A noise-absorbing road surface made of poroelastic asphaltic concrete
A noise-absorbing road surface made of poroelastic asphaltic concrete has been designed with a view to its acoustic properties. The aim was to achieve the greatest possible sound absorption in the frequency ranges that are most important as regards traffic noise as well as good civil engineering properties.

The material is an open-textured asphalt mixture with a very high voids percentage made possible by the addition of rubberized bitumen as a binder. The rubberized bitumen contains finely ground old tyre tread.

On a wearing course of 4 cm on a provincial road, with an average measured speed of about 80 km per hour, a noise reduction of about 3-5 dB was achieved relative to noise levels on dense asphaltic concretes.

Beside reducing traffic noise at the source, the use of this material also contributes to improving road safety and to solving the problem of getting rid of old tyres.

PEAC can be used on a large scale, employing technology already available in the road-building industry.
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1. Aim and design of the study

Attempts to curb traffic noise at its source have up to now been largely directed against engine noise made by passenger cars and lorries. Engine noise in this case includes noise made by the engine itself, the cooling system, the exhaust, the air intake and the transmission. At relatively low speeds, in urban traffic for instance, engine noise predominates, and the effect of reducing this is to reduce considerably the L_{eq} or urban traffic.

At high speeds, however (above about 70 km/h), such as occur on main roads and motorways, engine noise is drowned by noise from another source, that created by the interaction of the tyres with the road surface. Hence at high speeds, a reduction in engine noise hardly produces any effect. These points are illustrated in Figure 1.1 of [1.1].

Assuming that the engine noise, measured according to ISO 362 [1.2] is reduced in respect of all lorries by about 8 dB, and that of all cars by about 5 dB, then from Figure 1.1 it would seem that with a traffic flow including, say, 10% lorries, the L_{eq} would fall by about 4-5 dB in urban traffic while on a motorway it would only be reduced by about 1 dB.

Incidentally, it can be noted that the respective reductions in engine noise of 8 dB and 5 dB are technically feasible and can be accompanied by a not inconsiderable saving in fuel [1.1].
Since the noise alongside main roads is mainly caused by tyre/road noise, it follows that:

- any significant reduction in the $L_{eq}$ along main roads can only be achieved by reducing tyre/road noise

- only after this has been done can any effect on $L_{eq}$ along main roads be achieved by reducing engine noise.

Hence efforts to combat traffic noise should primarily be directed towards reducing tyre/road noise.

There are, in principle, two ways of tackling tyre/road noise at source, which are not mutually exclusive. They are:

- the development of low-noise tyres, and

- the development, or further improvement, of low-noise road surfaces.

With regard to the development of low-noise tyres, much research has already been carried out throughout the world. A brief assessment of this and a synopsis of the relevant literature can be found in [1.3] and [1.4]. The conclusion to be drawn is that, despite the enormous efforts made to get a low-noise tyre, results so far have not been satisfactory. The reason for this is not merely that the theoretical concepts as regards the creation of the noise, its dissemination and its transmission to the receiver, are not always convincing, but also that in the design of a tyre
considerations of safety and comfort in driving must prevail. This very much limits the scope of the designer of a low-noise tyre. Compared with research findings on low-noise tyres, little is as yet known about the effect of the road surface (see e.g. [1.5]-[1.15]).

The present study therefore is concerned with improving and achieving the best possible low-noise road surface. One starting point is that certain known road surfaces have a definite noise-absorbing potential and can therefore bring about a reduction in traffic noise. A prior condition for success is that the surface must not only give the best acoustic results, but must also meet all the appropriate civil engineering requirements such as durability, comfort in driving and safety.

The concept of this present study is a practical one. Hence the emphasis is on the planning and carrying out of experiments in conditions that are as realistic as possible. Where it appears that a more thorough theoretical approach is necessary, the particular problem is merely formulated in the hope that this may stimulate further research.

There were two stages to this experimental study. First, there was a laboratory experiment with small test specimens with a cross-section of 10 cm. Changes were made in the composition of the material and the thickness of the course until the optimum solution was found. Then a test section, made of this material, was laid on a provincial highway and studied.
2. Influence of sound-absorbing road surfaces on vehicle noise

2.1 Influence on tyre/road interaction noise

The amplification of sound waves emitted by a source by placing a hard sound-reflecting surface near the source (e.g. the baffle of a loud-speaker or the sounding board of a musical instrument) is a familiar acoustic phenomenon. It is also well known that the sound waves can be damped by placing an absorbent surface near the source.

This phenomenon also occurs in connection with the transmission of tyre/road noise. The source of this noise is located where the wheel meets the road surface and in the vibrating tyre a few centimetres above the road surface [2.1]. Whereas a sound-reflecting road surface amplifies the tyre/road noise, as a baffle does in the case of a loud-speaker, it is to be expected that a sound-absorbing road surface will damp the vibrations of the tyre/road noise.

A complete, quantified description of this process in connection with tyre/road interaction is, to the best of our knowledge, not available. One has therefore to start with the acoustic impedance of the road surface as well as the type and level of the source. It should be possible in principle to calculate, taking account of weather conditions, the transmission of the sound to receivers located at some distance.
With this approach one also has the basis for the analytical computation of the transmission of traffic noise with various types of road surface, various road widths, various distances and heights of receiver etc.

For the purpose of the present study, which is the development of a surface which reduces tyre/road noise as much as possible, it is however sufficient to aim at the greatest possible absorption coefficient in the frequency range most relevant to tyre/road noise. This approach rests on the supposition that a higher absorption coefficient also means more noise reduction.

For the sake of clarity, it should be pointed out that this property has nothing to do with the roughness or friction of the road surface, although these features that are so important as regards road safety also play a part in creating tyre/wheel noise [1.3].

2.2 Influence on engine noise

Although this study is primarily concerned with the reduction of tyre/wheel noise, it is to be expected that a sound-absorbing road surface will also have a dampening effect on engine noise. In this connection, however, two points must be borne in mind:

- the sources of engine noise (the engine, the gearbox, the exhaust) are high above the road surface, especially in the case of lorries. The effect of the sound-absorbing road surface on this noise will be less than on the tyre/road noise, the source of which lies much closer to the road.
- the spectrum of the engine noise is not the same as that of the tyre/road noise. The exhaust noise, in particular, contains strong low-frequency components. To reduce engine noise, therefore, the absorption coefficient of the road surface would have to be high enough at low frequencies, too.

It follows, therefore, that if one wants a sound-absorbing road surface perfectly suited for traffic moving at speeds well below 70 km/h (urban traffic), at which engine noise predominates, then somewhat different requirements must be met in designing the mix.

In this connection reference may be made to research now in progress at the Technische Hochschule, Karlsruhe [2.2] on the question of reducing engine noise by raising the absorption coefficient of the road surface, little attention, however, being given to practical road-building considerations.

As previously stated, the main aim of the present study is to achieve a maximum reduction of tyre/road noise, but any effect this might have on engine noise will also be indicated.
3. Design of a noise-absorbing road surface

3.1 Choice of road surface material

If the aim is to develop a sound-absorbing road surface and make practical use of it as soon as possible, then one must rely as far as possible on existing material and known technologies.

For technical and financial reasons, the road surfaces laid in the Netherlands are mainly asphalt. It was obvious therefore that this study should start with asphalt and modify this material in such a way as to achieve the best acoustic results within the framework of road-building requirements.

One of the many kinds of asphaltic concrete is the so-called open-textured asphalt (OTA) characterized by its high degree of porosity. This is due to the accessible voids in the mixture (the further percentage of voids in the mixture that is not accessible is of no interest). The main reason for the use of this asphalt is its capacity to hold water and allow it to drain away. It has also been noticed that the use of this type of asphalt entails less noise, a side effect that certainly is not unwelcome (see [1.12], [1.14], [1.16]).

The approach taken in the present study was therefore to improve as far as possible the acoustic qualities of open-textured asphalt, while maintaining the roughness and durability of the road surface and its ability to hold and to drain off water.
3.2 Road-building aspects

3.2.1 Properties of conventional open-textured asphalt (OTA)

In the Netherlands, experience with OTA dates back to 1972, when on the instructions of the Gelderland Provinciaal Public Works Department and under the supervision of working party B9 of the Road Construction Study Centre the first test section was laid on the provincial road S5 at Ugchelen. This was followed in 1973 by a test section on the national road A12 at Driebergen. The information gained from this test section, which reached the end of its useful life in autumn 1983, are discussed in detail in [3.1], [3.2] and [1.14]. Ref. [3.3] includes among other things reports on similar experience in foreign countries.

Sound absorption is not the only advantage conferred on OTA by its porosity. Other positive features, particularly for the road-user, are:

- elimination of splashing and spraying by water, owing to the good water-holding and water drainage properties of the porous surface,

- absence of disturbing light reflection from the wet surface,

- good surface grip even when the road is wet (no aquaplaning),

- high degree of evenness of surface, due to resistance to deformation.
With regard to durability, maintenance and skid prevention, the situation is not yet quite clear. It is known that relative to dense surfacing, open-texture asphalt has less resistance to mechanical damage and that thin layers in particular (20 mm) are susceptible to loss of aggregate. The composition of OTA as laid on the test sections is as follows:

Coarse aggregate 6/16 85.0% (All percentages by weight)
Fine aggregate 0/3 10.5%
Filler 4.5%
Bitumen 4.0-5.0%

3.2.2 Altering the mixture

One of the most important parameters determining sound-absorption is the effective void percentage. The effective void volume is the difference between the total void volume in the test section defined according to the Specifications for Roadbuilding Materials 1978 and the sealed void volume, defined as the difference between the volume of the test specimen enclosed in tissue paper and the volume not so enclosed.

The volumes are determined by weighing in air and under water. By applying a vacuum during the test with the non-enclosed samples the air present in the effective void volume is removed.
The volume determined in this way therefore includes the sealed void volume. The effective void percentage of the Marshall test samples of conventional open-texture asphalt is about 5% lower than the total void percentage.

In order to achieve as high a sound absorption as possible, the effective void percentage, or the porosity must be as great as possible. This point will be developed later.

One way to increase porosity is to alter the grading of the aggregate. A feature of conventional open-texture asphalt is that there is a "gap" in the grading of the aggregate at fraction 3/6. Porosity increases as the grading gap gets bigger, in other words as the grading range comprises a narrower distribution of sizes, for instance 8/11 or 11/16 instead of 6/16.

Greater porosity can also be achieved by reducing the quantity of binder in the mixture which to some extent fills the voids between the stones.

