent to those of "conventional" porous asphalts with about 4.5 percent of pure bitumen and without fibers; the addition of fibers allows an increase of the bitumen content and the durability, and avoids problems with binder drainage through the material. Working with binder content higher than 5.5 percent is not considered because observations and experiments on roads in Belgium have shown that 0/14 mixes that meet the Belgian grading standards, but contain more than 5.5 percent of binder with polymer additives, present less drainability and generate more rolling noise (*1*,*2*).

FULL SCALE TESTS ON ROADS

In April 1988, three porous asphalt mixes with cellulose fibers (Table 4) were laid on the N 56 Ath–Ostriches state road in Ath, Belgium (Figure 4), with a thickness of 4 cm. This road experiment is being monitored by the Belgian Ministry of Public Works. Using a falling head permeameter (*10*), drainability tests were carried out after two weeks and six months of rather dusty traffic. Although such traffic often causes local spot clogging of porous surfacings, the Belgian Ministry of Public Works found the drainability to be excellent: the drainage time is always less than the maximum average figure of 60 sec, which is stipulated after laying. It should be noted that, even with 6 percent of binder, no bitumen drainage has been observed.

In 1989, new applications were made in Belgium, more particularly at Kuurne (Figure 5) and in the center of the town of Ath.

All the coating plants of SCREG Belgium are equipped to work with fibers. The sealed polyethylene packs are poured into the mixer while the aggregates are being introduced. Dry mixing of the combination of aggregates (stone and sand) and fibers takes place before the bitumen and the filler are added. In the patented double mixing procedure used, for example, in the experiment at Ath, the fibers are added to the sand

TABLE 4 POROUS ASPHALTS ON N 56 AT ATH

Mix	A	B	C
Composition (%)			
Porphyry 7/14	85	85	85
Sand 0/2	11	11	11
Filler	3.85	3.7	3.5
Fibers	0.15	0.3	0.5
Bitumen 80/100	5.0	5.5	6.0
Drainage time (sec)			
- after 2 weeks	15	12	15
- after 6 months	32	14	16

FIGURE 4 Porous asphalt sections on N 56 Ath–Ostriches at Ath.

FIGURE 5 Porous asphalt sections on city streets at Kuurne.

before the bitumen and the filler are introduced; after this bituminous mortar has been mixed, the stones are added and thus coated with homogenous mortar.

COMPARISON OF COSTS

Belgian studies (*11*) have shown that, at equal binder content, the use of modified binders in porous asphalt surfacings entails an extra cost of about 40 percent as compared with pure bitumen. With respect to porous asphalts containing 4.5 percent of pure bitumen and no fibers, the extra cost of products with 5.5 percent of pure bitumen and 0.3 percent of cellulose fibers is about 10 percent. This means that these products not only perform well, but are also relatively cheap.

ACKNOWLEDGMENTS

The author wishes to express special thanks to the laboratories of R.T.E., Labofina, and CRR, whose assistance in carrying out the laboratory tests has been very valuable, as well as to the Belgian Ministry of Public Works, which has been monitoring the road experiments. The author has been honored by the invitation of J. Reichert, Chairman of the PIARC Technical Committee on Surface Characteristics, and J. Bonnot, Technical Manager of the Laboratoire Central des Ponts et Chaussées of France, to present this paper.

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Porous Asphalt Mixtures in Spain

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Currently Spain has 3 million m² of porous asphalt roads. Porous asphalt is being used for all types of traffic conditions and for any type roads and highways. The most common practice today is to use 4 cm layers with 0/12 gradings, with a very low amount of sand (about 15 percent) and 4.5 percent of pure or modified bitumens which results in a voids content in the mix of more than 20 percent.) In the first application of porous asphalt, a conservative approach was taken, primarily using mixes with a moderate content of voids (15 percent to 18 percent). The good durability of mixes with voids contents of more than 20 percent in the experimental road sections and the closing up observed in the mixes with a low voids content has meant that since 1986 the more open mixes have been preferred. Porous asphalts with voids content of less than 20 percent have varied widely in their behavior. With heavy traffic, they have closed up after 2 years' use. With medium traffic, however, they have maintained their drainage capacity after 9 years. None of the pavements using this material have shown any serious deterioration. Despite reduced drainage capacities, all the pavements, including those that have closed up, show a dry appearance during light rains or immediately after a heavy rainfall. Until now, the skid resistance has been very good. Porous asphalts with voids contents higher than 20 percent held up very well even under heavy traffic, although in this case the experience has covered only three years. As in the case of the other mixtures, these have not shown any serious deteriorations, and after several years, they maintain excellent skid resistance.

The first application of porous asphalt in Spain was in 1980 on four experimental road sections on one of the northern highways located in a region of frequent rainfall. Initially, the objective was to use these mixtures in rainy areas in order to improve traffic safety and comfort on wet surfaces.

The favorable results obtained from these mixtures has promoted the construction of new experimental pavements and small projects to be carried out in the next few years. But in 1986, this material started to be used extensively, after initial doubts about its durability were eliminated. Now, the purpose for using this material has changed. It is not only used to improve driving conditions in the rain, but also to provide a durable surface, with a smooth, safe, and quiet ride in any type of weather.

Currently Spain has 3 million m² of porous asphalt roads. Porous asphalt is being used for all types of traffic conditions and for any type of roads and highways. The most notable projects are the 44 km (about 500,000 m²) on Highway N-VI, between Las Rozas and Villalba, with some 20,000 vehicles per day per carriageway, 2,000 of which are trucks (13 ton axle load); the 70 km (about 800,000 m²) on the toll road between Bilbao and Behobia, with about 9,000 vehicles per carriageway, of which 1,200 are trucks, and the 33 km (400,000 m²) in ACESA toll roads, with traffic varying between 800 and 1,800 trucks per day.

The most common practice today is to use 4 cm layers with 0/10 or 0/12.5 gradings, with very little sand, and 4.5 percent of pure or modified bitumens which results in a voids content of more than 20 percent.

MATERIAL REQUIREMENTS

Gradings

The selected aggregate grading primarily influences the water drainage capacity, resistance to particle losses, resistance to plastic deformation, and macrotexture of the mix.

For porous asphalt, two grading bands have been defined, P 12 and PA 12 (Table 1).

The P grading band has a discontinuity in the 2.5 mm size. These gradings usually need three commercial aggregates (0/2.5, 2.5/5, and 5/10 to 12 mm). Using them, mixes with 15 to 22 percent of voids can be obtained. The PA grading band has a discontinuity in the 5 mm size and needs only two commercial aggregates. It was initially designed to reduce the number of commercial aggregates and obtain more open mixes. With these gradings, mixes with up to 25 percent of voids can be obtained.

Both P 12 and PA 12 have a large proportion of coarse aggregate (between 90 and 78 percent of particles exceeding 2.5 mm), in order to accommodate the other components in their interstitial voids, leaving the designed voids in the mix. The amount of fine aggregate must be low enough to prevent the voids from closing up and separating the coarse particles. A certain amount of filler (at least 3 percent) is thought necessary to give cohesion to the mix and avoid particle losses. Keeping this in mind, the tests used to define the grading bands were mainly directed towards the drainability and resistance to particle losses.

Today there is a tendency towards PA gradings, with 10 to 15 percent of particles passing through the 2.5 mm sieve and amounts of filler between 3 and 4.5 percent. With these mixtures, voids contents of more than 20 percent are being obtained.

The maximum particle size has been set at 10 or 12.5 mm for both gradings, although the 10 mm top size is generally

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TABLE 1 GRADINGS

	% PASSING						
GRADING	20mm	12,5mm	10mm	5mm	2.5mm	0.63mm	0,08mm
P - 12	100	75-100	60-90	32-50	10-18	6-12	3-6
PA - 12	100	70-100	50-80	15-30	10-22	6-13	3-6

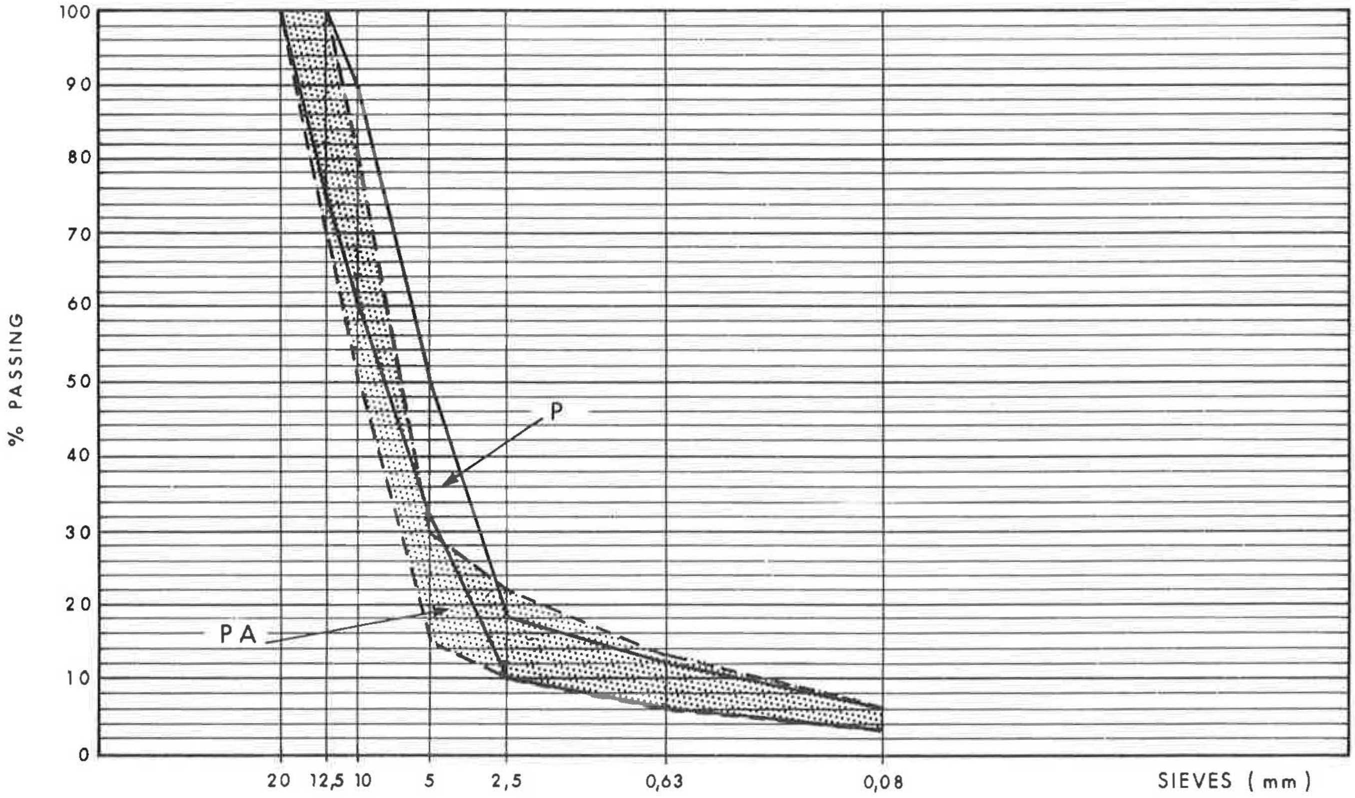

FIGURE 1 Gradings.

used. With this size, sand patch depths of between 1 to 2.5 mm can be obtained. These sizes are also related to the thickness of the layer being used (4 cm).

