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

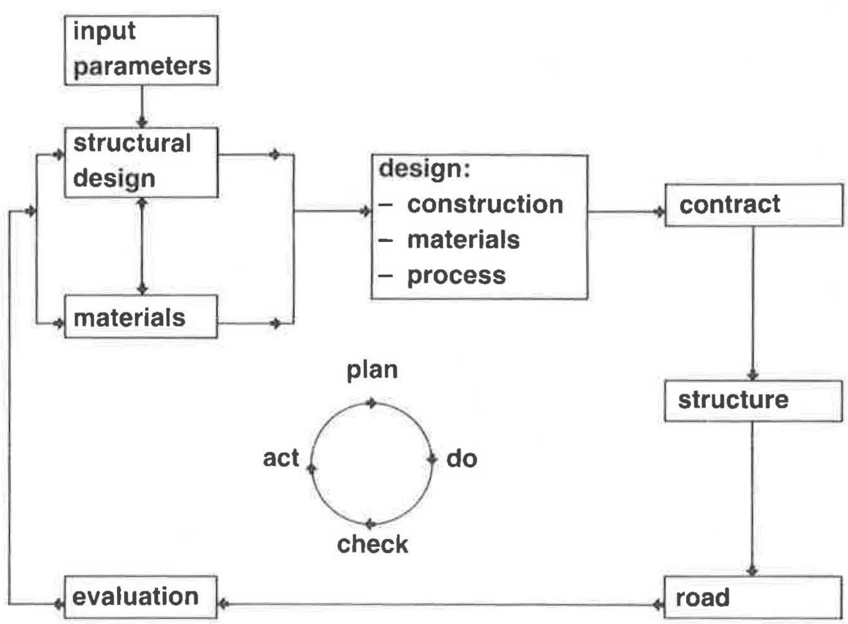

FIGURE 1 Quality circle for the production of asphalt concrete roads.

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

on sieve	mass percentage			
	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.

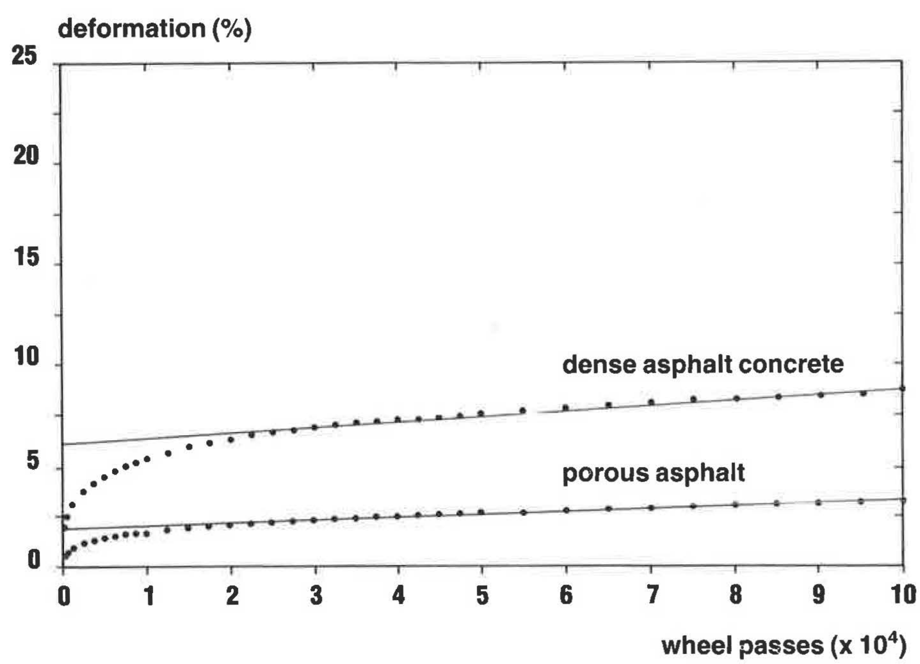

FIGURE 2 Deformation characteristics of dense asphalt concrete and porous asphalt obtained from wheel tracking tests.

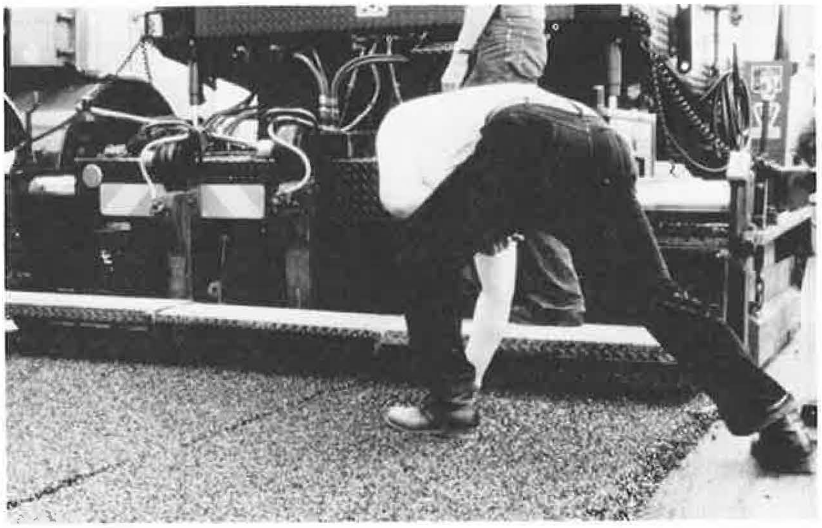

FIGURE 3 Laying porous asphalt with a paver.