A higher percentage of single-sized stones and a low binder content mean however that at a given viscosity the quantity of binder is smaller than in conventional OTA mixtures, with the result that chippings more easily come loose. In other words an increase in porosity sets especially high standards for the binding material as regards cohesive and adhesive properties, which traditional bitumen cannot meet. Hence in developing the mixture it was necessary to employ a different binding medium that would meet these requirements, namely rubberized bitumen.
3.2.3 Composition and properties of rubberized bitumen

Rubberized bitumen is a mixture of traditional bitumen 80/100 or 45/60, a mineral oil and fine rubber granulate. This modified bitumen was developed in America and introduced in the Netherlands by J. Heijmans B.V. Road Building Contractors, under licence from Esso, Belgium, which has carried out several projects in Belgium in which rubberized bitumen is used as a binding agent on the wearing course of asphalt and concrete surfaces and as a binder in open-texture asphaltic concrete [3.5]. The rubber granulate added to the bitumen is ground tyre-tread (utilization of waste). One needs a mixture of 50% natural rubber and 50% styrene-butadiene rubber, free from impurities in the form of steel wire and fibres, and finely ground, preferably at room temperature. In practice this means that the ground rubber comes in equal proportions from lorry tyres and car tyres. Rubberized bitumen can vary in composition within the limits given in Table 3.1, depending on the composition of the rubber granulate.

<table>
<thead>
<tr>
<th>Bitumen 60/100</th>
<th>73 - 77%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineral oil</td>
<td>2 - 4%</td>
</tr>
<tr>
<td>Rubber granulates</td>
<td>18 - 22%</td>
</tr>
</tbody>
</table>
The binder has the following properties:

**Viscosity**
Viscosity increases with the addition of rubber. Under the influence of the high mixing temperature and mineral oil some of the rubber particles devulcanize and dissolve in the bitumen. The product is workable if viscosity at a temperature of 200°C reaches levels of < 1000 cP.

**Hardness**
Penetration of rubberized bitumen at 25°C is 65-86 (0.1 mm).

**Softening point**
Depending on the percentage of rubber, this is 57-67°C, (ring and ball test).

**Temperature dependence**
Penetration index > 1.

Relative to the original 80/100 bitumen, rubberized bitumen is less brittle at low temperatures and much stiffer at high temperatures.

**Flexibility**
The flexibility of the binder, especially at low temperatures, can be demonstrated by the so-called Flex test. This test shows at what temperature shearing occurs when a specimen is bent at an angle of 90° over 10 seconds. Bitumen 80/100 shears at about -4°C, rubberized bitumen at -10°C.
Elasticity

The elasticity of rubberized bitumen can be demonstrated by means of the stamping test at 30°C. A loaded pin, 10 mm in diameter, is driven three times at very short intervals into the bitumen and the indentation in the material is measured after 5 minutes. Penetration in the case of bitumen 80/100 is 123.0.1 mm; with rubberized bitumen (20% rubber) it is 21.0.1 mm. It is noticeable that in the case of rubberized bitumen the pin springs back with the removal of the load, which must be due to the rubber in the bitumen.

Adhesion

Rubberized bitumen is very adhesive. The Vialit test is used to give an impression of adhesiveness. Dressed slabs, turned upside down, are tested by being impacted by a falling ball at various temperatures. The extent to which stones break loose indicates adhesiveness. Comparing the results of the Vialit test on rubberized bitumen with that on bitumen 60/70, it appears that at temperatures lower than 10°C, bitumen 60/70 begins to lose all its stones, whereas with rubberized bitumen there is still no loss of stones even at -30°C [1.3].

3.2.4 Poroelastic asphaltic concrete (PEAC)

The specific properties of rubberized bitumen as described in the previous paragraph make it very suitable as a binding medium in open-textured asphalt, its main characteristics being high porosity combined with elasticity. It is therefore proposed to call the new road surface material "poroelastic asphaltic concrete" or PEAC.
Properties of PEAC

In the following summary of the properties of poroelastic asphaltic concrete, stress is laid on those that are likely to make it a considerable improvement on the traditional open-textured asphalt.

Since rubberized bitumen is very cohesive, less sensitive to temperature, and relatively very elastic, it is possible to design a very open asphalt mixture with a very high effective void percentage, with a much higher binder content than is used in traditional open-textured asphalt.

It is expected that this will give better durability than open-textured asphalt while maintaining stability. In the United States practical experiments have been made with this material over the last twenty years, although no attention has been given to the noise aspect [3.4].

Moreover, owing to the outstanding merits of rubberized bitumen as regards adhesion, cohesion and elasticity, poroelastic asphaltic concrete is highly resistant to mechanical damage.

These are the most important engineering properties of poroelastic asphaltic concrete relative to traditional open-textured asphalt.
Composition of PEAC

On the basis of the acoustic research described later in this report, a PEAC mixture was chosen which, taking account of civil engineering requirements, appeared to be the most favourable.

The composition of this mixture was:

Coarse aggregate 8/11 87%
Fine aggregate 11%
Filler 2%
Rubberized bitumen 5.5%

3.2.5 Applications of PEAC

In combination with a "stress-absorbing membrane interlayer" (SAMI) of rubberized bitumen which not only gives a completely water-tight sealing layer for the underlying structure, but - in view of the specific qualities of the binding medium - can also cover up cracks, it is possible to apply PEAC on cracked asphalt or concrete surfaces.

PEAC can also be the answer in situations where the problem is noise prevention. One example of this is the Brussels Ring Road, where an existing concrete road surface was covered with poroelastic asphaltic concrete together with a SAMI [3.5].
3.3 Acoustic aspects

3.3.1 Optimizing the absorption coefficient

In selecting the mixture, stress was laid on the acoustic properties. A mix was aimed at that would result in the greatest possible noise reduction, without sacrificing structural properties. The use of rubberized bitumen seems particularly suitable for this purpose.

Starting from the assumption already mentioned (though not further developed) that the greatest reduction in noise due to tyre/road interaction would be achieved if the sound absorption coefficient of the road surface was greatest, the aim in designing the mixture was to develop a poroelastic asphalt with the highest possible absorption coefficient in the frequency range most relevant to tyre/road interaction, without adversely affecting surface friction, durability, resistance to mechanical damage or water-holding and drainage properties.

According to acoustic theory, the absorption coefficient $\alpha$ of porous materials depends on the following physical properties (see [3.6] and [3.7]):

- porosity $\sigma$, which is the ratio of effective void volume to total volume

- specific flow resistance $\Xi$, i.e. the resistance of the material to a current of air pumped through it (Ns.m$^{-4}$)
- the structure factor $\chi$, which indicates how the effective void volume is formed and how the pores are interconnected. For most absorbent materials with a fibrous structure, $\chi$ is equal to 1, but for granular structures such as road surfaces $\chi$ can have much higher values.

- thickness of the course $d$.

According to [3.7], a quantitative relationship between the absorption coefficient $\alpha$ and the above-mentioned physical properties can be obtained via the impedance $W$ of the absorbent course (thickness $d$) on a hard base (underlying road surface);

$$\alpha = 1 - \left| \frac{W - \rho c}{W + \rho c} \right|^2$$

$$W = - j \frac{\rho c}{\sigma} \sqrt{(1 - j \frac{\Xi_0}{\omega \rho X})} \cdot \cot \left[ d \frac{\omega}{c} \sqrt{(1 - j \frac{\Xi_0}{\omega \rho X})} \right]$$
where
\[ \sigma = \text{porosity of the asphalt mixture} \]
\[ \rho = \text{density of air (1.21 kg/m}^3\text{)} \]
\[ c = \text{velocity of sound in air (344 m/s)} \]
\[ \bar{E} = \text{specific flow resistance of asphalt mixture} \]
\[ d = \text{thickness of the course} \]
\[ \chi = \text{structure factor of the asphalt mixture} \]
\[ \omega = \text{angular frequency (}\omega = 2 \pi f).\]

From equation (3.1) we see that the maximum value of \( \alpha \),
\[ \alpha = 1, \]

is reached when
\[ \omega = \rho c \]

This condition is called "fitting".

To get some idea of the influence of various physical properties on the absorption coefficient, a few examples were worked out with equations (3.1) and (3.2), the results being shown in Figures 3.2 and 3.3.

The relationship of \( \alpha \) to frequency is shown, the parameters that are varied being the porosity \( \sigma \) and the structure factor \( \chi \) in Figure 3.2 and the flow resistance \( \bar{E} \) and course thickness \( d \) in Figure 3.3.
The following conclusions pertaining to mixture design can be drawn:

- porosity \( \sigma \) must be as high as possible to ensure a favourable influence on the absorption coefficient (see Figure 3.2).

- the structure factor \( \chi \) must be as high as possible, so that at the required frequency for the first peak of \( \alpha \), thickness \( d \) can be as small as possible (see Figures 3.2 and 3.3). From Figure 3.1 it would seem that the frequency range of greatest significance for tyre/road noise is 600-1600 Hz, so that the first maximum of \( \alpha \) lies at about 1000 Hz.

- the flow resistance \( \Xi \) determines the bandwidth of the absorption coefficient (see Figure 3.3); it must be neither too high nor too low. Assuming a porosity \( \sigma = 0.25 \) (this seems to be the maximum that is technically feasible), the optimal flow resistance \( \Xi \) is 40-80 kNs.m^{-1}, depending on course thickness (see Figure 3.3).

- the course thickness has much the same effect as the structure factor. A thicker course shifts the first maximum of \( \alpha \) towards low frequencies, but also reduces the overall maximum of \( \alpha \).
In deciding on the composition of the asphalt mixture, an attempt can be made to meet the above-mentioned conditions by varying the percentage of the binding medium (thus influencing $\sigma$ and $\varepsilon$), the grading of the aggregate (thus influencing $\sigma$ and $\varepsilon$), the shape of stones (thus influencing $\chi$) and the course thickness $d$.

For the purposes of this study, about 30 samples were prepared, varying the above parameters within the limits dictated by road construction requirements.

The shape and size of the samples can be seen in Figure 3.4. Using these samples, the absorption coefficient $\alpha$ and complex impedance $W$ were determined as a function of frequency in the impedance tube in accordance with DIN 52215.

The physical parameters were determined as follows:

$\sigma$: by immersing the sample in water and measuring the volume of water displaced;

$\chi$: by comparing the measured frequency of the first maximum of $\alpha$ with the frequency calculated from (3.1) and (3.2), inserting various values of $\chi$ until the best fit was obtained;

$\Xi$: by measuring the flow resistance for stationary flow in accordance with DIN 52213.

This measurement encountered problems, however, in connection with the preparation of the samples. The concentration of the binder always seemed to be somewhat greater at the base of the sample, so
the pores at the bottom were mainly closed. While this has hardly any effect on the acoustic aspects of flow resistance, the static flow resistance is considerably and unpredictably increased. The solution found for this problem was to saw off a thin layer from the bottom of the sample before measuring the flow resistance.

d: by measuring the thickness of the sample.

Results of the measurements

A few results of the measurement of α are shown as examples in Figure 3.3. The three curves in each diagram refer to a given composition mixture. As can be seen, the first maximum of α shifts to a lower frequency as the course thickness increases.

The two diagrams in Figure 3.5 relate to different composition mixtures, in which σ, χ and ξ are altered. It would appear that α is greater in the case of the more porous material, and that the maximum of α is sharper at a lower flow resistance. This was to be expected from calculations (see Figures 3.2 and 3.3).

Selecting the optimum mixture

From the measurements made, the acoustically optimum road surface and the best thickness can now be selected. In line with the starting principle, that is, maximum absorption in the frequency range most important for tyre/wheel noise (see Figure 3.1), the following weights were given to the absorption coefficients at different frequencies:
Using these weights, a weighted average absorption coefficient $\bar{\alpha}$ was determined for each sample. Figure 3.6 shows $\bar{\alpha}$ as a function of the most important physical parameters: porosity $\sigma$ and thickness $d$.

