LOW NOISE ROAD SURFACES.
A STATE-OF-THE-ART REVIEW

Ulf Sandberg

Swedish Road and Transport Research Institute
S-581 95 Linköping
Sweden

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SUMMARY

This paper provides a review of how vehicle noise emission and propagation is influenced by road/street surface design. The review is based partly on the author's own experiments, partly on information collected from other sources, particularly at a recent tyre/road noise conference.

The first part of the paper contains a review of the historical development of the subject as well as of the noise sources of a vehicle and the generation mechanisms of tyre/road noise.

In order to control traffic noise, i.e. reducing it to acceptable levels, it is necessary to employ effective combinations of most of the available measures. Tightened emission limits for vehicles will be necessary but they must be accompanied by subsequent control of tyre/road noise. This includes control of tyres as well as of road surfaces. Standardized methods are developed in order to make selection of road surfaces, based on objective noise assessment methods, possible.

Generally, one can obtain significant noise reductions by road surface selection. In this context, the use of drainage or porous asphalt stands out as the most promising noise reduction measure, although considerable problems with its long-term performance have been recorded; mainly in countries with a hard winter climate.

By using a porous surface it is usually possible to obtain an initial noise reduction of approximately 5 dB(A) on high-speed roads. Such a reduction could be obtained also on low-speed roads/streets but then more advanced types of porous surfaces are required, like multi-layer surfaces or the air voids content must be particularly high. Investigations consistently show that the air voids content is crucial. It should be 20-25% initially. In most cases, surfaces get clogged with time and the noise reduction is reduced down to 0 or 1 dB(A) in just a few years.

A porous surface of particular interest for noise reduction in urban areas is the "poroelastic surface", i.e. a surface made entirely of rubber and a binder which can be either polyurethane or bitumen. It could give 5-10 dB(A) of noise reduction, but so far several non-acoustical problems remain to be solved.

Special techniques are being developed in order to limit the noise on cement concrete surfaces. These rely on grinding the surface (old or new), putting a layer of small chippings on the surface (old or new) or exposing the aggregate in the (new) surface, which then must consist of only small chippings.
This paper aims at providing an up-to-date review of how tyre/road noise can be reduced by road surface design and selection. The main reasons for producing the review are, firstly, that some tyre and vehicle manufacturers tend to favour the use of low noise road surfaces in order to reduce traffic noise rather than to put further emphasis on noise emission from tyres and vehicles. Secondly, the international development in the testing of low noise road surfaces is very intense at the moment, and has been so for the last years. Therefore, within the subject of vehicle and tyre/road noise, for the last few years the focus has been on "low noise road surfaces".

This has led to a lack of an up-to-date overview of this subject, particularly taking into account the most recent developments. According to a literature search in (INFORMEX, 1991) there is no extensive review on the subject of low noise road surfaces before, even though there are more than at least 100 papers of high relevance to the subject. A brief summary could be found in (PIARC, 1987) and there are also some nationally orientated reviews, like (Kragh, 1990). Unfortunately, the latter is in Danish and thus not really useful internationally, and it is also somewhat limited in extent. A similar review was produced by this author one year ago (Sandberg, 1991-II) but many things have happened since then and the present one is updated in several parts. Consequently, it is hoped that this review can provide useful information in order to tie together the impressive work which has been reported in the past, as well as very recently, from different countries.

The review is intentionally limited, particularly in the respect that the art of detailed construction theories for porous surfaces, like absorption and propagation theories, modelling of these, influence of the exact structure of the porosities, etc, is not covered. Many researchers have concentrated on this part of the problem and to review all this work would have extended this paper considerably and beyond the current constraints.
1. HISTORICAL REMARKS

Road traffic noise has become one of the major environmental problems of this century. It is, however, a much older problem; already the old Romans were complaining over road traffic noise as their carriages were rattling over uneven pavements causing serious annoyance (Embleton, 1977). This is perhaps the earliest indication we have that tyre/road interaction really causes annoying noise. The Romans would certainly have had benefits from low noise road surfaces. However, people had more important things to worry about, and no significant measures were undertaken to reduce this noise.

Two thousand years later, in 1869, the problem seemed to be more or less the same, as noted by Sir Norman Moore, a British physician, who gave a graphic description of the noise in a London street: "Most of the streets were paved with granite sets and on them the wagons with iron-tyred wheels made a din that prevented conversation while they passed by. The roar of London by day was almost terrible - a never varying deep rumble that made a background to all other sounds" (Crocker, 1984).

An early application of "low noise" surfaces was to replace cobble stones or other paving stones with wood blocks. This made the surface less uneven and softer, both of which resulted in lower tyre/road noise. However, naturally, the advantage was won at the expense of durability and cost. Crocker writes further: "In the late nineteenth century the cobblestones in the streets of London were replaced with creosoted wood blocks or asphalt. This development occurred later in the big cities of North America so that cab and wagon noise was reduced". However, the noise abatement objective was often only secondary. See Fig. 1.