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

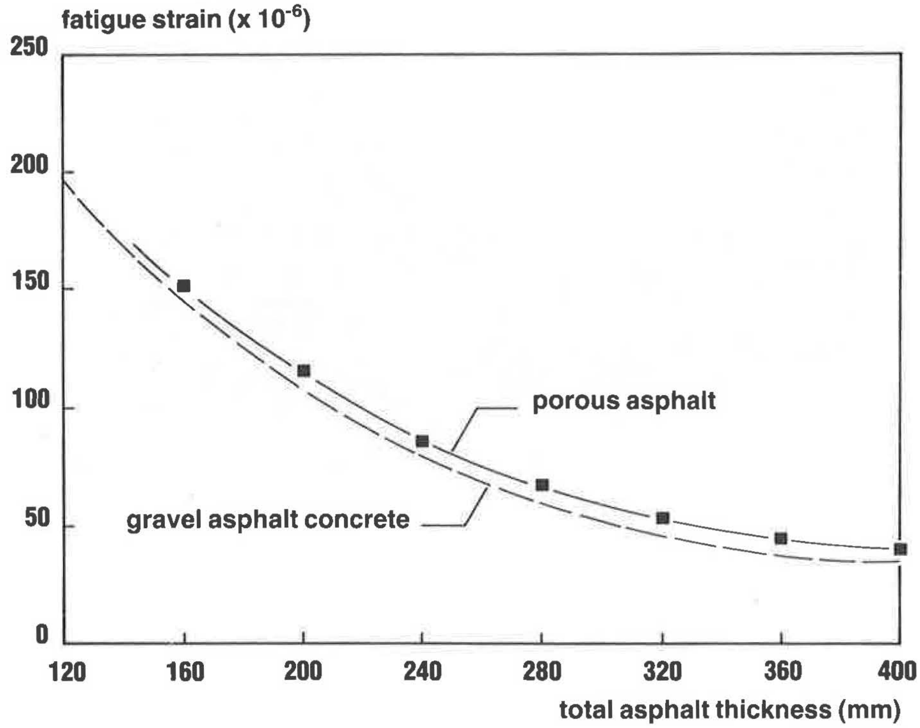

FIGURE 4 Strains in full-depth gravel asphalt concrete pavements and comparable structures with 40-mm-thick porous asphalt wearing courses when subjected to a standard axle load of (100 kN). (E subgrade = 100 MPa.)

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

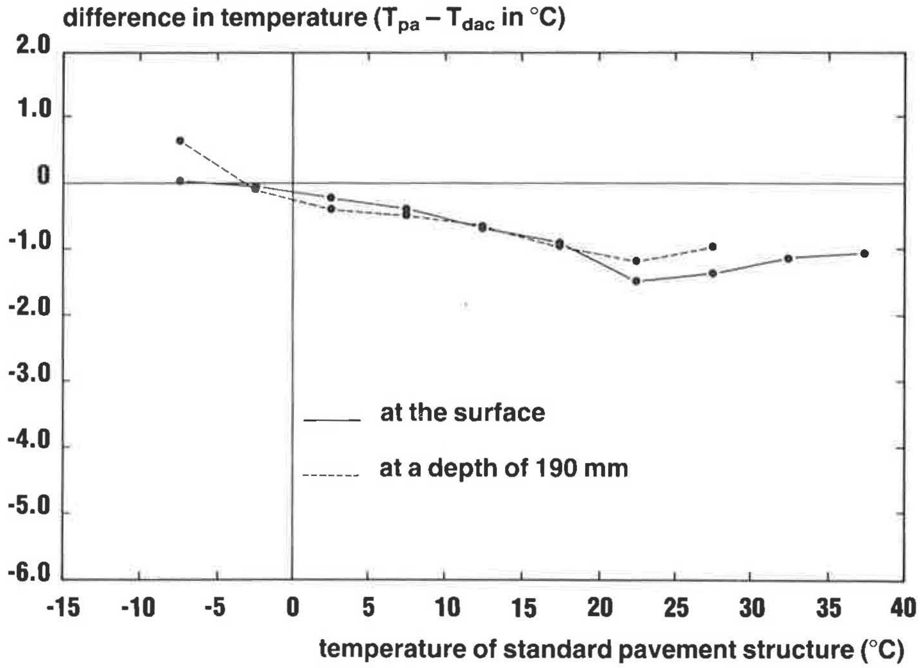

FIGURE 5 Differences in temperature of pavements with porous asphalt and dense asphalt concrete wearing courses as a function of the temperature of the standard structure.