Aggregates

Considering that the material is for a thin, open, top layer, coarse aggregates which show great resistance to fragmentation, good and stable microtexture, and adequate interlock are called for (Table 2).

Fragmentation of aggregates can lead to particle losses, raveling, and the closing up of the surface texture by the separate fines. An abrasion loss value (Los Angeles machine) of 20 percent is considered as a maximum. For the same reason, a flakiness index below 25 is required.

Frictional characteristics of the surface make a nonpolishing aggregate necessary for maintaining a good, durable micro-

TABLE 2 AGGREGATE CHARACTERISTICS

LOS ANGELES	< 20
FLAKINESS INDEX	< 25
POLISHED STONE VALUE	> 0.45 - 0.40
PARTICLES (%) WITH 2 OR MORE FRACTURED FACES	100 - 75
SAND EQUIVALENT	> 50

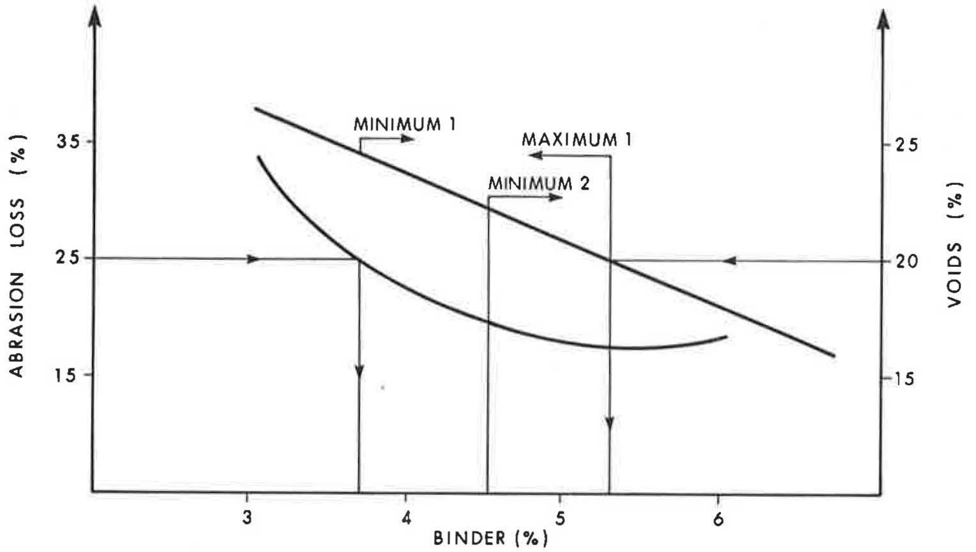

FIGURE 2 Binder design.

texture. The specification sets polished stone values (British polishing wheel) above 0.45 for traffic volumes of more than 800 trucks per day per lane, and 0.40 for other traffic volumes.

Porous asphalt mixtures are subjected to the direct effect of the traffic loads. A good level of internal friction in the course aggregate is necessary in order to avoid plastic deformations and the closing up of the voids. For traffic volumes of more than 800 trucks per day per lane, 100 percent of particles with two or more fractured faces are required. This is reduced to 90 percent for volumes of 200 to 800 trucks and to 75 percent for trucks below 50 per day per lane.

In projects carried out until now, coarse aggregates, which come from hard rocks with a high resistance to polishing (ophites, porphyry, and granite), have been exclusively used. In some cases, limestone has been used for shoulders. Another project used a coarse-grained limestone in a carriageway on the island of Mallorca where no other aggregates were easily available. Until now, the performance has been satisfactory.

Limestone is frequently used as fine aggregate because of its adhesion to the binder. Mineral filler is always added (commercial limestone dust or cement). To avoid the presence of detrimental fine dust, a sand equivalent value above 50 is required.

Hydrocarbonated Binder

In porous mixes, because of the open texture, a thick film of binder coating is sought in an attempt to offset early aging. From this viewpoint, hydrocarbonated binders with high viscosity would be preferred. On the other hand, hard bitumens would take less time to reach a critical hardness of the binder. For this reason, an equilibrium is necessary.

In selecting the binder, other factors to consider are weather and traffic volume. Soft bitumens tend to bleed under high temperatures and can lead to plastic deformations in the mix, particularly under heavy traffic volumes. In cold climates, hard bitumens can produce brittle mixes.

Taking all this into account, in Spain the grades of binder specified are B 60/70 and B 80/100. The former is recommended in areas of mild and hot climates for heavy traffic. But the binders more commonly used are polymer (EVA and SBS) modified bitumens. Today 80 percent of the porous mixes existing in Spain have a modified binder. The main purpose for using it are to improve the resistance against particle losses with very open mixtures through a higher cohesion, and get longer durability through thicker films of binder because of the higher viscosity. A reduction in the thermal susceptibility of the mix (porous mixes are very susceptible to temperature changes) is also sought in an attempt to get higher consistencies with high temperatures and more flexibility with low temperatures (Table 3).

Nevertheless, it has not been possible to confirm the laboratory results on the road. In the first experimental pavements, where mixes with a low amount of voids were laid, pure and modified binders were compared. Until now, there have been no differences in performance. With very open mixes in which the differences probably would be more marked, modified binders have always been used. It is therefore not possible to compare.

The current tendency is to continue using modified binders with the more open mixtures and with heavy traffic, but to experiment with the same mixtures with pure bitumens for medium and light traffic. (There is already an experimental pavement along these lines near Madrid.)

MIX DESIGN

The design of porous asphalt is based on:

- A minimum binder content to assure resistance against particle losses resulting from traffic and a thick film of binder on the aggregates, and
- A maximum binder content to avoid binder runoff and have a good drainability in the mix.

The resistance to particle losses is analyzed through the Cantabro test (NLT-352/86), an abrasion and impact test conducted in the Los Angeles rattler, without balls and at controlled temperature, on Marshall samples compacted with 50 blows on each side. The results are given as the weight loss, in percentage, after 300 drum revolutions (Table 4). The maximum abrasion loss value admitted is 25. With this test, a minimum amount of binder is determined. In any case, the binder content must be at or above 4.5 percent to ensure adequate coating thickness.

The calculation of voids is made on the same Marshall samples, considering the volume geometrically determined. For a specific grading, the minimum amount of voids set (20 percent), define a maximum content of binder. Also there is a maximum binder content to prevent drainage of the asphalt from the aggregates, although this is not yet under specification.

With this procedure, it must be considered that the use of the Marshall hammer for compacting the specimens can cause

TABLE 3 HYDROCARBONATED BINDERS

TRUCK ADT IN DESIGN LANE	SUMMER TEMPERATURE		
	HOT	MEDIUM	TEMPERATE
> 2.000	60/70		
2.000-800	60/70 OR 80/100		
200-800			
50-200			80/100
< 50			
BINDER			

TABLE 4 BINDER CONTENT DESIGN

BINDER CONTENT	PROPERTY OF THE MIX	SPECIFICATION
MINIMUM	RESISTANCE TO PARTICLE LOSSES (CANTABRO TEST)	25
	DURABILITY (% bitumen)	> 4.5
MAXIMUM	BINDER RUNOFF	-
	DRAINABILITY (% VOIDS)	20

some runoff of the binder, mainly with high binder contents. Nevertheless, this leaves the mixture on the safe side in relation to the results of the Cantabro test. Because of the good correlation between voids calculated with this method and drainability in the road and the results of the Cantabro test with laboratory specimens and road samples, this method has been chosen.

In the design of porous mixes, the Cantabro test after immersion and some laboratory permeability tests have been used, but they are not under a standard yet either. Sometimes indirect traction and wheel tracking tests have also been used.

This method usually gives binder contents of about 4.5 percent for normal specific gravity aggregates. With these in practice, no major problems of particle losses or binder runoff have been encountered.

PAVEMENT DESIGN

The design of the newly constructed pavements with layers of porous asphalt mixes has been given in the design standard *Instruction 6.1 and 2.1 C* of the General Direction of Roads of MOPU (*1*).

In this standard, a layer of 4 cm thick is established for porous asphalt. The possibility of using thicker layers has not been considered because the water absorption capacity with 4 cm layers is already thought to be sufficient. Thinner layers would lead to bad performance with heavy rains and could reduce the durability of the layer.

For pavements with granular or asphalt roadbases, the porous asphalt can substitute, in the same thicknesses, for open or semi-open conventional asphalt mixes. This approach has been taken because of the experience and calculations on which the design standard is based. It accounts for pavements with layers of open or semi-open asphalt mixtures, with a mechanical performance similar to those of the porous asphalt.