![Fig. 1 Laying of wood blocks in a street in Oslo around 1914.](image-url)
Only by the end of the 19th century, the invention in 1888 by the Irish veterinarian J.B. Dunlop of a practical air-inflated rubber tyre radically changed the tyre/road noise emission. The increased transportation work also required smoother and more even roads. In practice, this led to that tyre/road noise soon was negligible as a traffic noise component in relation to engine noise.

The increased public concern over the tremendous increase in traffic after the second world war, as well as the vehicle drivers requiring lower interior cab noise, soon forced the manufacturers to produce quieter power-trains of their vehicles. In the period 1955-1965, tyre/road noise again was observed to be of some importance, a tendency which was amplified by the ever-increasing speed of highway traffic.

Research on this matter was first initiated in the latter part of the sixties, although a handful of reports were presented also in the preceding ten-year period. The work was then often concentrated on tyre tread pattern optimizations - mainly randomization of the tread block impact period - by the tyre industry itself as well as a few investigations by acoustic consultants on behalf of environmental authorities.

The road surface development has been of great importance for tyre/road noise emission. During later decades this has mainly concerned the following four development trends:

1. With the purpose of reducing hydroplaning hazards, grooving of cement concrete surface has become common.

2. With partly the same purpose, partly for economical reasons, a change-over from smooth asphaltic surface to rough surface dressings (chip seals) has occurred on a large proportion of the road network.

3. In order to utilize a lot of advantages, not the least low noise, the interest in porous drainage asphalt surfaces has increased.

4. The observed noise and unevenness problems with cement concrete surfaces have resulted in extensive trials to find ways to improve their surface characteristics.

The first trend has essentially increased tyre/road noise emission; often resulting in frequent objections from people living close to these roads (and the drivers as well). Also the second trend has increased the noise somewhat - especially indoors - while the two last trends appear to have a considerable potential for reduced traffic noise.

The advantage in terms of noise reduction of drainage pavements was pointed out in British and American investigations already 15-20 years ago. However, there was never any breakthrough for these pavements as noise reduction measures. During the last 5 years there have been extensive investigations on this particular problem in many countries. In the years 1981-83 drainage pavements were first used as noise reduction measures in Sweden. At present, a common Nordic project deals with this subject. The recent "International Tyre/Road Noise Conference 1990" was dominated by papers on road surface design for reducing noise, which illustrates the current interest in this subject. See further (INTROC 90, 1990).
2. VEHICLE NOISE EMISSION

2.1 Noise Sources

Noise emission from a road vehicle is composed of several components. The various sources are indicated in Fig. 2. The two major components are tyre/road noise and power-train noise. It is necessary to discriminate between these since they are fundamentally different and are influenced differently by reduction methods and driving conditions.

![Diagram showing the most important noise sources of a road vehicle.]

Typically, one may say that the relation of tyre/road noise versus speed follows a logarithmic law: approx. 12 dB(A) increase in peak level per doubling of speed. Power-train noise, on the other hand, is only slightly influenced by speed. Therefore, there is a "cross-over speed" over which tyre/road noise dominates the overall noise and under which it is negligible. This speed presently lies in the range 30-50 km/h for cars and 40-70 km/h for trucks.

Since traffic work in cities is made up of traffic at speeds both above and below these "cross-over speeds", it is obvious that both power-train and tyre/road noise must be reduced in order to obtain a better environment. In highway traffic, almost no reductions of overall traffic noise are possible, unless tyre/road noise is reduced.
Currently, and with the new generation vehicles, it is being realized that tyre/road noise plays a bigger role in urban traffic noise than expected before. Measurements of full-throttle acceleration noise for new vehicles, according to present noise emission regulations, have shown that tyre/road noise may determine much of the overall noise even at acceleration on medium gears of the vehicles (Betzl, 1990 and Aahsberg, 1990).

2.2 The Shared Responsibility of Vehicle, Tyre and Road Manufacturers

Investigations at the Swedish Road and Traffic Research Institute (VTI) have shown that the spread of traffic noise levels on different road surfaces with similar traffic is as large as the spread of vehicle noise levels from separate vehicles on one surface. This applies to free-flowing traffic at a posted speed of more than 50 km/h. It is consequently as easy or as difficult to influence the overall traffic noise by choice of road surface as by selection of vehicles.