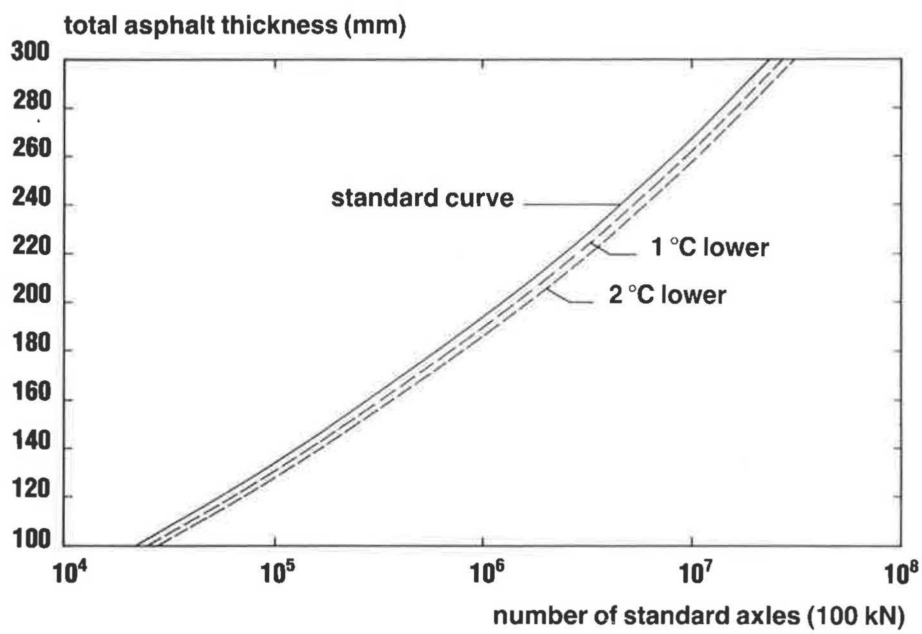

FIGURE 6 Effect of temperature reductions on pavement design curves resulting from the use of porous asphalt wearing courses. (E subgrade = 100 MPa.)

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 con-struction 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.

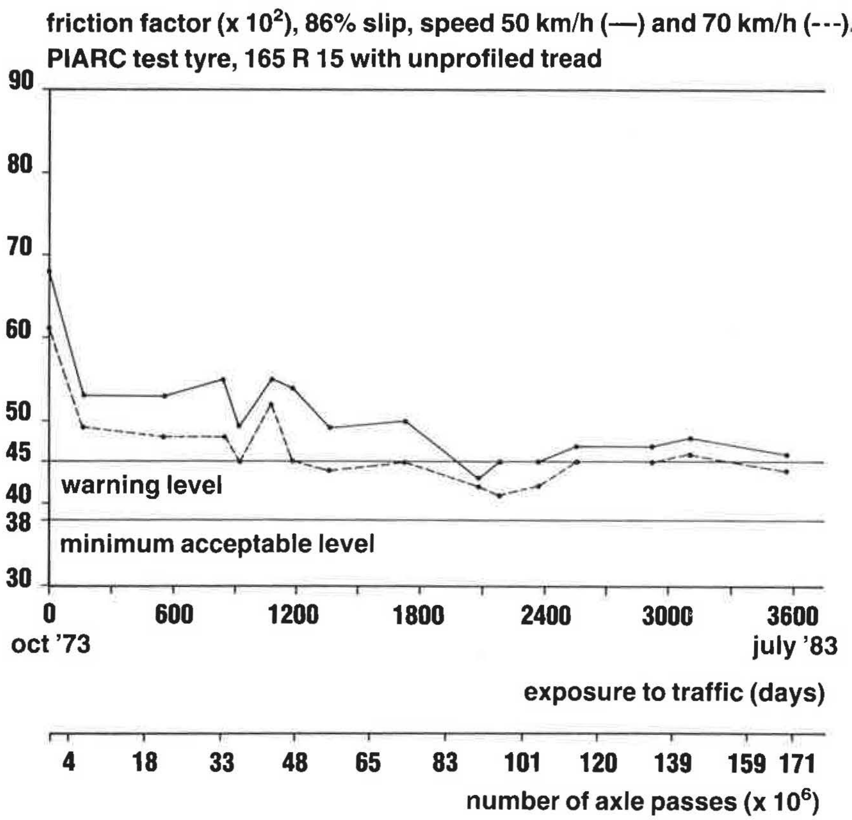

FIGURE 8 Typical example of the decrease in skid resistance of porous asphalt as a function of time.

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 nation-al 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)	110×10^6	50×10^6	25×10^6
motorways (ca. 60 km^2)	72×10^6	24×10^6	15 à 20×10^6
other roads (ca. 30 km^2)	36×10^6	26×10^6	5 à 10×10^6
motorways with more than 35,000 vehicles/day (ca. 18 km^2)	22×10^6	9×10^6	5 à 10×10^6
* 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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