In pavements with cement-treated road bases, in which one of the main objectives of the bituminous layer is to prevent reflective cracking, a 2 cm increase in total thickness is required for the bituminous layers when porous asphalt is used. This increase is intended to prevent the appearance of reflective cracking in the impermeable layer below the porous asphalt which can make repairs of the structure especially complex and costly.

FIELD OF APPLICATION

Although porous asphalt is used as the top layer of new pavements, the main application thus far has been in the repair of aged or slippery surfaces without structural problems. In this field, this alternative can be more advantageous, from the viewpoint of durability, than others such as those of thin layers of conventional dense-graded mixes, micro-asphalt mixtures, slurry seals, or surface treatments. In specific areas of short length (slippery curves) requiring a very high degree of resistance to skidding, conventional solutions are still preferable. They have also been used in short stretches (300 m) in areas of difficult drainage (change in the direction of the cross fall, low points).

Porous asphalt's use should be carefully studied for the following cases:

- Areas where it snows frequently, because of maintenance problems during the winter months,
- Urban or industrial areas where there is extensive wear from abrasion or where the impacts or spillage of oil or fuels occurs,
- Areas in which a strong risk of reflective cracking exits, either by retraction or fatigue, and
- Bridge pavements, especially in cold areas.

In any case, it is necessary to lay porous asphalt on impermeable and regular surfaces, and to assure adequate lateral drainage.

MANUFACTURE AND LAYING

If porous asphalt is placed over pavements, for surface rehabilitation of an aged or slippery surface, the deteriorated areas should be repaired first and the surface leveled if there are any large irregularities. When porous asphalt is used on pavements with reflective cracking in the surface, it is necessary to seal them first (but this is not a good solution for this type of problem).

In any case, it is necessary to make sure the layer is impermeable and has a satisfactory load capacity. Before the material is placed over new or old layers, an emulsion is extended over it (quick setting cationic emulsion), with a residual bitumen rate of 500 to 600 gr/m². In pavements with a highly polished or very open surface, it may be necessary to lay down slurry seals.

The manufacture of the mixture is made in conventional discontinuous plants. The production of the plant should correspond to the spreading equipment in such a way that stops are minimized. When establishing mixing temperatures, binder viscosity must be taken into account, but the drainage of the binder or cooling of the mix during transit from the mixing plant to the job site must also be considered. With B 60/70 or modified binders and the fines given in the specifications, mixing temperatures have oscillated between 140°C and 150°C without ever exceeding 160°C.

In transport, it is necessary to cover the trucks adequately with canvas. In cold weather and over long transport distances, it is necessary to watch out for agglomerated portions of the mixture in the front part of a truck's body.

According to established procedures, this material should not be spread when the temperature is less than 8°C. In any case, the temperature of the mix should never go below 120°C during compacting.

Compacting is carried out with metallic rollers having a total weight of 10 tons or more and without vibration. The usual procedure is to set up two similar compacters. The first compacts with 4 to 5 passes and the second with 2 or 3 in order to smooth out the tracks left by the first one and improve the surface finish.

Until now, shoulders constructed on pavements topped with porous asphalt layers have been built by extending the porous asphalt over the entire shoulder or 50 cm into the shoulder. The top layer of the shoulder in the second case or the intermediate layer in the first case must be of an impermeable material.

The differential aspects of control of this material with respect to conventional mixtures are

- In control of the manufacture, the Marshall test is substituted for the Cantabro Test of abrasion loss on samples in which the voids content has been previously determined, and
- The degree of compaction can be controlled indirectly by means of a permeability test in situ.

This test is conducted by means of the LCS drainometer (*2*). The equipment, developed by the University of Santander in 1981, is a variable charge static outflow meter used to measure the time necessary to drain 1,735 l of water through a pavement surface of 7 cm².

The voids content percentage, previously related in the laboratory with the degree of compaction, is then related to the time of water drainage by means of the expression (*3*):

$$H = 58.6/T^{0.305}$$

where

H = % voids content
T = time of water drainage (sec)

MAINTENANCE

The main problems have come in the form of particle losses in localized or large areas. This process usually occurs very quickly once the flow of traffic begins. This problem usually originates from laying the mixture cold, from too low a level of compaction, or from segregation of the binder. The solution has always been to mill and substitute the withdrawn material for another porous asphalt. In one case, the repair was made by laying one porous asphalt over another; so far, no problems have arisen. Rehabilitation has never been undertaken because the material closes up.

Experience with winter maintenance in Spain is not very extensive. Skidding problems have been detected because of ice formation after snowfalls and this has led to avoiding the use of these mixes in extremely cold areas. In warm areas where snow falls only a few days per year, the solution is to use more salt (more than double the normal amount) and increase the frequency of spreading.

PERFORMANCE OF EXISTING SURFACES

In the first application of porous asphalt, a conservative approach was taken primarily using mixes with a moderate content of voids (15 to 18 percent). The good durability of mixes with voids contents of more than 20 percent in the experimental road sections and the closing up observed in the mixes with a low voids content has meant that since 1986, the more open mixes have been preferred. Therefore, in the analysis of the performance of existing pavements with a top layer, it is useful to differentiate the cases in which mixes have been used whose voids content is less than or greater than 20 percent.

Porous mixes with voids content < 20 percent

Experience with these mixes goes back to 1980. They are generally type P gradings with pure bitumens in an application rate of between 4 and 5 percent. The voids content is usually found in the range of 16 to 20 percent. The evolution of the mixes has been studied through measurements of drainability, surface texture, skid resistance, and visual condition.

The initial drainage times (LCS drainometer) on the highway varies between 30 and 75 sec. The texture, measured in sand patch depth, varies between 1 and 1.5 mm. The Side Force Coefficient (SFC) measured with SCRIM type equipment at 50 km/hr and with 1 mm of water gives values of between 0.50 and 0.70. Values of the Skid Resistance Tester Coeficiente (SRC) between 0.45 and 0.70 are usually found.

Over time, a large decrease in the drainage capacity has been observed. The factors that come into play are the closing up of the surface voids caused by various types of deposits, or the silting up of internal voids because of the dragging of fine materials and densification from tires rolling over the surface.

The evolution shows a great degree of dispersion and depends on conditions in the area and the type of traffic. Closing up (defined as drainage times measured with the LCS drainometer of more than 600 sec) has taken place during various periods. With the more closed porous asphalts and with the heaviest traffic (16 percent of voids in mix and more than 2,000 trucks per day and per lane), this has taken place within two years of the opening of traffic and with the more open porous asphalts and with medium traffic (about 1,000 trucks per day) after 9 years they are not totally closed up.

Sand patch depth and SFC values show no appreciable change over many years, and today all the sections constructed with these mixtures are in good condition, without any serious deterioration. Despite the decrease in drainage capacity, all the sections, including those that are closed up, remain dry in light rains or immediately after heavy rains, with a marked difference in this aspect compared to conventional dense graded mixes.

Table 5 shows the values corresponding to the evolution of drainage times for the experimental pavements of Santander with these kinds of mixes. The level of traffic on this road is 5,000 vehicles a day per lane, of which 700 are trucks. It is a rainy area used mainly for agricultural traffic. As can be seen, some of them maintain a certain capacity of drainage after 7 to 9 years. The SFC and SRC values are 0.50 to 0.60 and 0.50 to 0.70, respectively, after the same period. The sand patch depth is 1.2 to 1.5 mm.

Table 6 shows the results obtained over 4 years on a highway located near Madrid. It has a double carriageway and two lanes going in each direction, with a level of traffic of about 10,000 vehicles a day per carriageway of which 1,800 are trucks. The initial voids content was 17 percent.

TABLE 5 PERMEABILITY (SANTANDER TEST SECTIONS)

Test Section	Permeability (seg)				
	Initial	4 Months	2 years	4 Years	9 Years
I	30	75	180	288	silting up
II	46	70	100	159	220

Test Section	Permeability (Seg)		
	4 Months	2 Years	7,5 Years
2	65	180	Silting up
3	58	220	350
4	45	140	300
6	120	300	Silting up
9	80	200	Silting up

TABLE 6 PERMEABILITY (SEC) IN DIFFERENT AREAS OF THE CARRIAGEWAY (NAVALCARNERO)

LEFT LANE				RIGHT LANE			
DISTANCE TO THE EDGE OF CARRIAGEWAY MARKING (m)							
0.70		1.70		1.70		0.70	
63	79	71	87	80	113	150	219
99	-	109	-	226	608	362	988

10 - 30 measures in each point

- Not measured

KEY

6 months	1 year
2 years	4 years

The drainage time was 200 sec after 1 year in some points on this pavement and in all the right lane after 2 years. After 4 years, this lane is almost closed up. Although it has been seen that the main factor in the closing up is the postcompaction in the wheel tracks, the area between them in the slow lane is also closed up because of spillage from trucks. The left lane of the same carriageway is still in good condition.

Porous mixes with voids content >20 percent

These mixes, first used extensively in 1986, today are the most widely used. They are generally of the PA grading type, with modified bitumens in percentages in the 4.3 to 4.8 range.

The initial drainage time varies between 15 and 25 sec and the sand patch depth between 1.3 and 2.2 mm. The SFC and SRC values are 0.60 to 0.80 and 0.54 to 0.80, respectively.

The mixes tested in the experimental pavements of Santander now have, after 7 to 9 years of service, drainage times of between 150 and 300 sec.

In the Las Rozas-Villalba road (44 km), with 2,000 trucks per day per lane, the mix initially had a voids content of 22 percent and registered initial drainage times of about 20 sec. Today after 2 years, the interval of drainage time values is between 20 and 50 sec. The texture is of approximately 2.2 mm and its coefficient of skid resistance is 0.55 to 0.60 and 0.60 to 0.80 measured with the TRRL pendulum and SCRIM, respectively.