![Spread in traffic noise on different road surfaces and from individual vehicles, according to measurements at VTI 1982-88 in free-flowing traffic at about 70 km/h. Only dry, bituminous road surfaces are included. The bars indicate approx. the 5 to 95 percentiles, i.e. there are generally 5 % more extreme values at either end.](image)
Fig. 3 illustrates the above. The bars show the spread in vehicle noise from the "most silent" to the "noisiest" case (the 95-percentile is referred to) for the case that the vehicles are different but the road surface is the same (the two bars to the left), as well as the case that the vehicle composition is constant but the road surface varies (the two bars to the right). Consequently, the left two bars show how much the noise from different vehicles vary (mainly due to tyres) and the right two bars how much the noise varies when driving on different road surfaces. Thus the result is that the road surface influences the overall noise about as much as the individual vehicle.

The figure refers to free-flowing traffic at about 70 km/h, but is valid also for higher speeds. At lower speeds, or for interrupted-flow traffic, the right two bars will decrease, i.e. the effect of the road surface will be reduced. The left two bars may then increase instead and power-train noise becomes the major factor. However, wet or extreme surfaces have not been included in the figure. If wet surfaces, cement concrete or paving-stone surfaces had been included, the effect of the road surface would have increased further.

A consequence of the above is that the road building and maintenance authorities as well as vehicle and tyre manufacturers and vehicle drivers should assume the joint responsibility for reduction of traffic noise.

2.3 Tyre/Road Noise Generation Mechanisms

In order to understand the influence of road surfaces on traffic noise it is necessary to have a basic understanding of how tyre/road noise is generated. Here is a brief summary of the mechanisms considered to be significant:

1. Radial vibration mechanism
   1A. Impact of tyre tread blocks or other pattern elements on road surfaces
   1B. Impact of road surface texture on the tyre tread.

2. Air resonant mechanism
   2A. Pipe resonance
   2B. Helmholz resonance
   2C. Pocket air-pumping (this may also be a special case of 2B)

3. Adhesion mechanism
   3A. Stick/slip motions causing tangential tyre vibrations (might give excitation to 2A and/or 2B)
   3B. Rubber-to-road stick/release (adhesive effect)
In addition to this, there are some phenomena influencing the amplitude:

I. The horn effect
II. Sound absorption in the road surface
III. The mechanical impedance effect

Comments:

Tread radial vibrations are caused by small deflections in the tyre tread due to the impact and release forces, and radiate as sound after low-pass filtering in the tyre.

The pipe resonance is due to standing waves in the "air tube" in the grooves of the tyre tread. Concerning the Helmholtz resonance, the volume of air in a cavity will act as a spring resonating with the mass of air in the "throat" between the cavity and the external air. In a tyre-axle-fixed coordinate system, a cavity in the tread travels out of the road contact area and up the tyre circumference. The resonance frequency and probably also the amplification then change with the tyre revolution.

Air pumping occurs when a cavity is closed and opened and the air is compressed/expanded with such a speed as to cause great air turbulence and thus noise. The Helmholtz resonance may amplify this noise.

At the leading and trailing edges of the tyre, between the curved tyre tread fore and aft of the tyre/road interface and the road surface, there is a space forming an acoustical horn which increases the radiation efficiency backwards and forwards. This may be largely ineffective if one side of the "throat", e.g. the road surface, is porous.

The stiffness of the road surface, or the matching of mechanical impedance tyre-to-road, influences the tread block or road texture impact so that it may be amplified (stiff road) or attenuated (soft road), i.e. it influences mechanism No. 1.

Mechanism No. 1 is limited to rather low frequencies (generally below 1 kHz) while mechanisms No. 2 and 3 seldom occur below 1 kHz. Mechanisms No. 2B, 2C and 3 should be most important at the trailing edge, accentuated also by the horn effect.

Thus, the generating mechanisms encompass many interesting acoustical phenomena of a fundamental nature, but altogether form a very complicated pattern.

2.4 Road Surface Influence on Noise

In a cooperative Belgian/Swedish program, a study was made to find which parameters of the road surface influence noise generation. Parameters such as macrotexture, friction, water drainage, sound absorption and mechanical stiffness of the roads were considered. The outcome was that there was no influence by friction or water drainage on noise that could not equally well or better be attributed to the macrotexture. Sound absorption influenced the noise, but only for drainage surfaces. Mechanical stiffness could perhaps influence the noise, but to a minor extent only.
It was preferred to replace the commonly measured sand-patch texture depth by a measurement of the profile curve of the road surface. This profile curve was analyzed either by filtering it using an analogue technique or by calculating its spectral content with a digital technique to obtain a third-octave band texture spectrum. The reason is that it was found that simpler values such as the sand-patch texture depth are not sufficient to describe the road texture in this case.

Over the range of road surfaces tested, the noise levels at each acoustic frequency were correlated against the road texture levels at each texture wavelength. The best correlation between noise and road texture was obtained for certain frequencies of the noise and certain spatial frequencies or wavelengths of the macrotexture. Fig. 4a illustrates the correlation of the noise at low frequencies with the texture at long wavelengths and Fig. 4b illustrates the same relation between high frequencies of the noise and short wavelengths of the texture. The relation appears to be reverse in these two cases!