From Figure 3.6 it can be deduced that for the acoustically optimum road surface mixture, porosity $\sigma$ and course thickness $d$ should be as follows:

$\sigma = 20$ to $25\%$
$d = 35$ to $40$ mm

As regards grading, it can be said that the finer the grains in the mixture, the greater the flow resistance $\Xi$.

From the measurements of $\Xi$ in accordance with DIN 52213 referred to earlier, it would seem that even with the finest grading that is technically feasible, the flow resistance remains below the optimum level. If, however, one compares the measured absorption coefficient as a function of frequency with the values calculated in accordance with equations (3.1) and (3.2), then it seems that a good fit can only be obtained by keeping the flow resistance 3-6 times higher than measured in DIN 52213. This is illustrated in the bottom diagram in Figure 3.7. Here, for instance, the best fit with

<table>
<thead>
<tr>
<th>frequency (Hz)</th>
<th>0-400</th>
<th>500</th>
<th>630</th>
<th>800</th>
<th>1000</th>
<th>1250</th>
<th>1600</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>weight</td>
<td>0</td>
<td>0.5</td>
<td>1</td>
<td>1.25</td>
<td>1.6</td>
<td>1.25</td>
<td>1</td>
<td>0.5</td>
</tr>
</tbody>
</table>
theory is obtained by keeping flow resistance five times higher, the result being about equal to the optimum level.

Without going further into the problem of measuring flow resistance with the help of a stationary flow (the "acoustic" flow resistance being caused by an alternating flow), it is assumed for the sake of this study that the flow resistances measured in accordance with DIN 52213 are considerably lower than those which have to be maintained according to the theory of equation (3.2), and that the method of the best fit gives more reliable results for flow resistance.

It would also appear that with a grading of, say, 8/11, one can get close to the optimum flow resistance (see Figure 3.7, lowest diagram). This grading can be used in a course thickness of 40 mm without technical problems.

An aggregate consisting of irregular stones with sharp angles has a high structure factor. Taking account of this, the appropriate frequency for the first absorption maximum can be obtained with a thinner course. The value obtained for the structure factor lies between 5 and 7.
An acoustically optimum mixture has the following composition:

- Coarse aggregate 8/11: 87%
- Fine aggregate: 11%
- Limestone filler: 2%
- Rubberized bitumen: 5%

(Mixture D in Figures 3.5 and 3.7).

3.3.2 Ground impedance

In addition to the absorption coefficient $\alpha$, the acoustic impedance $W$ is also measured in the impedance tube. The impedance measured is to be regarded as the ground impedance for vertical impact, it being possible to convert for other impact angles by applying the "cos $\theta$" law (assuming that the porous road surface behaves as locally reacting material).

As was pointed out in Section 2.1, ground impedance is an essential magnitude for calculating the transmission of noise from a vehicle to a reception point some distance away.

An example of the measured frequency behaviour of the real and imaginary parts of $W$ is given in Figure 3.7 together with the results for $\alpha$. This measurement concerns the $\alpha$-optimized asphalt mixture referred to in the previous section. Alongside the measured results Figure 3.7 also shows the frequency behaviour of $W$ as calculated from equation (3.2). The agreement between measurement and calculation is very good. Hence for an
analytic approach to noise transmission, one can make use of ground impedance $W$ in accordance with equation (3.2), certainly as regards the frequency band 500-1500 Hz, which is important for road-building applications.

For such an approach one must, moreover, have information on the effective height ($n$) of the noise source of the vehicle (tyres and engine) and on the impedance of the ground next to the road (see, for instance, [3.8]).

In the light of the above, it would be advisable to undertake a more theoretical study of sound transmission. In the present study, however, the experimental approach was chosen, namely to measure the difference in the noise emitted by traffic on several conventional surfaces and on poroelastic asphaltic concrete. This will be described in the following chapters.
4. Study of a test section

4.1 Laying of a test section in Zeeland

Choice of locality for section

With a view to ascertaining the influence of poroelastic asphaltic concrete (PEAC) on the noise level along the road, it was decided to lay an experimental surface. In choosing the locality, the following points had to be considered:

- for purposes of comparison, other forms of hard surface would have to be laid, if not already present, on the test section, in particular, the open-textured asphalt;
- further prerequisites were fast-flowing through traffic, freedom for the sound waves to disperse, preferably without reflection or screening, and a reasonably low noise interference level.

After consultation with the Ministry of Health, Physical Planning and the Environment, the Noord-Brabant Province, and the Zeeland Municipality, it was finally decided to lay the test section on the Eindhoven-Uden-Ravenstein provincial road S20 in the municipality of Zeeland between km 12.875 and km 14.848 (see Figure 4.1). The choice of this location was partly due to the fact that the experimental stretch skirts an area designated for improvement under the Noise Abatement Act. Altogether 135 housing units have a noise rating more than 60 dB(A) (about 12,000 vehicles per 24 hours). This is caused by the intensive through traffic on the road in question. Average speeds are about 80 km/h for cars and about 70 km/h for lorries. These speeds are thus somewhat lower than those for which PEAC was really designed (see Figure 3.1).
The road beyond the northern end of the test section (see Figure 4.1) has an asphalt surface of the dense asphaltic concrete (DAC) type that is generally used in the Netherlands. This course was laid only a few years ago, and seemed to be very suitable as a reference for acoustic measurements.

The design and building of the test section

The existing structure of the stretch chosen was the concrete surface type, with non-pinned concrete slabs and reinforced edges, laid on substrate slabs. At intervals of 25 m there was an expansion joint; the slabs had false joints at intervals of 6.25 m. The road consisted of two lanes, the overall width being 7.10 m, including on either side a strip of granite sets 0.30 m wide, as shown in Figure 4.2. A feature of this construction was the so-called step effect (uneven level of the slabs at the seams), which was to blame for the high level of noise along the road.

Before the laying of the low-noise asphalt, the stone sets were removed and on both sides a concrete extension of 0.60 m was added. The concrete surface, together with the extension, was then fractured, and for two weeks was allowed to settle, with the traffic passing over it. Over the fractured concrete a profiled layer of open-textured asphalt, traffic class four, which varied in thickness from 2 to 4 cm was applied.
Contrary to the usual practice in road repairing of overlaying fractured concrete with a 14 cm course of asphalt so as to prevent cracks, a different approach was made in this case. On top of the base layer, a membrane of elastic rubberized bitumen, a 'SAMI', was laid (see Section 3.2.5) and then a 4 cm course of poroelastic asphaltic concrete, so that overall the average thickness of the asphalt layer could be kept to 8 cm. The whole construction is illustrated in Figure 4.2.

In order to compare PEAC with the traditional open-texture asphalt, both acoustically and from the view of road-building, a traditional open-texture asphalt course, 500 m long, was laid on the same sub-structure of the test section. This is illustrated in Figure 4.1 (the hatched part).

The photographs in Figures 4.3 to 4.7 give an idea of the work involved in laying the test section.

The laying of the Zeeland test section made it possible to compare four different types of road surface:

- concrete slabs (the original situation)
- PEAC (shown in black in Figure 4.1)
- OTA (shown hatched in Figure 4.1)
- DAC (existing road at northern end of test section).

The study consists of an acoustic part and a road-building part. They are dealt with in the following sections.
4.2 Acoustics

4.2.1 Measuring road traffic noise: plan and implementation

The acoustic study entailed measuring the noise of traffic before and after laying the test section and calculating the results. In planning the noise study, it was possible to make use of the experience gained in an earlier study made by TPD/TNO [1.14]. The TPD/TNO was thus actively involved in planning and carrying out this programme*.

With a view to measuring the noise level of as many different vehicles as possible, and thus getting a representative picture of the traffic noise as it really is, most measurements were made with actual traffic flows (about 500 vehicles per hour).

The purpose of these noise measurements was:

To determine the sound level differences $\Delta L_{eq}$ for each waveband (bandwidth = one third of an octave) with reference to the A-level of all four surfaces in question (concrete slabs, PEAC, OTA and DAC). In particular, to determine the extent of the reduction in traffic noise with PEAC compared with the normally used DAC. A distinction was to be made between cars and lorries (light and heavy).

* The authors, particularly Ir. C.J.M. van Ruiten, are grateful for this cooperation.
Furthermore the traffic noise levels measured must refer to the actual speeds reached by each vehicle type within the traffic flow examined.

Measurements were made as follows:

- **Concrete slab measurements**
  These measurements were made on 2 May 1984, before the laying of the test section, at the spot where the PEAC measuring point is marked on Figure 4.1

- **DAC measurements (1)**
  These measurements were made at the same time as the concrete slab measurements, before laying the test section, at the spot where the DAC measuring point is marked on Figure 4.1

- **PEAC measurements**
  These measurements were made on 20 June 1984, after the laying of the test section, at the spot where the PEAC measuring point is marked on Figure 4.1

- **OTA measurements**
  These measurements were made at the same time as the PEAC ones, at the OTA measuring point marked on Figure 4.1

- **DAC measurements (2)**
  These measurements were made at the same time as the PEAC and the OTA ones, at the DAC measuring point marked on Figure 4.1.
The DAC series (1) and (2) thus serves as references for the measurements made before and after the laying of the test section.

Each measuring point in fact consists of two measuring points 7.5 m and 25 m distant from the near traffic lanes. The microphone was always 5 m above ground level (the road surface lies more or less at ground level).

In carrying out these traffic noise tests, the standard measuring techniques of Section 102 of the Noise Abatement Act were adhered to, but since it was sometimes a question of very small differences in equivalent noise levels of various road surfaces, much stricter requirements as to accuracy had to be met. This applied in particular to the time of measurement, the elimination of extraneous noise, and accuracy in reading and in calculation.

Driving speeds were determined with the help of radar equipment (provided by the TPD/TNO) at the DAC and PEAC measuring points. The peak dB(A) levels of individual vehicles at a distance of 7.5 m were measured at the same time as driving speeds.

Each of the above-mentioned measurement series included at least 100 vehicles, though in most cases between 200 and 500 were included. So as to be able to consider the two vehicle types separately, tape recording was interrupted as lorries were passing by, the tape being stopped when a lorry came in sight and started again when it disappeared. It was thus possible to obtain a reliable separate recording of cars.
Cutting out cars so as to record lorries separately proved less successful, and the measurements obtained were not processed further. This did not in fact appear to be very necessary since, as will be shown later, the equivalent noise levels emitted by the mixed traffic flow were mainly due to lorries.

4.2.2 Noise reduction at 70-80 km/h

The noise levels \( L_{eq} \) recorded beside the road refer to the traffic present at the time of measurement. The noise emitted by the traffic however is not entirely due to the road surface; it also depends on the traffic density, its composition (the proportion of lorries) and the average speeds of cars and lorries. These last three, surface-independent, parameters were not constant throughout the measuring series, especially on various days before and after the laying of the test section.