CONCLUSIONS

Porous asphalts with voids content of less than 20 percent have varied widely in their behavior. With heavy traffic, they have closed up after 2 years of use. With medium traffic, however, they have maintained their drainage capacity after 9 years. None of the pavements using this material have shown any serious deterioration. Despite reduced drainage capacities, all the pavements, including those that have closed up, show a dry appearance during light rains or immediately after a heavy rainfall. The skid resistance has been very good until now.

Porous asphalts with voids contents higher than 20 percent held up very well even under heavy traffic, although in this case the experience has only been over 3 years. As is the case with the other mixtures, these have not shown any serious deteriorations, and after several years, they maintain excellent skid resistance.

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Porous Asphalt Wearing Courses in the Netherlands: State of the Art Review

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Since 1972, research has been carried out in the Netherlands to assess the advantages of porous asphalt wearing courses in relation to conventional pavement structures. Efforts have also been made to quantify the extra costs incurred by road managing authorities when using such materials. The chief advantages of porous asphalt wearing courses to road users are expected to be improved road safety and reduced congestion. Furthermore, the noise nuisance on such roads is greatly diminished. On the other hand, additional costs are involved because of the shorter service life and more expensive maintenance required for porous asphalt, as well as the fact that thicker asphalt constructions are needed to provide the necessary bearing capacity. Based on a cost-benefit analysis, it has been shown that the extra expenditure associated with porous asphalt can be justified by the potential benefits. The Dutch Department of Public Works (Rijkswaterstaat) has therefore decided to install such wearing courses where possible on the national road network, particularly on motorways. The characteristic properties of porous asphalt and the related financial implications are discussed in this paper. Moreover, an outline is given of how the new policy of the Department of Public Works, which will take some 10 years to implement, has been developed.

The Netherlands, located in northwestern Europe, has a temperate climate with average temperature of 1.7°C in January and 17.0°C in July. The annual precipitation is almost 800 mm, which is equally distributed throughout the year. Despite the mild winters, the rather changeable weather conditions often lead to fog and slippery roads.

The Netherlands is one of the few countries which began the construction of its motorway system before World War II. The growth in motorway building in the period 1960 to 1985 coincided with major increases in traffic density on the primary road network. Additional general information about the Netherlands can be found elsewhere (*1*).

REASONS FOR APPLYING POROUS ASPHALT

The relatively high levels of precipitation in the Netherlands means that on average, road surfaces tend to be wet or moist about 13 percent of the time. In order to promote road safety under such conditions, the former Study Centre for Road Construction set up a working party in 1971 that was asked to formulate recommendations for improving the surface characteristics of wearing courses (*2*). This led to the first application of porous asphalt in the Netherlands in 1972. The significant potential of this material for improving road safety, coupled with the favorable experience gained during the trials, led to the establishment of a second working party to assess the possibilities for porous asphalt in more detail (*3*).

Although road safety aspects were initially considered to be of overriding importance when deciding to apply porous asphalt wearing courses, the favorable noise-reduction characteristics of this material have led to its more widespread use in the 1980s. Despite the fact that most of the earliest porous asphalt surfacing installed is in the United States and United Kingdom, (particularly at airports), considerable interest has also been shown on the Continent in recent years (*4,5*).

In an extension of previous work on establishing national properties, the factors that have influenced the decision of the Rijkswaterstaat to apply porous asphalt wearing courses on heavily traveled routes is discussed in this paper.

PREREQUISITES FOR INSTALLING POROUS ASPHALT WEARING COURSES

Before porous asphalt wearing courses can be applied, certain prerequisites must be set. The Rijkswaterstaat postulated that the cost-benefit ratio of porous asphalt should at least equal that of dense asphalt concrete wearing courses. Only then could the application of this new type of wearing course be justified.

Many of the factors that must be taken into account in such cost-benefit analyses have political connotations because public opinion can influence aspects of road safety, congestion prevention, and environmental pollution.

The political dimension is especially relevant because the potential benefits to road users in society, for instance of fewer accidents must be compared to the increased expenditure incurred by road managing authorities (government).

In the Netherlands, the factors that are used as the basis for such cost-benefit assessments are structural properties (such as service life and mechanical strength), material costs, road safety considerations, traffic behavior (fewer traffic backups in wet conditions), maintenance costs, and noise aspects.

Furthermore, efforts have been made to quantify the additional expenditure associated with porous asphalt in relation to the potential cost savings.

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METHODOLOGY

Before taking into account the named factors, something must be said about the method used in the Netherlands to design roads, because the parameters used in this method must be quantified for porous asphalt.

The design of highways in the Netherlands is largely based on semi-empirical methods (*6*). This implies that information about material characteristics and structural aspects is regularly updated in the light of practical experience obtained under realistic conditions. The various steps involved can be represented by the Deming quality circle, which is shown in its most complete form in Figure 1.

Because much knowledge about the behavior of materials and construction is empirical by nature, the models used strictly only apply to existing materials.

In the Netherlands, it is customary to use a multilayer elastic model for design analyses as proposed in the Shell Pavement Design Manual (*7*). Incorporation of the department's own research results and practical experience have made it possible to modify the model so as to enhance the accuracy of the predictions made (*8*). In view of the empirical nature of road engineering technology, it is essential to gain sufficient experience with porous asphalt before meaningful conclusions can be drawn about its general suitability. Although experiments carried out on a laboratory scale can be used to generate the basic properties of materials, it is necessary to use test sections to confirm these findings under practical conditions.

An integrated approach of this type is needed in order to provide a full description of the behavior of porous asphalt for modeling purposes. The factors relevant to such an analysis are discussed individually in the following sections, after which a combined cost-benefit balance is presented. The greater part of the national road network in the Netherlands has an asphalt concrete wearing course with a base course constructed from asphalt concrete, to which gravel has been added as aggregate (*9*). Most of the asphalt concrete road bases have been laid directly on the subgrade or on a subbase of unbound stone or cement-bound materials.

Because porous asphalt has been proposed as an alternative to dense asphalt concrete, direct comparisons have been made between these two materials in the cost-benefit analysis. The specific composition of the dense asphalt concrete mix is shown in Table 1.

CHARACTERISTICS OF POROUS ASPHALT MIXES

Materials

The porous asphalt mix currently being used in the Netherlands is comparable to that generally employed in porous friction courses in the United States. However, whereas a layer thickness of approximately 50 mm is normal practice in the Netherlands, 20 mm is standard in the United States. The choice of 50 mm relates to the higher water storage capacity of the layer. For the climatological conditions in the Netherlands, this means that only in exceptional conditions, water will be on the surface of the porous asphalt wearing course.

The precise composition and properties of the mix used in the Netherlands are given in Table 2. In view of the specific nature of the mixture and, in particular, its high porosity, strict demands must be made towards the bonding between the bitumen and mineral aggregate. The crushed gravel aggregate used for this type asphalt in the Netherlands originates from either the Rhine or Maas.

To improve the bonding of the bitumen, a limestone filler is added during the production process, which has a hydrated lime content of at least 25 percent. The formulation of the

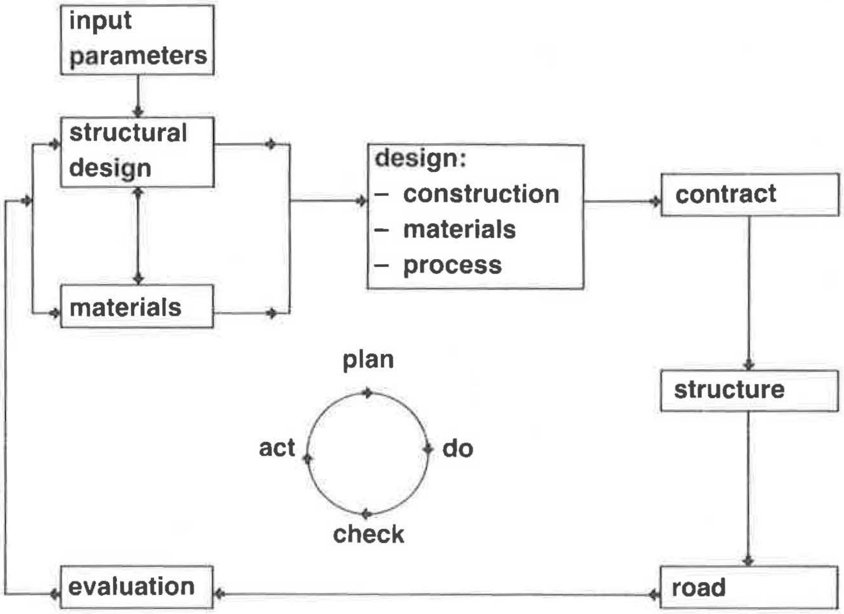

FIGURE 1 Quality circle for the production of asphalt concrete roads.

TABLE 1 COMPOSITION OF A DENSE ASPHALT CONCRETE 0/16 WEARING COURSE

	mass percentage			
on sieve	desired 2)	min.	max.	tolerance 5)
C 16 1)		0	2	± 1.0
C 11.2		5	25	± 8.0
C 5.6		30	55	± 7.0
2 mm	60 4)	57	63	± 5.0
63 μm	93 3)	92,5 *	94	± 1.0
bitumen content (% m/m) (on 100% mineral aggregate)		6.2	6.6	± 0.4

1) Sieves according to ISO-565.
2) Desired composition should lie between minimum and maximum values as specified in the Marshall procedure.
3) Correction applied depending on the density of the filler
4) All stone is crushed gravel.
5) Accepted difference between individual road sample (cores) and desired composition.

mixture has been standardized, such that Marshall tests can be used to quantify the pore volume that is used as the single design criterion (minimum value 20 percent). It should be noted that the porous asphalt mix is prepared with bitumen having an 80/100 penetration rating. Other mechanical properties used to characterize this type of material are its resistance to deformation and stiffness modulus (E modulus) from dynamic bending tests. Wheel tracking tests (*10*) have shown that the porous asphalt mix used in the Netherlands has a good resistance to deformation (Figure 2), while the E-modulus is known to be relatively high (only about 20 percent lower than dense asphalt concrete).