These facts imply that there is no simple and general relation between the overall noise level and texture. Rather, the overall noise level is composed of the sum of these two effects which may favour any of them depending on the exact circumstances.

Fig. 4 Illustration of how noise and texture are related for the two most pronounced cases:

a. Noise at a low frequency (approx. 400 Hz) versus texture at a long wavelength (approx. 80 mm).

b. Noise at a high frequency (approx. 3000 Hz) versus texture at a short wavelength (approx. 2-3 mm).
The correlation between noise and texture for all noise frequencies and all texture wavelengths is illustrated in a joint Belgian/Swedish study (Sandberg and Descornet, 1989). It was concluded that there are (at least) two major generation mechanisms which are uncorrelated with each other; one in the low-frequency range (below 1 000 Hz) with a positive correlation with road macrotexture and another in the high-frequency range (above 1 000 Hz) with a negative correlation with macrotexture.

The low frequency mechanism is No. 1 and the high frequency mechanism No. 2 and/or No. 3 described in section 2.3.

3. CORRECTIONS FOR ROAD SURFACES IN NOISE PREDICTION MODELS

It has been recognized for a long time that road surfaces influence road traffic noise. Consequently, when noise prediction schemes are used, it is desirable to include a road surface correction to the basic noise emission values in order that the noise predictions be as accurate as possible.

This principle is employed in, for example, the prediction methods used in the U.K. (DoT, 1988) and in Germany (RLS-90, 1990). The U.K. method utilizes a correction according to this:

"For roads which are impervious to surface water and where the traffic speed (V) used in Chart 4 is \( \geq 75 \) km/h the following correction to the basic noise level is required;

- for concrete surfaces
  
  \[ \text{Correction} = 10 \log (90 \, \text{TD} + 30) - 20 \, \text{dB(A)}; \]

- for bituminous surfaces
  
  \[ \text{Correction} = 10 \log (20 \, \text{TD} + 60) - 20 \, \text{dB(A)}; \]

where TD is the texture depth measured by the sand-patch test.

For road surfaces and traffic conditions which do not conform to these requirements a separate correction to the basic noise level is required.

**Impervious road surfaces**

For impervious bituminous and concrete road surfaces, 1 dB(A) should be subtracted from the basic noise level when the traffic speed (V) used in Chart 4 is \(< 75\) km/h.

**Pervious road surfaces**

Roads surfaced with pervious macadams have different acoustic properties from the surfaces described above. For roads surfaced with these materials 3.5 dB(A) should be subtracted from the basic noise level for all traffic speeds."
The German model has another construction of the correction; see Fig. 5.

### Tabelle 4: Korrektur $D_{\text{StrO}}$ für unterschiedliche Straßenoberflächen

<table>
<thead>
<tr>
<th>Straßenoberfläche</th>
<th>$D_{\text{StrO}}$ *) in dB(A) bei zulässiger Höchstgeschwindigkeit von</th>
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<tr>
<td></td>
<td>30 km/h</td>
</tr>
<tr>
<td>1.</td>
<td></td>
</tr>
<tr>
<td>nicht geriffelte Gußasphalte, Asphaltbetone oder Splittmastixasphalte</td>
<td>0</td>
</tr>
<tr>
<td>2.</td>
<td></td>
</tr>
<tr>
<td>Beton oder geriffelte Gußasphalte</td>
<td>1,0</td>
</tr>
<tr>
<td>3.</td>
<td></td>
</tr>
<tr>
<td>Pflaster mit ebener Oberfläche (Bild 1)</td>
<td>2,0</td>
</tr>
<tr>
<td>4.</td>
<td></td>
</tr>
<tr>
<td>sonstiges Pflaster (Bild 1)</td>
<td>3,0</td>
</tr>
</tbody>
</table>

*) Für lärmmindernde Straßenoberflächen, bei denen aufgrund neuer bau technischer Entwicklungen eine dauerhafte Lärmminderung nachgewiesen ist, können auch andere Korrekturwerte $D_{\text{StrO}}$ berücksichtigt werden, z. B. für offenporige Asphalte bei zulässigen Geschwindigkeiten $> 60$ km/h - 3 dB(A).

**Fig. 5** The German correction for road surface influence on traffic noise (RLS-90, 1990). Translation of the text to the left:

1. Non-grooved mastic asphalt, asphalt concrete or split mastic asphalt
2. Cement concrete or grooved mastic asphalt
3. Block surface, even
4. Other block surface.