The following range was noted:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic density</td>
<td>( 489 \text{ veh/h} \leq Q \leq 720 \text{ veh/h} )</td>
</tr>
<tr>
<td>Proportion of lorries</td>
<td>( 18% \leq P \leq 26% )</td>
</tr>
<tr>
<td>Average speeds (cars)</td>
<td>( 78 \text{ km/h} \leq V_C \leq 84 \text{ km/h} )</td>
</tr>
<tr>
<td>(lorries)</td>
<td>( 69 \text{ km/h} \leq V_L \leq 76 \text{ km/h} )</td>
</tr>
</tbody>
</table>
Standardization

In order to pinpoint the differences in sound level that are due entirely to different road surfaces, the noise level $L_{eq}$ measured is converted to a normalized noise level $L_{eq}'$ with the following standard parameters:

$$Q' = 500 \text{ veh/h}$$
$$P' = 20\%$$
$$V'C = 83 \text{ km/h}$$
$$V'L = 73 \text{ km/h}$$

To make this adjustment, use is made of the basic formula*

$$L_{eq}' = \frac{Q}{v} \cdot \exp\left(\frac{L_m}{10}\right)$$

or

$$L_{eq}' - L_{eq} = 10 \log \frac{Q'}{Q} + 10 \log \frac{v}{v'} + L_m' - L_m$$

(4.2)

where the average peak levels $L_m$ and $L_m'$ correspond to speed $v$ and the normalized speed $v'$ respectively.

For a traffic flow consisting of two kinds of vehicles (cars and lorries), equation (4.2) can be written:

---

* See, for instance, the Procedure for Calculating and Measuring Traffic Noise in Section 102 of the Noise Abatement Act.
\[ L'_{eq} = L_{eq} + 10 \log \frac{Q'_L \cdot \exp \left( \frac{L_m L - L_m C}{10} \right) + Q'_C \cdot \exp \left( \frac{L_m C - L_m C}{10} \right)}{Q_L \cdot \exp \left( \frac{L_m L}{10} \right) + Q_C \cdot \exp \left( \frac{L_m C}{10} \right)} \]  \hspace{1cm} (4.3)

whence

\[ L'_{eq} = L_{eq} + 10 \log \frac{\frac{Q'_L \cdot \exp \left( \frac{L_m L - L_m C}{10} \right) + Q'_C \cdot \exp \left( \frac{L_m C - L_m C}{10} \right)}{Q_L \cdot \exp \left( \frac{L_m L}{10} \right) + Q_C \cdot \exp \left( \frac{L_m C}{10} \right)}}{Q'_L \cdot \exp \left( \frac{L_m L - L_m L}{10} \right) + Q'_C \cdot \exp \left( \frac{L_m C - L_m C}{10} \right) + Q_C} \]  \hspace{1cm} (4.4)

or

\[ L'_{eq} = L_{eq} + 10 \log \frac{Q'}{Q} + \frac{p'n \cdot \exp \left( \frac{L'_m L - L_m L}{10} \right) + (1-p') \exp \left( \frac{L'_m C - L_m C}{10} \right)}{p \cdot n + (1-p) \cdot \exp \left( \frac{L'_m L - L_m L}{10} \right)} \]  \hspace{1cm} (4.5)

where

\[ n = \frac{V_C}{V_L} \cdot \exp \left( \frac{L_m L - L_m C}{10} \right) \]  \hspace{1cm} (4.6)
In equation (4.6), \( n \) denotes the number of cars that, in terms of noise emission, are equal to one lorry. Hence the term "lorry equivalent" will be used.

In applying equation (4.5), the differences in peak levels \( (L'_m - L_m) \) must be known \( (L_m \) levels are measured on the spot). The difference in level can be deduced from the known speed-dependence of the peak levels for the different vehicle types. Use can be made of the values given in the Procedure for Calculating and Measuring Traffic Noise:

\[
(L'_m - L_m) \ L = 0.03(v' - v) \ L \quad (4.7)
\]

\[
(L'_m - L_m) \ C = 0.21(v' - v) \ C \quad (4.8)
\]

Similar relationships can also be deduced from measurements of \( L_m \) and \( v \) made on the spot, but equations (4.7) and (4.8) are to be preferred since these are based on a larger number of individual measurements (as regards the final \( L'_{eq} \) level, the differences are only a few hundredths of a dB).

Finally it is assumed that the normalization described above is independent of frequency.
\( \Delta L_{eq} \) as a result of the use of various road surfaces

The traffic noise levels \( L_{eq} \) measured on the different road surfaces were normalized by means of equations (4.5)-(4.8). It turned out that the results of DAC measurements (1) and (2) at 7.5 m were within 0.2 dB. The equivalent noise level determined on DAC was therefore accepted as the reference level. The results obtained for the other road surfaces can thus be expressed as differences \( \Delta L_{eq} \) from the DAC level.

Tables 4.1 and 4.2 give the results obtained on the A-scale.

At a distance of 7.5 m, A-scale differences of 0.1 dB can still be regarded as significant, whereas at 25 m, in view of the fact that measurements are less accurate, only differences of 0.3 dB and over are significant.
### Table 4.1 Difference in noise levels, on the weighted A-scale, of various road surfaces ($\Delta L_{eq}$)

#### Mixed traffic

<table>
<thead>
<tr>
<th>Road surface</th>
<th>$\Delta L_{eq}$ at a distance of</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7.5 m</td>
<td>25 m</td>
<td></td>
</tr>
<tr>
<td>DAC</td>
<td>0 dB</td>
<td>0 dB</td>
<td></td>
</tr>
<tr>
<td>Concrete slabs</td>
<td>-4.3 dB</td>
<td>+3.4 dB</td>
<td></td>
</tr>
<tr>
<td>OTA</td>
<td>-2.6 dB</td>
<td>-2.4 dB</td>
<td></td>
</tr>
<tr>
<td>PEAC</td>
<td>-3.4 dB</td>
<td>-3.0 dB</td>
<td></td>
</tr>
</tbody>
</table>

Average speeds: 83 km/h for cars  
73 km/h for lorries

Proportion of lorries in traffic: $p = 20\%$

### Table 4.2 Difference in noise levels, on the weighted A-scale, of various road surfaces ($\Delta L_{eq}$)

#### Cars only

<table>
<thead>
<tr>
<th>Road surface</th>
<th>$\Delta L_{eq}$ at a distance of</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7.5 m</td>
<td>25 m</td>
<td></td>
</tr>
<tr>
<td>DAC</td>
<td>0 dB</td>
<td>0 dB</td>
<td></td>
</tr>
<tr>
<td>Concrete slabs</td>
<td>+3.3 dB</td>
<td>+3.5 dB</td>
<td></td>
</tr>
<tr>
<td>OTA</td>
<td>-3.0 dB</td>
<td>-3.1 dB</td>
<td></td>
</tr>
<tr>
<td>PEAC</td>
<td>-3.7 dB</td>
<td>-3.4 dB</td>
<td></td>
</tr>
</tbody>
</table>

Average speed: 83 km/h
Figures 4.8-4.11 give the results, plotted against waveband (bandwidth = one third of an octave), showing the A-level reductions.

From the results shown in Figures 4.8-4.11, one can deduce the reduction in level for each waveband, and these reductions are shown for PEAC in Figure 4.12.

Leaving aside the results for concrete slabs (Figures 4.10 and 4.11), a comparison of the two noise-absorbing surfaces with DAC shows (see Figures 4.8, 4.9 and 4.12) that:

- both OTA and PEAC owe their A-level reduction to absorption capacity at medium and high frequency, from say, 500 Hz;

- as regards OTA, the results obtained by van Ruiten [1.14] on a motorway are confirmed. The A-level reduction is somewhat smaller in our case, but this is due to the considerably lower speeds on the Zeeland test section;

- in the frequency range 500-1600 Hz, reductions achieved by PEAC are clearly greater than those achieved by OTA. Hence PEAC has a greater A-level reduction than OTA. The extent to which noise reduction can be attributed to differences in the material properties will be further examined in Section 4.3.4.4;
- it is clear from Figure 4.12 that for PEAC the greatest reduction occurs at the frequencies where the material, owing to its composition and thickness, reaches its first sound absorption peak (see Figure 3.3). This is the 1000 Hz frequency band, where the traffic noise spectrum also reaches its maximum. From this one can conclude that the aim of optimizing the absorption coefficient has been achieved (see Section 3.3.1);

- the reduction registered at 25 m is somewhat smaller than that at 7.5 m (see also Figure 4.12). The explanation for this must be sought in sound transmission close to the ground (the influence of ground impedance). As was pointed out in Section 3.3.2, further study should be given to this;

- the reductions registered are hardly affected by the traffic mix, whereas it was expected that the reductions would be smaller where lorries were involved, since with them it is engine noise rather than tyre/road noise that predominates. When the lorry percentage is 20%, as in the present study, one can even assume that the equivalent noise level is mainly due to lorries (and thus to engine noise). This is brought out by Table 4.3, which shows 'lorry equivalents' calculated with the help of equation (4.6).
Table 4.3: Lorry equivalent n for the different surfaces on the Zeeland test section

(n = number of cars equivalent to one lorry in terms of noise)

<table>
<thead>
<tr>
<th>Road surface</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete slabs</td>
<td>6.7</td>
</tr>
<tr>
<td>DAC</td>
<td>10.4</td>
</tr>
<tr>
<td>OTA</td>
<td>12.2</td>
</tr>
<tr>
<td>PEAC</td>
<td>12.2</td>
</tr>
</tbody>
</table>

This means that on surfaces such as OTA and PEAC, the noise made by one lorry equals that of about 12 cars. This means that where lorries form 20% of the traffic, the noise emitted by lorries is 5 dB more than that of cars.

It is therefore not to be expected that reductions in the case of lorries by themselves will be very much different than in the case of mixed traffic, as in Figures 4.8, 4.9 and 4.12.

Finally Figures 4.10 and 4.11 show the PEAC results, relative to the results for concrete slabs, plotted against waveband. Here it is possible to compare the situation before and after the laying of the test section. The A-level reductions of 6.4-7.7 dB are considerable.
4.2.3 Noise reductions at 55 km/h (an indicative measure)

From the results discussed in the previous paragraph, it would seem that the noise-absorbing surfaces reduced not only the tyre/wheel noise but also the engine noise. With a view to measuring engine noise directly, further measurements on the test surface were made in respect of a car travelling at a speed of 55 km/h, with the engine turning fairly fast at 3,500 revs per minute (in 3rd gear).

Readings were taken at a distance of 7.5 m from the following surfaces:

- PEAC
- OTA
- DAC.

For each run the $L_{eq}$ for each waveband was noted, and the results were then averaged over the runs (there were 6 runs, but only 4 were suitable for processing). The readings were taken at night in the absence of other traffic. The results are given in Figure 4.13. It appears from this, as in earlier figures, that PEAC gives especially high reductions in the frequency bands between 500 Hz and 1000 Hz. Hence A-level reductions for PEAC are somewhat higher than for OTA. However, the A-level reductions measured only apply to the spectrum of the particular kind of car used (it appears from Figure 4.13 that this is clearly fitted with a good silencer), and cannot simply be taken as applying generally.
One can, however, conclude from this indicative testing that porous asphalt, especially PEAC, has an effect at lower speeds too. Given that there are further possibilities of varying the composition of PEAC, thanks to the binder used, one might aim at optimizing the absorption coefficient in terms of the specific spectral properties of engine noise. In this way one could arrive at an acoustically optimal PEAC composition for urban traffic.