It should be noted, however, that the fatigue and creep properties are difficult to interpret with current test methods. Because the mixture has an open stone structure, held together by a relatively small amount of mortar, it fails extremely rapidly during creep tests (*11*), because of the lack of lateral restraint. Similar shortcomings prevent the results of long-term fatigue tests being used for design purposes as would be appropriate for dense asphalt concrete mixes.

Processing and Application

In the Netherlands, asphalt concrete is produced in batch mixing plants, which can be used in a relatively straightforward manner to handle porous asphalt.

The different material characteristics require a stricter temperature control in the drying drum, whereas some production losses are incurred as a result of the somewhat longer mixing times. Mechanized processing (Figure 3) is essential for porous asphalt because hand-laying gives poor results and therefore should be avoided. Compaction is best achieved by means of static rollers. During this process, temperature control is critical. Too high a temperature affects the viscosity of the mortar, leading to segregation and demixing. Too low a temperature, on the other hand, hampers the compaction.

Laying and compaction temperatures should be between 140°C and 170°C. Current estimates suggest that the material costs, including laying and compactions of porous asphalt, are comparable to those of dense asphalt concrete. To assist with project management aspects, contract specifications have been

TABLE 2 COMPOSITION OF POROUS ASPHALT

	mass percentage			
on sieve	desired	min.	max.	tolerance
C 16		0	4	± 1.0
C 11.2		15	30	± 8.0
C 8		50	65	± 7.0
C 5.6		70	85	± 7.0
2 mm	85			± 4.0
63 µm 3)	95.5			± 1.0
bitumen 4) content (% m/m) (on 100% mineral aggregate)	4.5			± 0.5

1) Crusher sand only.

2) Void content after laying and compaction: minimum 15.0%, maximum 25%.

3) Limestone filler only.

4) Penetration bitumen 80/100.

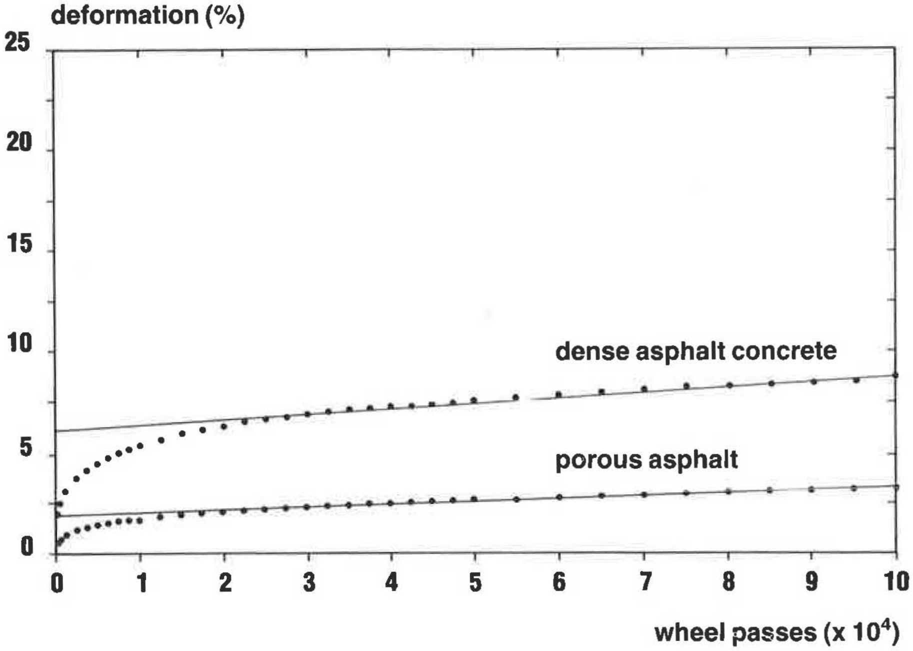

FIGURE 2 Deformation characteristics of dense asphalt concrete and porous asphalt obtained from wheel tracking tests.

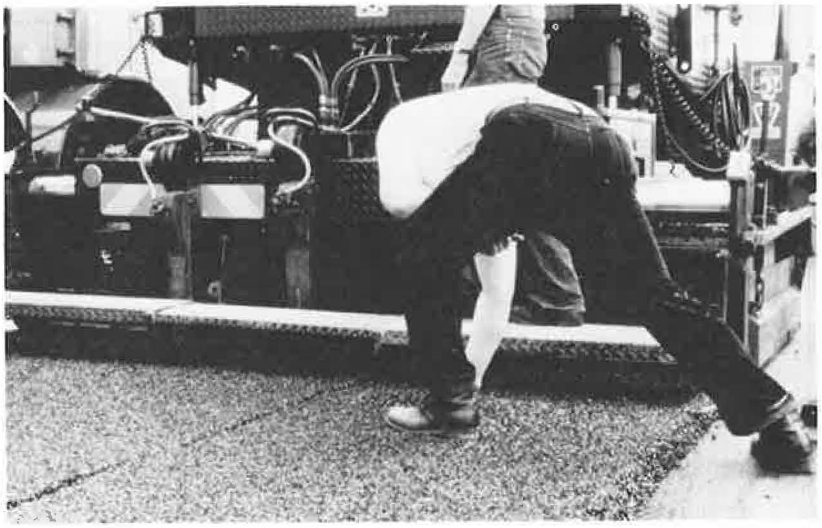

FIGURE 3 Laying porous asphalt with a paver.

drawn up for the production and application of porous asphalt wearing courses (*12*).

Structural Properties

The impact of replacing a dense asphalt concrete wearing course with one of porous asphalt on the structural integrity of the pavement can be assessed using the Department of Public Works' standard multilayer elastic design analysis.

Existing bituminous pavements are modeled with a dynamic E-modulus of 7,500 MN/m^2 and specific fatigue characteristics depending on the material concerned (*13*).

In the current model, it is assumed that the fatigue resistance of road pavements is determined by the lower part of the structure, which ignores the fact that, under certain circumstances, fatigue cracks can also develop in the upper part of the structure (*14*). However, no evidence of such cracking has been found in any of the porous asphalt test sections examined to date. Studies have indicated that three specific aspects need to be addressed when considering the bearing capacity of porous asphalt. At first the effects of these aspects are discussed individually, afterwards they will be integrated.

Initial Stiffness Modulus

Fatigue tests have shown that the initial E-modulus of porous asphalt (E = 5,400 MN/m^2) is approximately 80 percent of that of dense asphalt concrete and about 70 percent of that of gravel asphalt concrete.

By substituting the above data in the elastic design model, estimates have been made of the effective contribution of a porous asphalt wearing course to be bearing capacity of the pavement structure. The results are shown in Figure 4. It can be seen that the initial effective contribution is about 80 to 90 percent of that attainable with gravel asphalt concrete, depending on the thickness of the structure.

Aging and Stripping Characteristics

As a result of the rather open structure of porous asphalt, the binder is likely to undergo accelerated aging because of oxidation, which in turn will considerably increase the stiffness of the material. On the other hand, water ingress will lead to stripping in the lower part of the surface layer, which will adversely affect the cohesive properties of the material, as well as the adhesion to the underlying base course, thus impairing the load transfer characteristics of the structure. Although no direct evidence has been forthcoming from practical trials, suggesting that the actual performance is drastically modified by such effects, it has been conservatively assumed that the adhesion to the underlying pavement is effectively reduced to zero at the end of the service life because of this stripping effect.

Calculations performed with the BISAR program have shown that, under such circumstances, the effective bearing capacity of the debonded layer is reduced to between 2 and 10 percent of the original value. By applying Miner's modified linear damage law (*15*) over the service life of the wearing course (*16*), the weighted effective contribution can be estimated to be about 35 to 40 percent.

Effect of Temperature on Dimensioning

In view of the relatively open structure of porous asphalt, it is expected that the thermal characteristics of such wearing courses will differ significantly from those of conventional materials.

It has been postulated that the suction and pumping action of tires passing over porous asphalt surfaces, coupled with wind motion, will promote a continuous circulation of air within the pores. Consequently, the temperature in porous asphalt wearing courses is likely to remain closer to the prevailing air temperature than with closed surfacing materials. This is especially important in the summer months, when the

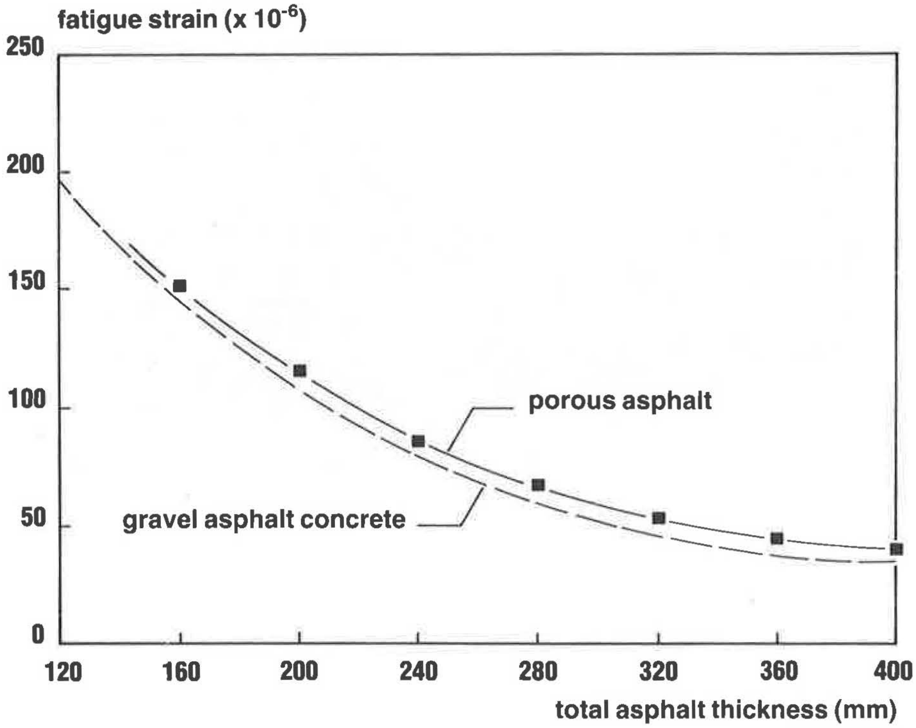

FIGURE 4 Strains in full-depth gravel asphalt concrete pavements and comparable structures with 40-mm-thick porous asphalt wearing courses when subjected to a standard axle load of (100 kN). (E subgrade = 100 MPa.)

temperature of dense asphalt concrete roads has been known to rise to 60°C. Under such conditions, the stiffness of the material decreases because of the visco-elastic nature of bitumen. To investigate the extent of temperature differences between various surfacing materials, experiments have been carried out on instrumented test sections.