The footnote is translated:

For low noise road surfaces, for which on the basis of new developments in construction a long-lasting reduction is obtained, also other corrections $D_{\text{StrO}}$ can be observed, e. g. for open-porous asphalt at posted speeds $>60$ km/h - 3 dB(A).

These are just examples, however from two of the major prediction methods, illustrating that there is no consensus regarding how road surfaces are classified with respect to noise emission.

This therefore identifies an important subject for research, investigation and European standardization. See further the chapter about measurement methods.
4. MEANS OF NOISE CONTROL BY AUTHORITIES

Environmental and traffic authorities may control noise in urban areas by using four main principles:

1. By controlling traffic.
2. By specifying a certain design of roads/streets, buildings, barriers, etc, as well as the location of such structures (design strategy).
3. By specifying limiting values in terms of noise level(s) which must not be exceeded at a certain time or location (performance strategy).
4. By encouraging the use of "low-noise devices" by providing certain advantages to the constructor, supplier or user (encouragement strategy).

It has appeared that, for free-flowing traffic, the type of road surfacing influences the traffic noise as much as the individual vehicles do (within each vehicle class) as was described in Chapter 2.2. It implies that it is equally efficient to encourage the use of quiet road surfaces as the use of quiet vehicles or quiet tyres. In those urban areas where the traffic is not free-flowing the effect of surfacings is less but it is rarely completely unimportant. The following, therefore, focuses the noise control on road surface selection.

The first approach to noise control as stated above has no relevance to road surface design or use.

The second approach can be used, for example, to limit or exclude the use of "noisy" road surfaces in disturbed areas. It is not uncommon that block pavements are replaced by other pavements in towns and cities, for example. In some cases, authorities may also exclude the use of transversely grooved cement concrete or rough-textured chip seals in such areas.

It may also be required that a porous surface be used. This has been decided in the Netherlands where all the state road network (for roads with a traffic intensity above a certain threshold) is to be surfaced with porous asphalt when re-surfacing is necessary. This is indeed a very ambitious program!

Another possibility which may be implemented very soon is to require that cement concrete surfacings in noise sensitive areas are provided with surface treatments which reduce noise, e.g. longitudinal grinding, surface dressings with optimum chipping sizes or exposed aggregate with suitable chippings (Sommer, 1992-I).

The third approach is indirectly related to road surface selection, since it may be easier to comply with certain noise limits when using a low noise surface. The use of a low noise surface may also relax the requirements for other noise control measures, e.g. the complexity and cost of a noise screen could perhaps be reduced if it is combined with a low noise road surface.

The fourth approach is applied in certain cases today regarding vehicles. Special "low noise vehicles" may get a certain tax relief, or they may be allowed (alone) to travel in certain areas at certain times. The latter is employed in Austria where there is a ban for night-time heavy traffic on some transit roads, with the exception for trucks which emit max.
80 dB(A) during type approval. Some countries define "low-pollution" vehicles which may be required in certain areas or be given other advantages. The European Commission has recently addressed the possibility of tax incentives for vehicle noise control (EC, 1991).

Even though this principle is not yet utilized for roads, one could consider to give an economical advantage to the road administrative organization or road constructor which makes use of some low noise road surface.

In a recent document from the European Commission (EC, 1991) it is stated that "Subsequent measures intended, in particular, to limit the noise arising from contact between tyres and the road surface shall be decided upon before 1 October 1995 by the Council". It is therefore not unlikely that the actions to be taken by the end of this decade will also require some measure or recommendations against "noisy" road surfaces.

One problem is common to the approaches above (except traffic control) and that is how the noise classification of road surfaces shall be made. This problem is addressed later in this paper and it shall be mentioned here that the practical implementation of road surface selection is more or less based on the assumption that there is an accepted way of measuring the influence on noise of road surfaces.

5. MEASUREMENT STANDARDS AND REGULATIONS

5.1 Introduction

Standardized methods to measure noise from different types of vehicles exist today (specified for instance within the ISO, the ECE and the EC). This is justified since different vehicles can be designed for different noise levels and these methods enable the desired control of vehicle noise. Similarly, it has been proposed to impose regulations on noise emission from tyres and proper measurement methods are already suggested (ECE, 1990). A recent document from the European Commission (EC, 1991) suggests future limitations of tyre/road noise. International methods to measure traffic noise, corresponding to those used for vehicle regulations, do not exist, nor are there methods to separately measure the influence of the road surface on traffic noise.

Therefore, it has been realized that a new measuring method for classification of road surfaces ought to be developed. This method should allow comparable and reproducible measurements of the effect of different road surfaces on traffic noise. It would then supplement existing methods which allow the measurement and comparison of noise emission from different vehicles and also supplement the suggested method(s) for classifying tyres.