4.2.4 Summary of acoustic findings

The most important acoustic results produced by this study may be summarized as follows:

- The PEAC mixture optimized for motorway conditions with a course thickness of 4 cm had a maximum absorption coefficient at about 1000 Hz. The maximum value for perpendicular impact was

  \[ a_{\text{max}} = 0.9. \]

- A surface made of this optimal mixture, 4 cm thick, laid on a provincial road (with a speed limit of 80 km/h) results in a reduction in the A-weighted equivalent noise level of the traffic of

  \[ \Delta L_A = 3.0 \text{ to } 3.7 \text{ dB}, \]

relative to the normally used dense asphaltic concrete, and dependent on distance to the measuring point and the composition of the traffic. The reduction to be obtained by laying PEAC on a motorway should be somewhat greater.
- An A-level reduction of several dB relative to DAC was also noted in connection with a car travelling at lower speeds, where engine noise predominated.

This result suggests that it would be worthwhile to study the application of PEAC in urban situations.

4.3 Physical and engineering properties of road surface

4.3.1 Study design

The road engineering study relates both to poroelastic asphaltic concrete (PEAC) and to conventional open-textured asphalt (OTA). There are three phases:

- study prior to laying the test section
- study during the laying of the test section
- study after the laying of the test section.

Prior to laying the test section

1. Wheel track study
   The PEAC was submitted to wheel track tests at various binder contents. As regards the OTA, only the mixture to be laid was tested.

2. Ascertaining the effective voids volume (this term, used in road-building, means the same as 'porosity', a term used earlier in this report). The effective voids percentage of the samples used for the wheel track test is determined. The effective voids percentage of samples prepared according to the Marshall method is also determined.
3. The degree of compaction of the samples used in the wheel track test was determined.

During the laying of the test section

1. Checking the composition of the PEAC and OTA mixtures.
2. Determining the voids percentage of the Marshall samples made from milled mixture.
3. Determining the characteristics of the rubberized bitumen (pen 25°C, TR&k and PI).

After the laying of the test section

1. Ascertaining the initial structural condition of the PEAC and OTA surfaces by measuring deformation.
2. Ascertaining the initial longitudinal flatness by means of the viagraph.
3. Ascertaining the initial friction of both test surfaces.
4. Determining the effective voids percentage and other acoustically relevant parameters of the cores bored from the works.

The following sections discuss the principal results of the individual phases. A separate report on the works [4.1] gives individual results from a large number of tests, together with the interim computer calculations.
4.3.2 Study prior to laying the test section

4.3.2.1 Wheel track test

To obtain some idea of the formation of ruts under practical conditions, asphalt can be tested in the laboratory by means of the so-called wheel track test. A sample of the asphalt mixture under examination is submitted to pressure from a moving wheel. The depth of the rut or the change in the total layer thickness is measured as a function of the number of times the wheel passes over it.

The wheel track test on the PEAC and the OTA was carried out with the wheel track equipment of the Research and Consultancy Bureau of J. Heimans B.V., road-building contractors.

In the wheel track equipment the samples (dimensions 400 x 110 x 60 mm³), which are sealed on each side, are subjected to pressure from a wheel (dimensions Φ 200/50-140, pure rubber Continental Elastic) moving to and fro. The wheel pressure on the asphalt is 0.55 N/mm². The average loading time per wheel pass is about 0.10 sec.

Throughout the test the sample is maintained at a constant temperature of 40°C by means of a water bath. The permanent deformation is measured and expressed as a percentage of the original layer thickness \( H_0 \):

\[
\varepsilon_w = \frac{AH}{H_0} \times 100\%
\]
The wheel track test was carried out on three PEAC mixtures with different percentages of binder. The aim of the test was to establish the effect of binder content on the resistance of the poroelastic asphaltic concrete to deformation.

Conventional open-textured asphalt like that used by the Public Works Department on the A50 near Ravenstein was taken as the reference material. The compositions of the mixtures examined are given in Table 4.4.

Table 4.4: Wheel track test: composition of test samples (% m/m)

<table>
<thead>
<tr>
<th></th>
<th>Mix A</th>
<th>Mix B</th>
<th>Mix C</th>
<th>Mix D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate 11/16</td>
<td>30</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Aggregate 6/11</td>
<td>25.5</td>
<td>67</td>
<td>97</td>
<td>87</td>
</tr>
<tr>
<td>Aggregate 4/8</td>
<td>30</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Crushed sand</td>
<td>10.5</td>
<td>10.5</td>
<td>10.5</td>
<td>10.5</td>
</tr>
<tr>
<td>Crushed gravel</td>
<td>4</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Rubberized bitumen</td>
<td>4.8</td>
<td>-</td>
<td>5.5</td>
<td>6</td>
</tr>
<tr>
<td>Bitumen 80/100</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The results of the wheel track test on each mixture are given in Appendices 4.1-4.4 as an average of three tests. Table 4.5 gives the relationships between the permanent deformation $\varepsilon_w$ and the number of wheel passes $N$ as deduced from the tests.
Table 4.5: Deformation \( \varepsilon_w \) as a function of the number of wheel passes \( N \) \( \varepsilon_w \) in %

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Bitumen 80/100</th>
<th>Rubber bitumen</th>
<th>Rubber bitumen</th>
<th>Rubber bitumen</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (OPA)</td>
<td>4.8 %</td>
<td>5.0 %</td>
<td>5.5 %</td>
<td>6.0 %</td>
</tr>
<tr>
<td>B (PEAC)</td>
<td>-1.10 + 0.43 ( \ln N ) ( R^2 = 0.86 )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C (PEAC)</td>
<td>-1.41 + 0.46 ( \ln N ) ( R^2 = 0.97 )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D (PEAC)</td>
<td>-0.88 + 0.40 ( \ln N ) ( R^2 = 0.79 )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-1.14 + 0.42 ( \ln N ) ( R^2 = 0.99 )</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.3.2.2 Density, effective voids volume and compaction

The effective voids volume, density and compaction of the samples for the wheel track test are determined in advance. Compaction is ascertained by comparing the density of the sample with that of Marshall cylinders.

The results are shown in Table 4.6. Each value is the average of four tests.

Table 4.6: Mean density and mean effective voids percentage of samples

<table>
<thead>
<tr>
<th>Mix A</th>
<th>Mix B</th>
<th>Mix C</th>
<th>Mix D</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mar. cyl.</td>
<td>Wh. tr. sample</td>
<td>Mar. cyl.</td>
<td>Wh. tr. sample</td>
</tr>
<tr>
<td>Density (kg m(^{-3}))</td>
<td>2.052</td>
<td>2.000</td>
<td>1.922</td>
</tr>
<tr>
<td>Effective voids volume (%)</td>
<td>16.9</td>
<td>18.9</td>
<td>22.1</td>
</tr>
<tr>
<td>Compaction (%)</td>
<td>97.5</td>
<td>97.9</td>
<td>97.9</td>
</tr>
</tbody>
</table>

Figure 4.14 shows the relationship between effective voids percentage and binder content for wheel track test samples and Marshall cylinders.
4.3.2.3 Assessment of the study

The results show that there are no great differences in performance by the mixtures studied as regards deformation level and deformation increases per $10^4$ passes. Table 4.7 shows in respect of the various mixtures the permanent deformation $\varepsilon_w$ at $N = 5.10^4$ and at $N = 10^5$ passes and the deformation increase $\varepsilon'_w$ per $10^4$ wheel passes.

Table 4.7: Permanent deformation $\varepsilon_w$ after $N$ wheel passes and deformation increase $\varepsilon'_w$

<table>
<thead>
<tr>
<th></th>
<th>Mix A</th>
<th>Mix B</th>
<th>Mix C</th>
<th>Mix D</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_w$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N = 5.10^4$</td>
<td>3.55</td>
<td>3.57</td>
<td>3.45</td>
<td>3.40</td>
</tr>
<tr>
<td>$\varepsilon'_w$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N = 10^5$</td>
<td>3.85</td>
<td>3.89</td>
<td>3.73</td>
<td>3.70</td>
</tr>
<tr>
<td>$\varepsilon'_w$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.060</td>
<td>0.064</td>
<td>0.064</td>
<td>0.060</td>
</tr>
</tbody>
</table>

Though the compaction of the samples is not very high, the deformation level is low for all mixtures. The effective voids volume is influenced to a considerable degree by the quantity of binder as appears from Figure 4.14. On the one hand one seeks as high a voids percentage as possible in view of the acoustic effect (low binder percentage), on the other hand one wants maximum durability (high binder percentage).

In view of this and the results of the wheel track test, mixture C was chosen, in consultation with the Noord-Brabant Public Works Department, as the material for the Zeeland test section.
4.3.3 Study during the laying of the test section

4.3.3.1 Composition of the material

The compositions of the poroelastic asphaltic concrete and the open-textured asphalt were related to the preliminary study by taking samples of the bulk material. The results of this test are given in Table 4.8.

**Table 4.8: Results of analysis of samples taken from lorries**

<table>
<thead>
<tr>
<th>% on sieve</th>
<th>2.560</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PEAC</td>
</tr>
<tr>
<td></td>
<td>Req.</td>
</tr>
<tr>
<td>C 16-</td>
<td>7</td>
</tr>
<tr>
<td>C 11.2</td>
<td>7</td>
</tr>
<tr>
<td>C 8.0</td>
<td>7</td>
</tr>
<tr>
<td>C 5.6</td>
<td>7</td>
</tr>
<tr>
<td>2 mm</td>
<td>87</td>
</tr>
<tr>
<td>2.0 mm - 500 μm</td>
<td>7</td>
</tr>
<tr>
<td>500 μm - 180 μm</td>
<td>7</td>
</tr>
<tr>
<td>180 μm - 63 μm</td>
<td>7</td>
</tr>
<tr>
<td>Filler</td>
<td>2.5</td>
</tr>
<tr>
<td>Bitumen</td>
<td>5.5</td>
</tr>
</tbody>
</table>

n = number of measurements, x = mean, s = standard deviation.

* The binder content of the poroelastic asphaltic concrete as determined in the bulk sample has to be corrected.

Rubberized bitumen consists of 80% 80/100 bitumen and 20% rubber granulate. 10% of this rubber granulate dissolves so that one reckons the bitumen at 82%, the other 18% counting with the filler. The proportion of rubberized bitumen thus comes out at 5.7%.
4.3.3.2 Voids volume (Marshall cylinder test)

Marshall cylinders were made from the bulk samples and tested for total and effective voids percentage. The results of the test are given in Table 4.9.