Temperatures were measured through the thickness of asphalt concrete constructions both with newly laid and 8-year-old porous asphalt, as well as in similar constructions with a dense asphalt concrete wearing course. By taking continuous measurements with specially installed gauges, it was possible to plot comparable temperature gradients. An example of the measured temperature profiles is given in Figure 5.

Analysis of the results, which were collected over 1 year, including both summer and winter conditions, has clearly shown the significance of thermal insulation effects in wearing courses. The weighted average temperature over a year was found to be about 1°C lower in pavements surfaced with porous asphalt than in comparable structures with a dense asphalt concrete wearing course. Consequently, the stiffness of asphalt concrete structures with porous asphalt wearing courses is less affected by warm weather.

Compared with structures with dense asphalt concrete wearing courses, the relative stiffness of the structure effectively increases, which reduces the strain in the lower part of the structure and therefore extends the fatigue life. This means that thinner constructions can be used in order to achieve a given fatigue life as shown in Figure 6.

Overall Effect on Structural Design

The combined effect of the above-mentioned factors is illustrated in Table 3, assuming an average temperature reduction of 1°C attainable with porous asphalt. It can be seen that depending on the thickness of the structure, porous asphalt can be expected to contribute about 50 percent of the equivalent bearing capacity achievable with dense asphalt concrete (*16*). If good adhesion can be maintained throughout the service life, the effective contribution of a porous asphalt wearing course can amount to 100 to 110 percent of conventional systems.

Effect of Temperature on Rutting

The higher the prevailing ambient temperature, the greater the impact temperature reductions in the wearing course are likely to have on rutting. Unfortunately, it was not possible to quantify these effects fully under extreme summer temperatures (typically 50 to 60°C at the road surface) because of the unseasonably cool weather conditions during the period when the temperature profiles were being measured.

Because the temperature differences between structures with porous asphalt and dense asphalt concrete wearing courses are expected to increase as a function of the ambient temperature, structures with porous asphalt are likely to retain a far better resistance to rutting. Practical observations have

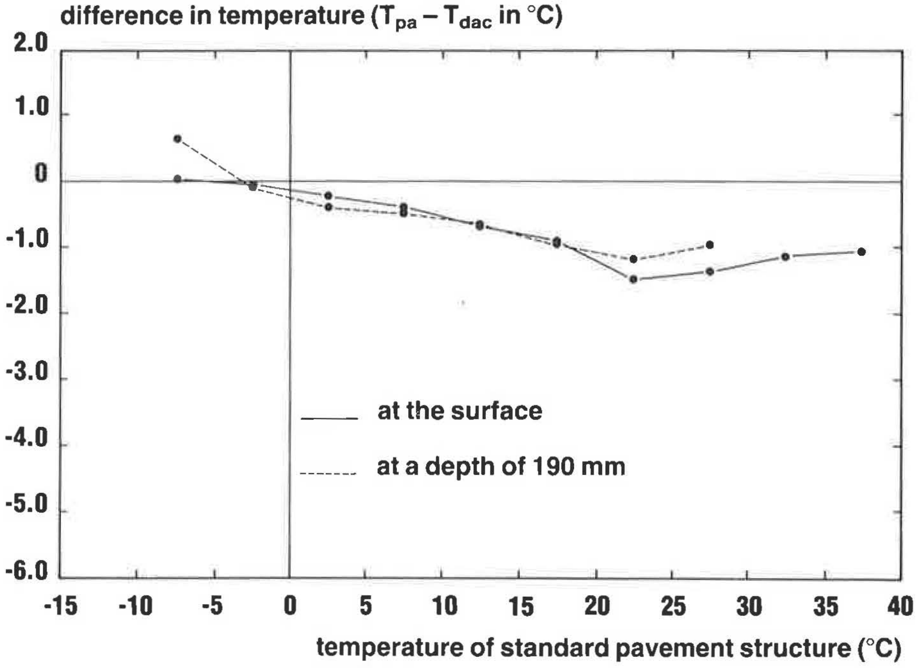

FIGURE 5 Differences in temperature of pavements with porous asphalt and dense asphalt concrete wearing courses as a function of the temperature of the standard structure.

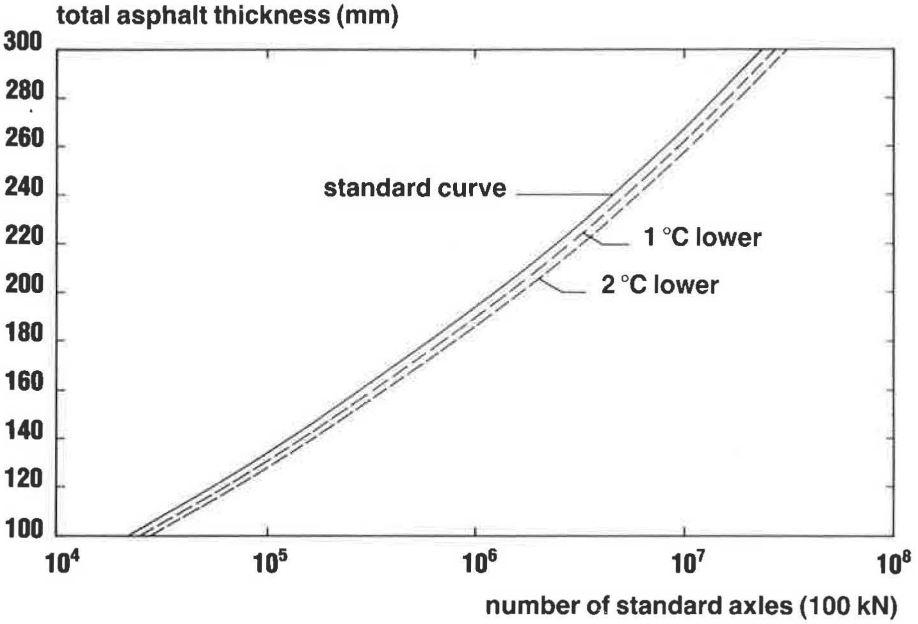

FIGURE 6 Effect of temperature reductions on pavement design curves resulting from the use of porous asphalt wearing courses. (E subgrade = 100 MPa.)

TABLE 3 DIFFERENCES IN EFFECTIVE CONTRIBUTION OF A 50 MM THICK POROUS ASPHALT WEARING COURSE TO THE BEARING CAPACITY OF A FLEXIBLE PAVEMENT AS A FUNCTION OF THE DIFFERENCE IN PROPERTIES RELATIVE TO DENSE ASPHALT CONCRETE

	Difference in bearing capacity expressed in mm gravel asphalt concrete for a 50 mm porous asphalt wearing course instead of dense asphalt concrete.			
total thickness of asphalt construction	due to lower initial E-modulus	due to aging and loss of adhesion	due to lower construction temperature	total effect
120	-10	-22	+2	-30
240	- 6	-24	+6	-24
360	- 4	-25	+9	-20

tended to confirm this hypothesis in that hardly any evidence of rutting could be found on porous asphalt test sections during a service life of 10 years where, under similar circumstances, an average rut depth growth of 1.5 mm/year was measured on similar structures with conventional surfaces.

Service life

The service life of wearing courses is an extremely important factor to be considered when performing cost-benefit analyses. The experience gained with test sections of porous asphalt since 1972 is discussed at length elsewhere (*3*).

Data have been collected from 11 test sections, with a total length of approximately 10 km, which were constructed at various locations in the Netherlands, particularly along extremely busy motorways with traffic densities of approximately 60,000 vehicles per day. On the basis of these trials, it can be concluded that the service life of porous asphalt wearing courses under Dutch traffic and weather conditions is expected to be about 10 years, compared with a service life of approximately 12 years for dense asphalt concrete.

The shorter maintenance cycles that are needed for porous asphalt are therefore a clear disadvantage. Subsequent evaluation of the test sections has revealed that the prevailing damage mechanism is the loss of material that results when stones become separated from the pavement surface.

Generally, the deterioration process takes place relatively slowly and does not have any catastrophic effects. Other types of damage such as rutting and cracking have not been observed. However, it should be noted that porous asphalt is sensitive to mechanical damage in the first year after installation.

ROAD SAFETY ASPECTS

The qualitative improvements in road safety that can be produced by using porous asphalt wearing courses have been known for some time. By eliminating continuous water films on the road surface, splash and spray effects are reduced considerably, ensuring that road markings remain clearly visible even in wet weather.

Moreover, troublesome reflections can be avoided and the chance of aquaplaning eliminated (Figure 7). However, before cost-benefit analyses can be performed to assess the economic impact of such advantages, the financial savings resulting from fewer accidents need to be quantified.

Much of the early Dutch research into porous asphalt focused on skid resistance properties. All the results collected to date clearly show that the skid resistance of pavements surfaced with porous asphalt satisfies the requirements laid down over the prescribed service life (Figure 8). In addition, it was found that the reduction in skid resistance on porous asphalt surfaces at higher speeds was far less marked than that observed on conventional wearing courses (*17*). Standardized measurement techniques are employed in the Netherlands to determine the skid resistance properties of pavements (*18*), involving the use of a braked tire with 86 percent skid on a wet road surface.

FIGURE 7 Visual improvements stemming from the use of porous asphalt.