A working group with the task of developing such a method was established at the beginning of 1991 within the International Organization for Standardization (ISO). The group is named ISO/TC 43/SC 1/WG 33 and is convened by this author.
With the intensified European co-operation and commercial exchange it is important that classification of road surfaces from the point of view of noise is uniform so that a surface which is proven to be good in one country also can be accepted in another country (of course, considering also climatic influences). Results of measurements should be comparable from time to time, from place to place and from country to country.

5.2 Main Types of Measuring Methods

The following main types of methods suitable for measuring tyre/road or traffic noise with respect to road surfaces have been used:

1. The coast-by method
2. The trailer method
3. The laboratory drum method
4. The on-board microphone method (variant of the trailer method)
5. The drive-by method (variant of the coast-by method)
6. The controlled pass-by method
7. The propagation or sound absorption methods
8. The statistical pass-by method

In the coast-by method, a test vehicle presumably equipped with some test tyres is rolling (coasting-by) with the engine switched-off past a road-side located microphone. The microphone is 7.5 m from the center of the test or road track on which the vehicle coasts. The peak noise level is recorded when the vehicle coasts by, usually with the FAST time constant.

The method is often used to classify the road surface influence on noise, but it has some disadvantages:

- It is impractical and sometimes even impossible to use on motorways
- It requires special test vehicles and, furthermore, a low traffic intensity in order not to be disturbed by noise emitted by the traffic
- It requires some sets of reference tyres which can always be used on all road surfaces

The trailer method requires fewer reference tyres and is not very sensitive to noise from traffic. The test tyre is mounted on a trailer which is towed by a vehicle. Close to the test tyre, generally within 0.1-0.5 m, one or more microphones are located. The noise level is measured as an average over a certain time interval, generally 4-60 s. Most trailers have an enclosure around the microphone and test tyre in order to provide screening from wind and traffic noise. Some trailers may utilize more than one test tyre.

The method has the advantages of being fast, simple, precise, requires relaxed demands on the topography and areas close to the road, and is nearly independent of surrounding traffic. It has, nevertheless, some disadvantages:
- It measures only tyre/road noise. Traffic noise must be estimated from this.

- It underestimates the noise reduction of porous road surfaces since it measures close to a test tyre and so does not consider the noise absorption of these surfaces over longer distances.

- It requires reference tyres.

- It requires a special trailer.

The main questions are what reference tyres are to be chosen (this is likely to be a controversial issue), how typical and longlived these are, and how the disadvantage of not considering the sound propagation effect of porous road surfaces is to be compensated.

The disadvantages have, however, not prevented some researchers to use this method also to measure on porous road surfaces.

The laboratory drum method can be excluded for road surface classification since it is impossible to test actual road surfaces on a drum surface. This is a sheer laboratory method and there is yet no generally available equipment that admits samples from road surfaces to be mounted into or onto a drum without presenting unacceptable problems.

The on-board microphone method is somewhat similar to the trailer method. The main difference is that one of the tyres of the test vehicle is used as the test tyre and the microphone/tyre are never screened.

The method's only advantage compared to the trailer method is that no trailer is needed, but it has a whole range of additional disadvantages, which makes further consideration superfluous; for example it is sensitive to disturbances from surrounding traffic and very sensitive to air turbulence noise in the microphone.

The drive-by method, which is measuring tyre/road noise (or vehicle noise) from an accelerating vehicle, is difficult and impractical. Often, uniform testing is made according to the ISO 362 or ISO 7188 procedures. It is irrelevant here, since in those cases where the properties of the road surfaces are important, the traffic probably flows freely without much acceleration, which makes this method unrepresentative in this context.

The controlled passby-method is a variant of the coast-by and drive-by methods. Like in the coast-by method there is a microphone at 7.5 m from the center of the tested road lane, but the vehicles are passing the microphone at constant speed with the engine switched on. Therefore, in this case the vehicles must be "standardized" or at least of a well-defined and constantly available type and they must always be in the same condition. As in the coast-by and trailer methods, reference tyres must be selected. This method has been preferred in an extensive French-German co-operation project.
The sound propagation or sound absorption method is used to study only a part of the problem: the sound propagation from source to receiver, i.e. the immission. Either samples of the road surface are mounted at the end of a tube (Kundt’s tube) and the sound absorption coefficient measured, or a loudspeaker emits a "reference" noise which is picked up by a microphone at some distance (generally the same source-receiver configuration as in the coast-by method). By doing the latter on different surfaces, their relative influence on propagation can be studied. The method is useful in this context to study porous asphalt coatings but it cannot alone provide the desired information about the noise properties of road surfaces in general since their influence on the emission is not being considered with this method.

The statistical pass-by method has been used in different forms during more than a decade and is the method with the closest resemblance to a real traffic situation. The procedure is that one or several microphones are mounted by the roadside (usually 7.5 or 10 m, and not more than 15 m from the road) and the sound levels and/or noise spectra from the passing traffic are measured during a time period long enough to let a large number of vehicles pass by so that an average for "typical" and "normal" traffic is obtained.