Table 4.9: Mean voids volume (%) in PEAC and OTA Marshall cylinders

<table>
<thead>
<tr>
<th></th>
<th>Total voids (%)</th>
<th>Effective voids (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$n$</td>
<td>$\bar{x}$</td>
</tr>
<tr>
<td>PEAC</td>
<td>20</td>
<td>24.4</td>
</tr>
<tr>
<td>OTA</td>
<td>6</td>
<td>27.6</td>
</tr>
</tbody>
</table>

$n =$ number of measurements  
$\bar{x} =$ mean voids volume (%)  
$s =$ standard deviation

It is to be noted that the voids percentage is somewhat higher in the OTA than in the PEAC. That this is so despite the fact that stones with a narrower size distribution were used may perhaps be explained by the edge effect in the preparation of the cylinders.

A coarser stone is used in making OTA, and so the edge effect is greater and the voids percentage is higher. This hypothesis will be checked with the help of cylinders bored from the works, which will give a more realistic picture of the effective voids volume (see Section 4.3.4.4).
4.3.3.3 Properties of rubberized bitumen

During the production of the rubberized bitumen at the asphalt plant in Den Bosch, samples were taken with a view to determining the characteristic properties of the binder. The characteristics of the finished product are given in Table 4.10.

Table 4.10: Characteristic properties of bitumen

<table>
<thead>
<tr>
<th>Batch</th>
<th>Pen 25°C</th>
<th>T_F6k</th>
<th>PI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>80</td>
<td>58</td>
<td>1.9</td>
</tr>
<tr>
<td>2</td>
<td>84</td>
<td>57</td>
<td>1.9</td>
</tr>
<tr>
<td>6</td>
<td>72</td>
<td>59</td>
<td>1.8</td>
</tr>
<tr>
<td>7</td>
<td>81</td>
<td>59</td>
<td>2.2</td>
</tr>
<tr>
<td>9</td>
<td>84</td>
<td>57</td>
<td>1.8</td>
</tr>
<tr>
<td>10</td>
<td>74</td>
<td>59</td>
<td>1.9</td>
</tr>
</tbody>
</table>

No attempt was made to determine the characteristics of bulk bitumen samples taken on site at the roadworks, because in recovering rubberized bitumen that part of the rubber granules that has not dissolved is withdrawn from the binder. The degree to which the rubber dissolves depends on temperature and the stage of production at which the sample was taken.

The properties of recovered rubberized bitumen are therefore not at all representative of the binder.
4.3.4 Study after the laying of the test section

4.3.4.1 Load-bearing capacity

In order to get an idea of the structural contribution of the base layer on top of the fractured concrete surface and the structural condition of the test sections immediately after laying, the load-bearing capacity of the subsoil and of the road surface at the various stages of the work was determined by means of deformation measurements using a falling weight.

The following parameters were measured: size of falling weight \( F \), air temperature \( T_1 \), asphalt temperature \( T_a \), and six deformation values 1-6 at 0, 300, 500, 1000, 1500 and 2000 mm from the centre of the weight. These values were processed by means of the computer program FWD-1 of Delft University of Technology. The program recalculates the deformations as though caused by a weight of 50 kN.

From the deformation at 2000 mm the elasticity modulus \( E_3 \) of the subsoil is calculated. One also defines \( h_{es} \) as the equivalent layer thickness for a subsoil modulus of 100 MPa.

\[
h_{es} = h_e \cdot \sqrt[3]{\frac{E_3}{100}}
\]

\( h_e \) = equivalent layer thickness (m) corresponding to the actual subsoil modulus \( E_3 \) [MPa].

\( h_e \) is calculated thus:

\[
h_e = 0.9 \sqrt[3]{\frac{h_n}{n}} \cdot \sqrt[3]{\frac{E_n}{E_3}}
\]
By converting the equivalent layer thickness $h_e$ to an equivalent layer thickness $h_{es}$ based on a reference subsoil modulus of 100 MPa, it is possible to compare constructions one with another. The rule is that the greater $h_{es}$, the better the structural properties of the construction, independent of the subsoil.

The results of the measurements and calculations are set out in Tables 4.11-4.13.

Table 4.11: Deformation measurements on fractured concrete

<table>
<thead>
<tr>
<th></th>
<th>Middle of lane</th>
<th>Outer edge of lane</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>St. dev.</td>
</tr>
<tr>
<td>1</td>
<td>549 µm</td>
<td>97 µm</td>
</tr>
<tr>
<td>2</td>
<td>420 µm</td>
<td>72 µm</td>
</tr>
<tr>
<td>3</td>
<td>297 µm</td>
<td>43 µm</td>
</tr>
<tr>
<td>4</td>
<td>119 µm</td>
<td>22 µm</td>
</tr>
<tr>
<td>5</td>
<td>65 µm</td>
<td>14 µm</td>
</tr>
<tr>
<td>6</td>
<td>44 µm</td>
<td>7 µm</td>
</tr>
<tr>
<td>Subsoil modulus</td>
<td>163 MPa</td>
<td>26 MPa</td>
</tr>
<tr>
<td>Equivalent layer thickness $h_{es}$</td>
<td>0.53 m</td>
<td>0.10 m</td>
</tr>
<tr>
<td>No. of observations</td>
<td>76</td>
<td>78</td>
</tr>
</tbody>
</table>

Table 4.12: Deformation measurements on fractured concrete base layer

<table>
<thead>
<tr>
<th></th>
<th>Middle of lane</th>
<th>Outer edge of lane</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>St. dev.</td>
</tr>
<tr>
<td>1</td>
<td>278 µm</td>
<td>57 µm</td>
</tr>
<tr>
<td>2</td>
<td>225 µm</td>
<td>40 µm</td>
</tr>
<tr>
<td>3</td>
<td>179 µm</td>
<td>27 µm</td>
</tr>
<tr>
<td>4</td>
<td>97 µm</td>
<td>12 µm</td>
</tr>
<tr>
<td>5</td>
<td>60 µm</td>
<td>10 µm</td>
</tr>
<tr>
<td>6</td>
<td>36 µm</td>
<td>4 µm</td>
</tr>
<tr>
<td>Subsoil modulus</td>
<td>196 MPa</td>
<td>24 MPa</td>
</tr>
<tr>
<td>Equivalent layer thickness $h_{es}$</td>
<td>0.77 m</td>
<td>0.20 m</td>
</tr>
<tr>
<td>No. of observations</td>
<td>45</td>
<td>45</td>
</tr>
</tbody>
</table>
Table 4.13: Deformation measurements on fractured concrete + base layer + top layer

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>St. dev.</th>
<th>Mean</th>
<th>St. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle of lane</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>248 µm</td>
<td>30 µm</td>
<td>261 µm</td>
<td>29 µm</td>
</tr>
<tr>
<td>2</td>
<td>207 µm</td>
<td>20 µm</td>
<td>215 µm</td>
<td>21 µm</td>
</tr>
<tr>
<td>3</td>
<td>167 µm</td>
<td>16 µm</td>
<td>171 µm</td>
<td>15 µm</td>
</tr>
<tr>
<td>4</td>
<td>97 µm</td>
<td>10 µm</td>
<td>99 µm</td>
<td>9 µm</td>
</tr>
<tr>
<td>5</td>
<td>60 µm</td>
<td>13 µm</td>
<td>62 µm</td>
<td>10 µm</td>
</tr>
<tr>
<td>6</td>
<td>37 µm</td>
<td>6 µm</td>
<td>39 µm</td>
<td>6 µm</td>
</tr>
<tr>
<td>Outer edge of lane</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Subsoil modulus | 196 MPa | 28 kPa | 181 MPa | 23 kPa |

Equivalent layer thickness $h_{es}$ | 0.87 m | 0.19 m | 0.83 m | 0.14 m |

No. of observations | 78     | 78     |

These results show that by laying a base layer (with an average thickness of 40 mm) on top of the fractured concrete, a considerable structural advantage is obtained. As a result of laying the base layer, the maximum deformation of the fractured concrete is reduced by about 50%. The load-bearing capacity, expressed as equivalent layer thickness, is also increased considerably by the presence of the base layer ($\Delta h_{es}$ is about 0.21 m).

On the basis of the equivalent layer thickness given in Table 4.11, one can calculate the elasticity modulus of the fractured concrete thus:

$$E_{\text{fractured concrete}} = 1700 \text{ MPa}.$$
On the basis of Table 4.12, the elasticity modulus of fractured concrete + base layer is:

\[ E_{\text{fractured concrete + base layer}} = 3 \ 200 \ \text{MPa}. \]

Thus the stiffness of the road surface is increased considerably through the addition of the base layer about 4 cm thick. No further increase in stiffness is obtained by the addition of open-textured asphalt: from the data in Table 4.13 we see that

\[ E_{\text{fractured concrete + base layer + top layer}} = 3 \ 100 \ \text{MPa}. \]

4.3.4.2 Road flatness measurements

The flatness of the test sections in the longitudinal direction was determined by means of a profile recorder (viagraph) towed by a car at 5-10 km/h. The device consists of a hinged bridge construction, with 4 small bridges and a main frame in the middle of which there is a measuring wheel. The eight support wheels and the measuring wheel are in line. In passing along the road, the movements of the measuring wheel relative to the midpoint of the frame are registered. The quality of the evenness is expressed as a deviation percentage, C5, as laid down in VUCW 1978 (Regulations on the Laying and Checking of Road Surfaces 1978).

The viagraph measurements on the test section show that profile deviations only occur at places where work stopped at the end of the day. The results are shown in Table 4.14.
Table 4.14: Results of viagraph measurements on the S20

<table>
<thead>
<tr>
<th>Location</th>
<th>C5</th>
</tr>
</thead>
<tbody>
<tr>
<td>North km 13.7 - 13.6</td>
<td>0.2%</td>
</tr>
<tr>
<td>South km 13.6 - 13.7</td>
<td>1.8%</td>
</tr>
<tr>
<td>South km 14.3 - 14.4</td>
<td>2.0%</td>
</tr>
<tr>
<td>South km 14.5 - 14.6</td>
<td>0.8%</td>
</tr>
</tbody>
</table>

On the basis of the Public Works Department requirement that new roads should have a deviation $C5 \leq 2\%$, it may be said that a very firm profile can be achieved with open-textured asphalt mixtures, and that particular attention should be given to end-of-day work.

4.3.4.3 Friction measurements

The friction of the OTA and PEAC surfaces was determined by the 86% slowed wheel method in which, at a constant speed of 50 km/h, the measuring wheel is obliged to rotate at a turning speed 86% lower than a freely turning wheel would do. Where the road surface and the tyre meet, there is thus 86% slip.

The resulting friction force is measured. The ratio of the friction force to the load on the measuring wheel is the friction coefficient, taken as the average value over a measuring distance of 100 m.

During the measurement the road surface just in front of the measuring wheel is moistened with sufficient water to give a 0.5 mm film of water at average surface texture. The test is carried out with a high-profile Piarc tyre. According to VUCW 1978 the friction coefficient should be at least 0.52.
The measurements were made on 29 June 1984 by the Road Survey Department of the Regional Laboratories. The results show that friction is everywhere satisfactory, ranging from 0.52 to 0.56, with an average of 0.54.

4.3.4.4 Acoustically relevant properties

Traffic noise measurements along the test section showed that a somewhat higher reduction was achieved with the PEAC than with the OTA (see Figures 4.8, 4.9 and 4.13).