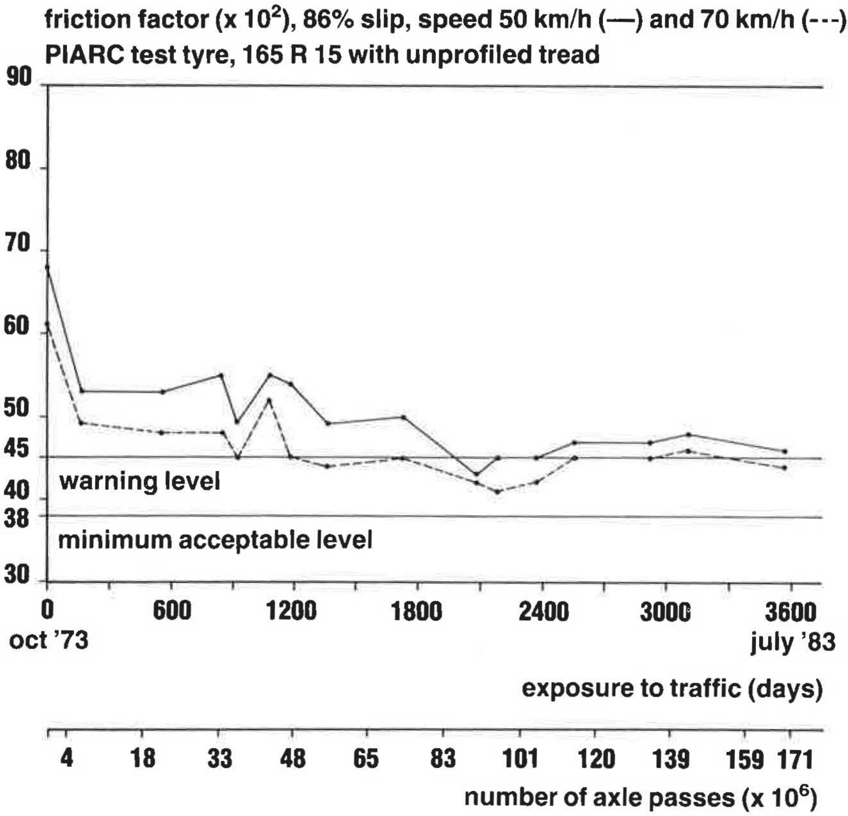

FIGURE 8 Typical example of the decrease in skid resistance of porous asphalt as a function of time.

This method allows practical situations to be simulated and enables the coefficient of friction between tire and road to be measured under unfavorable conditions. The thickness of the water film on porous asphalt wearing courses is generally lower than that of dense asphalt concrete in view of the relatively open structure of the former, which allows water to drain away, as opposed to the closed structure of the latter. Nevertheless, skid resistance measurements made under the prescribed test conditions are considered to be valid because this closely reflects the actual conditions encountered on these types of wearing course.

It is noted, however, that the values obtained for the different materials are not strictly comparable in a scientific sense because of the different film thicknesses.

Research conducted in the Netherlands into the relationship between skid resistance and accident rates (*19*) has shown that increases in skid resistance tend reduce the number of traffic accidents in wet conditions. To complete the picture, the effects of porous asphalt under dry circumstances should also be given. Although porous asphalt wearing courses have been found to have a lower skid resistance than dense asphalt concrete surfaces under these conditions—as a result of the reduced contact area—hardly any difference in accident rates will occur. This is a result of the extrememly high levels of skid resistance obtained under dry conditions for both types of pavements. These results are in accordance with foreign tests which have also shown that the braking distance required on porous asphalt wearing courses is longer than that needed on nonporous surfacing (*20*).

Generally, skid resistance in only one of the factors that affects road safety. The other aspects outlined in the opening paragraph of this section also have a significant impact on the driving behavior of road users and hence on traffic safety.

Accident statistics in the Netherlands show that the number of accidents on wet roads is 3.5 higher per million vehicle kilometers than on dry roads. Drivers apparently fail to adapt their driving behavior sufficiently to account for the changed conditions.

Because no accurate data were available on road accidents on porous asphalt, the advantages of using this type of wearing course should be estimated in another way. Given the hypothesis that the performance offered by porous asphalt wearing courses in wet conditions will be comparable to that of dense asphalt concrete surfacing in dry weather, it can be postulated that the accident rates should also be similar. On this hypothetical basis, the number of accidents that could be avoided with porous asphalt wearing courses can be determined and hence the potential financial benefits quantified (*21*). An example of such a calculation is given in Table 4. It should be noted that these figures represent the maximum savings

TABLE 4 ESTIMATED SAVINGS FROM THE INCREASED TRAFFIC SAFETY

	total length of roads (km)	annual financial savings 1) (guilders)	savings per km (guilders)	savings per m^2 (guilders)
motorways	1825	44,101,20	24,165	≈ 1.00 2)
limited access roads	486	10,112,70	20,808	≈ 2.30 3)
highways	490	8,416,20	17,176	≈ 2.15
other national roads	1809	30,513,60	16,868	≈ 2.00
all national roads	4610	93,143,70	20,204	≈ 1.65 4)

1) Based on the following average costs per accident:

material damage only f 3,900 (≈US $ 1,750)

casualties involved f 39,000 (≈US $ 17,500)

2) Two traffic lanes with a hard shoulder (total width ≈ 23 m).

3) Single carriageway (width ≈ 9 m).

4) Weighted average.

achievable within the framework of the above hypothesis. On the other hand, no allowance has been made for the fact that drivers may compensate for wet (road) conditions.

CAPACITY EFFECTS

Most experts agree that traffic congestion builds up more rapidly in wet weather. This is only partially because more people tend to use their cars under such circumstances. The major contributory factor affecting congestion is the significant reduction in traffic capacity brought on by changes in driving behavior. Measurements have shown that on average, reductions in capacity of approximately 10 percent can be expected in wet weather (*22*).

Because a large number of roads in the Netherlands are used at full capacity during the rush hour, the impact of such weather conditions can be considerable. On the basis of the hypothesis outlined above, it may be assumed that porous asphalt will also reduce the number of backups, resulting in considerable benefits to society.

Calculations have shown that backups cost the Dutch economy about F 325 million a year (*23*). A large proportion of these backups occur at regular congestion points because of overloading, with bad weather conditions being mainly responsible for difficulties at other parts of the network. It has been calculated that approximately F 25 million could be saved in lost waiting time if porous asphalt wearing courses were installed on all national highways. Efforts are currently being made to quantify these benefits more precisely.

ENVIRONMENTAL ASPECTS

Noise Reduction

It is now widely recognized that porous asphalt is highly effective in reducing noise levels on roads. Greater understanding of the potential offered by this material in the 1980s has led to its more extensive use. The rapid increase in traffic density and growing concern for the environment in a densely populated country such as the Netherlands have meant that increasing emphasis is being placed on minimizing the impact of noise nuisance.

Measurements performed in the Netherlands have shown that by installing porous asphalt wearing courses, noise levels can be reduced by approximately 3 dB(A) compared with more conventional dense asphalt concrete surfacing (*24*). These figures, which apply to passengers cars traveling at speeds exceeding 80 km/hr in dry conditions, strongly agree with findings published in other countries (*25,26*).

In order to study noise reduction aspects in more detail in the Netherlands, special test sections have been installed of varying composition and having different layer thicknesses, as illustrated in Table 5.

No significant differences in noise reduction have been observed within the group of porous asphalt wearing courses that have been tested (*24*). In accordance with the regulations laid down in the Dutch Noise Nuisance Act, all the tests were performed on dry road surfaces (*27*). However, it is recognized that noise reduction effects are generally more pronounced (up to about 8 dB(A)) in wet weather.

Measurements were made at speeds of more than 80 km/hr, because, under these conditions, the noise produced between the tires and road surface tends to dominate. The differences in texture between porous asphalt and dense asphalt concrete not only bring about a reduction in noise levels on porous asphalt surfacing but also produce shifts in the noise spectrum. On the one hand, less noise is generated and on the other hand, more noise is absorbed because of the relatively open structure.

It should be noted, however, that installing porous asphalt wearing courses can diminish the effectiveness of existing noise screens because of changes in the noise spectrum and the reduced noise levels.

The suitability of porous asphalt as a noise-reducing measure has been clearly demonstrated in an extensive series of trials. The benefits in relation to other provisions such as acoustic barriers can readily be quantified. Compared with the costs of noise screens, which are generally put at about F 800/m porous asphalt is seen as representing a competitive option. This reason alone has stimulated much interest in porous asphalt.

More Environmental Aspects

Apart from variations in the noise transmission characteristics of porous asphalt compared with dense asphalt concrete, there may also be other differences between the two materials in terms of their environmental impact, such as:

- The rate at which chemicals are removed from the asphalt by leaching,
- The formation of abrasion products from tires and the road surface, because of changes in the coefficient of friction,
- The amount of exhaust fumes emitted per kilometer traveled, and
- Changes in the water/dirt balance of the road.

Differences of this type could affect the amount of pollution produced by road traffic, but are as yet not well defined. In view of the importance of such matters, this subject is currently receiving further attention.

ROLLING RESISTANCE

A number of reports appearing in foreign publications indicate that the rolling resistance of vehicles on porous asphalt wearing courses is relatively low. To what extent this information is relevant in the context of highway construction depends heavily, of course, on the reference materials used in such studies. In the Netherlands, tests have shown that under dry conditions, the rolling resistance on porous asphalt surfaces tends to be slightly higher than that on dense asphalt concrete (*28*).

However, in view of the extremely small differences observed, considerably more tests would need to be conducted to quantify these effects more precisely. It is expected that in wet weather, the results of a similar study would be reversed. Because the overall variations are likely to be small and comparable information is not available for other road surfaces

TABLE 5 PARAMETRIC VARIATIONS IN TEST SECTIONS USED FOR MEASURING NOISE REDUCTION CHARACTERISTICS

test sections	type of asphalt	max stone size 3) (mm)	thickness (cm)	binder	$L_{A,max}$ (dB(A)) 4)
1	porous asphalt	11	4	1)	73,8
2	porous asphalt	11	6	1)	74,2
3	porous asphalt	11	4	2)	75,9
4	porous asphalt	11	6	2)	74,9
5	porous asphalt	16	4	1)	75,2
6	porous asphalt	16	6	1)	76,0
7	dense asphalt concrete	16	4	1)	77,7

1) Penetration bitumen 80/100.