Normally, also the speeds of the vehicles are measured and the number of vehicles of various types are registered. If the mean speed and/or the vehicle composition deviates from a "normal value", corrections are made so that the obtained values be comparable.

Either the equivalent sound level from all the traffic is measured (often the whole distributive or cumulative sound level distribution is measured at the same time), or else the peak levels from separate passing vehicles, or both, are measured. Frequency spectra may also be measured.

The advantages are:

- The method measures actual traffic noise and can distinguish between light and heavy vehicles
- The procedure is relatively fast and requires only two persons to conduct the measurements
- Reference tyres or special test vehicles are not required
- The method is already utilized in various forms in a number of countries

The disadvantage is:

- The obtained noise levels apply to the vehicle mix that passes precisely while the measurement is being made. By measuring a sufficient number of vehicles, an accurate average can be obtained. However, over time periods of several years, the noise emission can change due to new types of vehicles and tyres.
5.3 Future standardization

ISO/TC 43/SC 1/WG 33 has made a preliminary systematic evaluation of the methods which resulted in four major candidate methods being identified:

* The statistical pass-by method
* The controlled pass-by method
* The trailer method
* The trailer method supplemented with sound absorption measurement

Furthermore, the conclusion of this preliminary evaluation was that the statistical pass-by method appeared to be the best one on an overall basis with the trailer method as second. Further work now mainly concerns how to specify the details of the statistical pass-by method and to continue to evaluate the trailer method (in case it could become an alternative method). The work is targeted to be finished in 1994 with a possibility of a final standard becoming approved in 1996.

At the time of printing, ISO is preparing for voting among the member bodies regarding a proposal for a new work item: To develop a method for measuring road surface sound absorption on-site. Since ISO/TC 43/SC 1 has tentatively approved this, it is likely that this work will start in 1992-93. Such a method will have significant influence on the work with development and testing of low noise road surfaces which exhibit sound absorption.

5.4 Regulations or guidelines

There is not yet any regulation known to the author regarding the use of road surfaces with respect to noise reduction. Such regulation must be based either on a "design strategy" or a "performance strategy". The former gives no incentive for improvements, so the latter should be preferred. However, it is impossible to apply the "performance strategy" until the measurement problem is solved.

There may be guidelines issued by authorities to avoid "noisy" surfaces in certain countries but the author is not able to pin-point any specific reference.
6. ASSESSMENT OF POROUS SURFACES

6.1 Terminology

Road surfaces which have a porosity allowing water to flow vertically through them have been given many names, for example:

- Drainage asphalt
- Drainage surfaces
- Porous surfaces (or asphalt)
- Pervious surfaces (or asphalt)
- Pervious macadam
- Open-graded asphalt
- Open-graded friction mix
- Porous friction mix
- Open-textured asphalt
- etc (the author could mention at least twice as many)

This author thinks that the most relevant terms would be "porous surfaces" or "pervious surfaces". "Asphalt" or "cement concrete" could replace the word "surfaces" if that distinction is necessary. Porous surfaces evidently possess a significant porosity, i.e. air voids. However, at least in principle, this does not always make them pervious. Pervious means that water and air can flow through the surface, i.e. that the pores are open, and should be the characteristic that determines the acoustical properties. However, usually the pervious and porous characteristics are well correlated.

In this paper, the term porous is used consistently, even though it is recognized that pervious may be a more relevant term. This is because the term porous seems to be more commonly used than pervious, although people very often mean pervious when they speak about porous.

6.2 Construction

In a conventional asphalt concrete wearing course, the mix that is laid on the road is composed of:

- Stones or "chippings" of max. sizes 2-16 mm (bigger ones may occur but are rarely used due to the rough texture caused by them). Typically the weight fraction of the stones lies in the range 40-55 % (by total weight of the mix).

- Sand of grain sizes 0.06-2 mm. The weight fraction of sand is usually in the range of 35-45 %.

- Filler, a very fine sand with grain sizes < 0.06 mm. This weight fraction may be around 5-10 %.

- Binder, i.e. bitumen ("asphalt") or corresponding. Typical binder fractions are around 4-8 % by weight.
Thus, an "asphalt" road surface is mainly made up of stones and sand and the real "asphalt" is often not more than 6 % of the total weight.

The "concrete" that is created by this mix is bound together by the binder to which it is nowadays common to add polymers, rubber powder, fibers, etc. The intention with this mix is to combine strength with high compaction. Typically, the air voids in the mix will be around 3-5 % by volume, and these voids are mostly not interconnected.

The mix of stones, sand and filler is proportioned according to "grading curves" like the ones in Fig. 6 which describe the fraction of stones or sand passing a certain sieve size.