Cores with a diameter of 0.10 m taken from the road surface were examined with a view to ascertaining to what extent the difference in noise reduction was due to a difference in physical properties. As has been pointed out in Section 3.3.1, these are:

- porosity (or effective voids volume) $\sigma$

- flow resistance $\Xi$

- structure factor $\chi$

The first attempt to extract cores which would give a true picture of the road surface material was not a success. Despite attempts to cool with water, heat was generated during the drilling process, and consequently the binder in the asphalt oozed from the bore wall and became smeared over the surface of the core.
Only by locally cooling the asphalt with liquid nitrogen was it possible to extract representative samples, which yielded the following results:

Porosity (effective voids volume)

The relevant measurements were made by the Southern Highway Engineering Laboratory in Vught; not only the effective voids volume but also the total voids volume and the density were determined.

The results are given in Table 4.15. The values quoted are averages for 7 OTA cores and 15 PEAC cores. The individual results are given in Appendix 4.5.

Table 4.15: Effective voids volume, total voids volume and density of OTA and PEAC, determined from cores bored from the road

<table>
<thead>
<tr>
<th></th>
<th>Effective voids volume</th>
<th>Total voids volume</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>OTA</td>
<td>22.6%</td>
<td>23.9%</td>
<td>1697 kg/m³</td>
</tr>
<tr>
<td>PEAC</td>
<td>21.4%</td>
<td>22.8%</td>
<td>1698 kg/m³</td>
</tr>
</tbody>
</table>

It emerges from Table 4.15 that the effective voids volume of the poroelastic asphalt is on average 1.2% below that of the open-textured asphalt.

This is in line with the results obtained from the Marshall samples of milled material (see Section 4.3.3.2). This is striking, the more so since the use of a higher percentage of stones of more uniform size should lead to a higher voids percentage. This higher voids percentage was desirable, from the acoustic point of view, in order to achieve a greater noise reduction (see Section 3.3.1).
Although the difference of 1.2% in porosity is too small to make any significant difference in noise reduction, it is nevertheless interesting that PEAC, despite a somewhat lower porosity, still achieves a higher noise reduction. This must therefore be due to one of the other physical properties.

Flow resistance

The flow resistance was measured in accordance with DIN 52213, using 4 cores from each of the PEAC and OTA test sections. The resulting values of the flow resistance $\Xi$ were:

for PEAC

$$\Xi = 6.3 \cdot 10^3 \, \text{Ns m}^{-4} \quad (s = 23\%)$$

for OTA

$$\Xi = 4.2 \cdot 10^3 \, \text{Ns m}^{-4} \quad (s = 34\%)$$

This difference in $\Xi$ can just about be regarded as significant. The flow resistance of PEAC is greater than that of OTA and therefore comes closer to the optimal value of 40 to 80 kNs m$^{-4}$. It should be borne in mind, as was explained earlier in Section 3.3.1, that resistances measured in accordance with DIN 52213 seem to be about 3-6 times too low.

It can, however, be concluded that the differences in $\Xi$ are also too small to account, by themselves, for the different noise reductions of PEAC and OTA.
Structure factor

The structure factor for the core samples of PEAC and OTA was determined by means of absorption measurements in the impedance tube, as described in Section 3.3.1.

The same core samples were used for these measurements as for the flow resistance measurements. A representative example of the results obtained is given in Figure 4.15. The values for each core sample are grouped around the first maximum of the absorption coefficient within the accuracy of the readings.

From the frequency of the first maximum of the absorption coefficient $\alpha$, the structure factor can be determined as explained in Section 3.3.1.

For PEAC we obtain
\[ \chi = 5.0 \]

and for OTA we obtain
\[ \chi = 3.2 \]

This difference in the structure factor is significant and is large enough to go at least some way in explaining the differences in noise reduction between the two road surfaces:

If one starts from the already accepted premise that a higher absorption coefficient means a higher noise reduction, then it is seen from Figure 4.15 that, at frequencies of 1000 Hz and below, PEAC provides greater noise reduction than OTA, and that at frequencies above 1000 Hz, OTA gives a higher reduction than PEAC. However this effect will diminish at higher frequencies.
since the height of the source increases relative to the wavelength, so that the properties of the road surface will have a smaller influence on the sound emission.

This behaviour is also to be found in the roadside readings shown in Figure 4.13 and, somewhat less clearly, in the lower graphs in Figures 4.8 and 4.9. The other results (the upper graphs in Figures 4.8 and 4.9) merely confirm that PEAC at lower frequencies must show greater reduction than OTA. The difference at higher frequencies cannot be explained by Figure 4.15.

Generally speaking, these comparisons, especially the results in Figure 4.15, indicate the importance of optimizing in terms of frequency, which is what is aimed at when deciding on the composition of the PEAC mixture.
5. Assessment of results obtained

5.1 Implications for the Procedure for Calculating and Measuring Traffic Noise (Section 102 of the Noise Abatement Act)

The procedure stipulated in Section 102 of the Noise Abatement Act for determining the noise level due to a road takes account of the "road surface correction" $C_w$. In this way allowance is made for the influence of the road surface on the noise level.

The term $C_w$ is an adjustment, per octave band, of the noise emitted by a given category of vehicle, $C_w$ having the value of zero in the case of a coarse dense asphaltic concrete. The results set out in Tables 4.1 and 4.2 are relevant here in the sense that the values of $\Delta L_{eq}$ determined in the present study can also be interpreted as road surface corrections though with reference to the A-weighted equivalent noise level (and so not dependent on frequency). It should be borne in mind that this only applies to results where $v = 80 \text{ km/h}$ for cars and $v = 70 \text{ km/h}$ for lorries.

On this condition, the values given in Table 5.1 can, tentatively, be regarded as "road surface corrections" in the meaning of the Section 102 procedure in respect of the two noise-absorbing surfaces under examination at Zeeland.
Table 5.1: "Road surface correction" $\Delta L_{eq}$ for two surfaces on roads where the speeds are 80 km/h for cars and 70 km/h for lorries

<table>
<thead>
<tr>
<th></th>
<th>Cars</th>
<th>Lorries</th>
</tr>
</thead>
<tbody>
<tr>
<td>OTA</td>
<td>-3.0 dB</td>
<td>-2.5 dB</td>
</tr>
<tr>
<td>PEAC</td>
<td>-3.5 dB</td>
<td>-3.2 dB</td>
</tr>
</tbody>
</table>

As regards the dependence of $\Delta L_{eq}$ on frequency, reference should be made to Figure 4.12, which gives the "road surface correction" per waveband for PEAC. This shows that for lorries there is a certain displacement of the frequency characteristic with distance.

At this stage of the study it would be premature to draw general conclusions. The effect might be connected with transfer phenomena, on which further research will be necessary (see Section 3.3.2).

A table similar to Table 5.1 can be prepared for motorway conditions and urban traffic, once the supplementary study is complete. For motorways it is to be expected that the reductions would be somewhat greater, partly in view of the earlier study of OTA [1.14]. It is also possible that the difference between OTA and PEAC could be greater (PEAC was after all designed for motorways).

As regards the urban traffic situation, one may conclude tentatively from the results of Section 4.2.3 that PEAC will give a road surface correction of about 3 dB, which might be increased further if the composition of the material were further improved. A more accurate and reliable estimate would only be possible after further study.
All in all it can be stated that with Table 5.1 the first step has been taken towards supplementing the Procedure for Calculating and Measuring Traffic Noise with a correction factor for noise-absorbing road surfaces, but that more experimental and theoretical work is necessary to be able to determine in a reliable manner the extent to which this factor is dependent on frequency and speed.

5.2 Other aspects

Although this present study is mainly concerned with the reduction of traffic noise, account must also be taken of other likely environmental effects, albeit for the moment in only a very general fashion.

Road safety

The most important reason for the use of the conventional open-textured asphalt in the past has been its capacity to hold and drain off water. These properties are also a feature of the new PEAC, along with superior mechanical properties over time. As was pointed out in Section 3.2.1, this material gives considerably better road safety results in wet weather, since splashing and spraying are eliminated and aquaplaning is no longer to be feared. Moreover, one no longer gets the dazzling effect of reflections from the wet surface. In this respect there is no difference between PEAC and OTA.
Recycling of old car tyres

The binder used in PEAC contains, as was explained above (Section 3.2.3), a certain percentage of rubber. The rubber is obtained from old tyres which, after the removal of fabric and steel, is finely ground and then mixed in by means of a special process. In order to give some idea of the extent to which this addition of rubber can usefully contribute to the recycling of old car tyres, a few figures may be in order:

For each ton of binder, 180 kg of ground tyres are used, with equal weights of car and lorry tyres. A car tyre, after the removal of fabric and steel, yields about 3.5 kg of rubber, a lorry tyre about 22 kg. Hence for each ton of binder, 25 car tyres and 4 lorry tyres are used.

Applying these data by way of example to the Zeeland test section, with a length of only 1.5 km and a width of 7.2 m, this means that 2400 old car tyres and 400 old lorry tyres were used.

Fuel economy

A further feature of PEAC is its excellent long-term flatness. This is connected with its great resistance to deformation. In view of the open structure of the surface of the wearing course, the dimensions of the contact area between the wheel and the road surface are smaller than in the case of a very compact surface. This together with the great evenness of the surface reduces the vehicle's wheel resistance and therefore fuel consumption too. On this matter however no quantitative study has been made or at any rate published.*

* A manufacturer of open-textured asphalt speaks of a 10-12% reduction in wheel resistance.
It is not to be expected that the reduction in fuel consumption per individual vehicle would be very big, but the reduction might well be considerable in respect of all vehicles affected if this type of road surface were used on a larger scale.

Anti-skid measures

One point to be noted in the use of open-textured asphalt in general is the anti-skid aspect. Owing to the open structure, the salt strewn disappears with the melted water into the pores of the asphalt. This means that salt has to be strewn more frequently. A critical point is where an open-textured surface gives way to a dense one, such as DAC. In contrast to a DAC surface, very little salt is picked up by passing vehicles on an open-textured asphalt surface. This means that when traffic reaches a DAC stretch, the salt strewn on the first few metres is quickly picked up, which increases the risk of skidding.

In the last winter season, no difference was noticed between the PEAC and OTA test sections as regards skid prevention. It was noted, however, that on both types of open-asphalt surface, salt had to be strewn on black ice quicker and more frequently than on the adjoining DAC.

As regards macro-economic effects, "road safety" and "recycling of old tyres" are the most important of the points mentioned above. While improved road safety can also be credited to conventional OTA, only PEAC can claim the credit of "recycling old tyres".
5.3 Cost implications

At the moment the new poroelastic asphaltic concrete is still more expensive per unit area and thickness than conventional open-textured asphalt. However, as is often the case with new products, the cost of producing PEAC could well fall if the production process is improved and enlarged. The use of PEAC on a larger scale will certainly justify the initial costs of developing improved production technology and investment in new material.

The price differential is largely due to the new binder, rubberized bitumen. The cost of processing the old tyres has to be passed on. Against this one must set the considerable gain from recycling old tyres and enhanced road safety compared with DAC (see the previous section).