2) Rubber modified bitumen.

3) Maximum sieve size C 11.2 and C 16 respectively.

4) A weighted maximum noise level, passenger cars. ($\bar{v}$ = 100 km/h)

such as cement concrete or surface dressings, it has been decided not to proceed with this type of research at present.

DEALING WITH ICY ROADS IN WINTER

Icy roads are a recurrent problem in the Netherlands during the winter months. To ameliorate these conditions, salting operations are carried out as and when required. Under such circumstances, a porous asphalt wearing course is likely to behave differently.

Measurements have shown that the temperature of a porous asphalt wearing course will remain below 0°C longer than that of dense asphalt concrete surfacing. As a result, problems with ice on porous asphalt surfaces are likely to develop sooner and last longer than on conventional roads. An electronic monitoring system is being installed along the main road network in the Netherlands. This will allow road managers to anticipate the onset of dangerous conditions at an early stage and hence take appropriate action.

The relatively open structure of porous asphalt wearing courses also needs to be considered when planning salting operations because part of the salt will disappear immediately into the interstitial voids. This will be further exacerbated by some of the salt being removed from the surface by melting ice. As a result, the residence time of salt on porous asphalt wearing courses is relatively short compared with that attributed to surfacing materials with a closed structure.

Experience has shown that special attention needs to be given to transitions between porous asphalt and dense asphalt concrete, as little salt transport takes place at these points because of passing traffic. It has been shown, for instance, that by increasing the frequency of salting operations and by using wet rather than dry salt, such difficulties can be overcome. Using more salt, of course, has negative environmental effects.

The introductin of revised salting schedules of this type has meant that road managing authorities now report few, if any, differences in behavior between the two types of wearing course. Moreover, few difficulties have been encountered to date with snowfalls because this form of precipitation is relatively infrequent in the Netherlands.

Although evidence of differences in performance has been reported in other countries (e.g. *29*, *30*), no negative consequences have been attributed to such variations. On balance in The Netherlands, porous asphalt wearing courses are therefore considered to be as safe as dense asphalt concrete surfacing during the winter period, provided that timely measures are taken to compensate for the differences in behavior.

ROAD MAINTENANCE

It is accepted practice for road managers to distinguish between maintenance work during the service life of a road and the major repairs required at the end of its service life. Experience has shown that minor repairs can be carried out to porous asphalt using conventional means, provided that care is taken to preserve the inherent drainage characteristics.

Two specific issues remain to be addressed concerning the major repair work required after the service life of a wearing course has expired. The first concerns how best to apply a new wearing course. The approach currently favored is to mill away the old porous asphalt layer and apply a new wearing course, where necessary in combination with an strengthening layer.

Tests have been performed with *in situ* techniques such as repaving (*31*) and remixing, but further work will be required to improve the results obtained before such methods could be recommended.

The second issue related to major repair work concerns the monitoring operations that are carried out to determine whether highway maintenance work needs to be performed. Semi-empirical methods have been developed for conventional pavement structures and mixtures, which allow such decisions to be made. Typically, this involves measuring the bearing capacity of a pavement using a falling-weight deflectometer and combining this with the results of visual inspections for cracks. However, because cracks in porous asphalt are less visible, it is more difficult to assess the maintenance requirements from such observations and determine the residual life of the pavement structure.

COST-BENEFIT ANALYSIS

In the preceding sections, a number of characteristics properties of porous asphalt have been identified, which differ significantly from those of dense asphalt concrete. By translating these inherent differences into financial terms, the potential benefits in favor of porous asphalt can be assessed in light of the additional costs involved. Because the effective contribution of porous asphalt to the bearing capacity of the pavement structure is 50 percent of that of conventional wearing courses, an extra 25 mm asphalt base course is required, when applying porous asphalt in a thickness of 50 mm.

The shorter maintenance cycles predicted for this type of surfacing will also add extra costs, as shown in Table 6. On an annual basis, it is expected that porous asphalt will be about F 1.50/m^2 more expensive to maintain than dense asphalt concrete. However, with the advent of cheaper maintenance techniques, it is thought that an annual cost differential of approximately F 1.00/m^2 will be achievable in the future.

These figures, which refer to global estimates for the network as a whole, will, of course, vary from project to project and depend on the construction and maintenance strategies employed (*32*).

The maximum benefits that are likely to accrue from installing porous asphalt wearing courses by virtue of increased traffic safety are shown in Table 4. On the conservative assumption that only half these benefits are realized, about F 50 million per year would be saved. The potential benefits from reductions in traffic congestion have been estimated to be approximately F 25 million per year, as summarized in Table 7.

It should be noted that no account has been taken of the extra costs that would be incurred for salting operations in winter. Although the additional expenditure for salting porous asphalt roads is currently estimated to be about 1.5 times that required for conventional surfaces, the lack of accurate data to substantiate this figure, coupled with the fact that these costs are generally insignificant in relation to the overall level of expenditure, have led to this aspect not being included at this stage. Further studies will be required to investigate whether these costs can be reduced.

Other factors not included in the cost-benefit analysis are the noise reduction capabilities of porous asphalt and the rolling resistance. This stems from the fact that porous asphalt is already considered to be an economically sound method of minimizing noise nuisance on specific locations where this property is of no importance to other locations, while the differences in rolling resistance were found to be insignificant.

POLICY IMPLICATIONS

On the basis of the cost-benefit analysis just described, the Dutch Department of Public Works has decided that porous asphalt wearing courses shall preferably be applied

- On busy motorways (with an average of more than 35,000 motor vehicles per day),
- On limited-access roads and highways prohibited to slow moving traffic,
- At discontinuities such as superelevations and so forth where excess surface water may cause difficulties, and
- On roads with a recognized noise nuisance problem.

Wherever possible, porous asphalt wearing courses should only be installed as part of normal maintenance activities. To maximize the effective use of capital, structures not needing major repairs should not be treated in this way. It has also been decided to apply porous asphalt only on stretches of road of at least 3 to 5 km, because the degree of variation on shorter sections could impair road safety. As a consequence of this policy, porous asphalt wearing courses will be applied on about 100 km of motorway a year.

RECOMMENDATIONS FOR FURTHER RESEARCH

In order to be able to perform a more detailed cost-benefit analysis regarding the merits of porous asphalt, a number of questions must still be answered. The costs of appropriate maintenance techniques must be established and assessments made about the effect of differences in the monitoring procedures. In addition, studies should be carried out to identify methods for extending the service life of porous asphalt without detracting from its advantages. Studies will be conducted

TABLE 6 EXAMPLE OF NONCAPITALIZED MAINTENANCE COSTS FOR ROADS WITH POROUS ASPHALT WEARING COURSES COMPARED WITH THOSE SURFACED WITH DENSE ASPHALT CONCRETE

dense asphalt concrete wearing course (d.a.c.)			porous asphalt		
year	maintenance provision	costs fl/m^2	year	maintenance provision	costs fl/m^2
0	strengthening with 0.05 cm d.a.c.	12.50	0	strengthening with 0.025 m g.a.c. 1)	5.-
				overlay with 0.05 m porous asphalt	9.-
12	strengthening with 0.05 m d.a.c.	12.50	9	milling away 0.05 m porous asphalt	4.-
				strengthening with 0.05 m g.a.c.	10.-
				overlay with 0.05 m porous asphalt	9.-
24	as in year 12		18	as in year 9	
maintenance costs per year		1.05	maintenance costs per year		2.55

1) Gravel asphalt concrete.

into the possible use of different aggregates, adhesion agents, fibers, and modified binders.

The potential for recycling should also be considered in this context. The benefits of using porous asphalt should be quantified more fully by carrying out systematic research into road safety. A prerequisite for such an investigation is the facility to monitor sections of road long enough to allow accidents to be registered effectively. In order to provide a firm basis for assessing the effects porous asphalt has on the capacity of roads, measuring gauges have been incorporated into porous asphalt wearing courses and reference sections. Finally, further research is needed to quantify the drainage and noise-reduction characteristics of porous asphalt as a function of time, with particular reference to the effects of dirt accumulation. Studies into the environmental impact of porous asphalt wearing courses are already in progress.

CONCLUSIONS

The results of extensive scientific research, coupled with many years of practical experience, have made it possible to give a sound justification for using porous asphalt wearing courses on motorways. A cost-benefit analysis based on this information has allowed particular categories of road to be identified where preference should be given to the installation of porous asphalt surfacing. Further research is planned to verify a number of hypotheses on which the analysis has been based.

The conclusions contained in this paper are only strictly valid for the type of porous asphalt mix used in the Netherlands and for the circumstances pertaining in this country. Changes in these conditions could affect the applicability of these findings.

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TABLE 7 SUMMARY OF ESTIMATED EXTRA COSTS AND SAVINGS FROM USE OF POROUS ASPHALT RATHER THAN DENSE ASPHALT CONCRETE WEARING COURSES

	annual costs	annual savings	
	increased costs of porous asphalt (guilders)	traffic safety (guilders)	traffic capacity (guilders)
national road network (ca. 90 km^2)	$110x10^6$	$50x10^6$	$25x10^6$
motorways (ca. 60 km^2)	$72x10^6$	$24x10^6$	15 à $20x10^6$
other roads (ca. 30 km^2)	$36x10^6$	$26x10^6$	5 à $10x10^6$
motorways with more than 35,000 vehicles/day (ca. 18 km^2)	$22x10^6$	$9x10^6$	5 à $10x10^6$

* savings due to noise reduction not included

** savings due to winter maintenance not included

Construction who reported on "asphaltic concrete wearing courses with modified surface structures" and on "porous asphalt" respectively.

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