However, the resulting financial advantages are difficult to quantify. Only the acoustic advantages obtained through the use of PEAC can in many cases be calculated, in cases where through the use of PEAC, other noise reducing devices, along the road or on the fronts of houses, can be dispensed with or made less obtrusive. Despite the fact that PEAC is more expensive than other road surfaces at the moment because of the relatively high cost of rubberized bitumen, it may already be financially attractive, as the following example shows:
The volume of noise along a provincial highway can be reduced by 3.5 dB through the use of PEAC, 4 cm thick, as readings on the test section at Zeeland show. The same reduction can also be achieved by erecting a noise barrier.

Let us compare the costs of these two alternatives:

The calculation is based on a project area of 10,000 m². In line with the calculation procedure in Section 102 of the Noise Abatement Act, calculations were made to determine the height of a screen along a two- or four-lane road with a view to achieving a noise reduction of $\Delta L_A = 3.5$ dB. The results of these calculations are given in Figure 5.1.

The requisite screen height ranges from 1 to 3 metres, depending on the type of road and the distance between the built-up area and the road. The costs of a noise barrier like this depend on the characteristics of the soil and the system used.

The Ministry of Housing, Physical Planning and Environmental Management, in the context of allocation, speaks of an all-in cost for erecting the barrier of 400 florins per square metre.

Converting to the cost per square metre of road surface, this means that for a two-lane road (2 x 3.60 m lane) the cost of the screen per square metre of road surface is about 56 florins.
For a road with two lanes in each direction (2 x 7.20 m plus 2 x 2.50 m hard shoulder) the cost of the screen per square metre of road surface comes out at about 21 florins.

The use of poroelastic asphalt will thus be financially attractive if the costs per square metre are less than or equal to the above-mentioned sound-barrier prices expressed per square metre of road surface.

The cost price of poroelastic asphalt largely depends on the cost of production of the rubberized bitumen. However, despite the fact that the cost of rubberized bitumen is relatively high, the market being still too small, poroelastic asphalt can already compete with sound barriers. In the case of a two-lane road, this is certainly so. In the case of two lanes in each direction it would depend on the size of the scheme.

Moreover, PEAC, which exercises its effect close to the source of the noise, has the acoustic advantage that upper storeys too are protected from the noise nuisance.

In choosing the type of wearing course, it is not only the costs of laying that decide; maintenance also has to be taken into account. Open-textured asphalt has to be maintained, especially in places that are not much ridden over (hard shoulders for instance). The risk of fouling and the growth of weeds is greater compared with the traffic lanes which are kept uncluttered by the passage of vehicles. Attention has been given to this pollution aspect abroad, especially by BROWN [5.1].
Special attention has to be given to local repair of open-textured asphalt. The use of mixtures high in aggregate makes it difficult to carry out the work by hand. In order to achieve a smooth combination of old and new asphalt, one needs to apply the proper technique, preferably mechanically.

The overlaying of poroelastic asphalt and open-textured asphalt is feasible, possibly in combination with a waterproof membrane (SAMI). Moreover, if for one reason or another the PEAC is removed, the presence of rubberized bitumen does not prevent recycling. The recycled material would be used not as a raw material for open-textured asphalt but as a component of base-layer asphalt.
6. Conclusions and recommendations

From this study the following conclusions can be drawn:

- With the development of poroelastic asphaltic concrete a wearing-course material has become available in which acoustic and highway-engineering properties are combined in the best possible way. To date, acoustic optimization relates to motorway situations.

- In the production of PEAC, use can be made of established road-building technology. The material can therefore be applied on a large scale at short notice.

- The traffic noise reduction obtained with PEAC, compared with the generally used dense asphaltic concrete (DAC) on through roads with a speed limit of 80 km/h is

  3.2 dB for lorries
  3.5 dB for cars

  which is 0.5-0.7 dB more than with conventional open-textured asphalt (OTA).

- The highway-engineering properties of PEAC comply with all the relevant current requirements of the highway authorities. On the basis of the present study it is naturally not yet possible to draw any definite conclusions as regards long-term and winter performance.
- Since the production of PEAC involves the reprocessing of old car tyres, the use of PEAC on a large scale could make a significant contribution to the recycling of waste.

- Other positive effects of the use of PEAC would be an increase in road safety and, possibly, a decline in fuel consumption. These advantages are not peculiar to PEAC, but apply to open-textured asphalt mixes generally.

- The material and processing costs for PEAC are higher than for other conventional asphalt wearing courses. It is expected that the difference in costs will become smaller as and when PEAC is produced on a larger scale.

- Where it is a question of reducing the noise level near roads, the use of PEAC as a means of reducing road noise could mean that other acoustic devices (such as sound barriers, sound insulation in buildings) might be dispensed with or used more sparingly. In such cases the saving achieved might balance or indeed outweigh the extra cost of PEAC.

- PEAC in combination with a stress-absorbing membrane interlayer is especially appropriate from the point of view of maintenance.
As a result of this study, the following recommendations can be made:

- Further studies should be made on the possibilities of using PEAC in urban situations. One should primarily aim at optimizing the acoustic properties of the material in view of the specific properties of noise from vehicles moving at low speeds;

- A PEAC test section should be laid on a motorway (national highway) so as to ascertain the noise reduction at higher speeds. The noise reduction achieved in this case could well be somewhat greater because of the lower position of the noise source (tyre/road noise only);

- A more theoretical acoustic study should be made of the specific transfer phenomena in the use of noise absorbing road surfaces. This study should preferably be undertaken in conjunction with a University of Technology (TH Delft, for instance);

- In addition to these three recommendations, a road surface correction for sound-absorbing wearing courses should be derived which could be incorporated into the Procedure for Calculating and Measuring Traffic Noise (Section 102 of the Noise Abatement Act);
- The macro-economic gains to be expected from the use of PEAC on a fairly large scale should be quantified in terms of:

- the recycling of old car tyres
- increased road safety
- reducing the consumption of fuel.

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M + P ACOUSTIC CONSULTANTS B.V.

Ir. J.C.P. Heerkens
J. HEIJMANS B.V.
Road Building Contractors
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APPENDICES 4.1 - 4.4

Results of wheel track test
Open-textured asphalt
4.75% bitumen 80/100

\[ \varepsilon_w = -1.10 + 0.43 \ln N \%
\]

\[ R^2 = 0.86 \]
Poroeastic asphaltic concrete
5% rubberized bitumen

\[ \varepsilon_w = -1.41 + 0.46 \ln N \quad \% \]

\[ R^2 = 0.97 \]
Poroelastic asphaltic concrete
5.5% rubberized bitumen

$$\varepsilon_w = -0.88 + 0.40 \ln N \quad \%$$

$$R^2 = 0.99$$
Poroleastic asphaltic concrete
6.0% rubberized bitumen

\[ \varepsilon_{w} = -1.14 + 0.42 \ln N \]

\[ R^{2} = 0.99 \]
Individual measurements of samples extracted from road

**Open-textured asphalt (OTA)**

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<th>Effective voids volume (%)</th>
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**Poroelastic asphalt (PEAC)**

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Estimated reduction $\Delta L_{eq}$ in traffic noise as a function of the percentage of traffic represented by lorries, if engine noise has been reduced by 8 dB for lorries and by 5 dB for cars, while tyre/road noise is unchanged.
Normalized A-weighted tyre/road noise level versus waveband (bandwidth = one-third of an octave) for dense asphalt wearing courses at speeds of about 80 to 120 km/h (average values from own measurements and from literature).
Absorption coefficient as a function of frequency, calculated from equations (3.1) and (3.2). Influence of porosity and structure factor.
Absorption coefficient as a function of frequency, calculated from equations (3.1) and (3.2). Influence of flow resistance and thickness of layer.
Samples of poroelastic asphalt mixture to be measured in the impedance tube.
Results of measurements on samples (see also Figure 3.4). Values were determined as follows: $\phi$ and $\chi$ in the impedance tube in accordance with DIN 52215, $\Xi$ with the help of a stationary flow in accordance with DIN 52213, and $\sigma$ by water displacement.
Figure 3.6

Weighted average absorption coefficient \( \bar{\alpha} \) as a function of \( \sigma \) and \( d \).
Wall impedance $W$ and absorption coefficient $\alpha$ (measured and calculated) of poroelastic asphalt mixture $D$ versus frequency.
Figure 4.1

Map of Zeeland test section
Zeeland test section. Old and new road structures.
Zeeland test section. Above: fractured concrete slabs
Below: laying the base layer
Zeeland test section. Above: laying the stress-absorbing membrane interlayer (SAMI)

Below: strewing the SAMI with precoated chips
Zeeland test section. Above: laying the PEAC
Below: compacting the PEAC
Zeeland test section. First lane completed.
Zeeland test section. Structure of the PEAC.
Figure 4.8

Mixed traffic
\[ p = 20\% \]

\[ L_{A, DAC} = 70.0 \text{ dB(A)} \]
\[ Q = 500 \text{ veh/h} \]

Measured at a distance of 7.5 m

\( \text{DAC} : 0 \text{ dB} \)
\( \text{OTA} : -2.6 \text{ dB} \)
\( \text{PEAC} : -3.4 \text{ dB} \)

Measured at a distance of 7.5 m

\[ L_{A, DAC} = 68.5 \text{ dB(A)} \]
\[ Q = 500 \text{ veh/h} \]

\( \text{DAC} : 0 \text{ dB} \)
\( \text{OTA} : -3 \text{ dB} \)
\( \text{PEAC} : -3.7 \text{ dB} \)

A-weighted spectra (bandwidth = one-third of an octave) of different road surfaces as measured on the Zeeland test section (provincial road S20).
Figure 4.9

Mixed traffic

\[ \rho = 20\% \]

Measured at a distance of 25 m

\[ L_{A, \text{DAC}} = 64.8 \text{ dB(A)} \]

\[ Q = 500 \text{ veh/h} \]

Cars only

\[ L_{A, \text{DAC}} = 63.5 \text{ dB(A)} \]

\[ Q = 500 \text{ veh/h} \]

Central frequency of waveband

A-weighted spectra (bandwidth = one-third of an octave) of different road surfaces as measured on the Zeeland test section (provincial road S20).
A-weighted spectra (bandwidth = one-third of an octave) of different road surfaces as measured on the Zeeland test section (provincial road S20).
Figure 4.11

Mixed traffic

\[ p = 20\% \]

Measured at a distance of 25 m

A-weighted spectra (bandwidth = one-third of an octave) of different road surfaces as measured on the Zeeland test section (provincial road S20).
Figure 4.12

Reduction in equivalent noise level versus frequency (bandwidth = one-third of an octave) for PEAC relative to DAC at two distances.
Figure 4.13

A-weighted spectra (bandwidth = one-third of an octave) for a LADA 1500 S car on different road surfaces.
Dependence of effective voids percentage on binder content.
The absorption coefficient as a function of frequency for PEAC and OTA as measured in the impedance tube. The structure factor $X$ has been determined from the position of the first maxima and with the help of eqs. (3.1) and (3.2).
Screen height required for a traffic noise reduction of $\Delta L_A = 3.5$ dB. Calculated in accordance with the Procedure for Calculating and Measuring Traffic Noise as specified in Section 102 of the Noise Abatement Act.