When the binder is cement instead of bitumen, one speaks of a "cement concrete" surface, commonly called just "concrete". The latter is not a recommended term here since "concrete" technically refers just to a certain mix which could be bound by any binder, including asphalt. Cement concrete surfaces have slightly different proportions of the ingredients above as compared to the asphalt concrete surfaces.

![Grading curves for conventional asphalt concrete and porous asphalt concrete](image)

**Fig. 6** The grading curves for conventional asphalt concrete with max. stone size 12 mm (broken lines show the upper and lower tolerances) and for a porous asphalt concrete, "Drainage Asphalt" (solid lines show the upper and lower tolerances). Note: This figure refers to the Swedish standard (BYA, 1984). Other countries may have slightly different standards.
To get a porous mix, the proportions of stones, sand and filler are changed radically, in the direction that the "medium sized" fractions are reduced (in the case of Fig. 6: sizes approx. 1-4 mm). This will result in the air voids increasing radically, i.e. a porosity is created between the dominating bigger stones. Typically one aims at a porosity in the range of 15-20 % by volume, although even higher porosities are desired from the drainage point of view. However, it is always a balance between strength and drainage. The porous surface according to Fig. 6 will have an initial air voids content of 15-25 %.

In the following, the term "semi-porous" is used for surfaces which have an air voids content around 10-15 %.

6.3 Acoustical Reduction Properties

The porous surface obtains three major properties of importance to vehicle noise reduction:

1. Its porosity will eliminate the compression and expansion of air entrapped in the tyre/road interface when tyres are rolling over the surface. "Air pumping and air resonant tyre noise" will then be reduced (mechanism No. 2 in Chapter 2.3).

2. Its porosity will also reduce the amplifying effect of the acoustical horn existing in the space between the curved tyre tread and the plane road surface (the phenomenon No. 1 in Chapter 2.3).

3. Finally, the porosity will give the surface an acoustical absorption, which will influence the reflection and propagation of the noise. This will influence not only tyre/road noise but also other types of vehicle noise (phenomenon No. II in Chapter 2.3).

Several investigations have penetrated the theoretical effects of porous surface design parameters on noise reduction. Characteristics like porosity, thickness, flow resistance, shape factor and tortuosity have been considered. The reader is referred to papers by Hammet, Attenborough, Berengier, Storeheier and von Meier in (INTROC 90, 1990) if further information is required. However, in this paper only a brief summary of the parameters which can most easily be influenced by the road constructor are reviewed.

6.4 The Importance of Air Voids

As mentioned earlier, it has been desired to obtain an air voids content of 15-20 %, preferably even higher. An air voids content of 15-20 % is supposed to correspond to sound absorption around 0.20-0.30. However, recently, it has been shown that a sound absorption coefficient in the range 0.10-0.20 also affects the noise; see Fig. 7 which is based on data collected in a round robin test conducted by the working group ISO/TC 43/SC 1/WG 27 which has produced a proposal for a low noise test track surface with negligible sound absorption (Sandberg, 1991).

For higher air voids contents, the next two figures could supply interesting data. In order to achieve a noise reduction of about 3-5 dB(A), 20-25 % voids are obviously required.
The relation between noise level (tyre/road noise and noise from accelerating vehicles, respectively) and sound absorption coefficient. Data averaged for 5 vehicle/tyre combinations, measured at 7.5 m from the centre of lane.

Traffic noise reduction as a function of air voids content. Measured at the roadside for roads/streets in the Oslo area with posted speeds 50 km/h and mixed traffic (Storeheier & Arnevik, 1990).
6.5 Thickness of the Layer

Already in Fig. 9 it is indicated that the thickness of a porous surface has a positive influence on noise reduction. Generally, the effect of thickness is to displace the frequency at which sound absorption is maximum to lower values. At the same time the absorption versus frequency dependence is smoothed out from a very "peaky" curve at small thickness (30 mm) to a much smoother curve at big thickness (600 mm). See e.g. (Hamet, Berengier and Jacques, 1990). In most cases this will increase noise reduction since the fit between the sound absorption frequency spectra and that of the emitted noise coincides better then.

Several of the papers in (INTROC 90, 1990) show thickness influence on noise reduction. For example, (Storeheier and Arnevik, 1990) shows that the effect in an urban area of using a double layer of porous surface instead of a single one (80 instead of 50 mm) is one additional dB(A) of traffic noise reduction. The two layers had the same max. chipping size but the voids content were different, i.e. higher in the top layer.

Some further information on this subject can be found below in 6.8.2. (the Netherlands).
Some researchers have also experimented with super-thick porous structures; in some cases up to 700 mm. Preliminary results indicate a total noise reduction of approx. 8 dB(A), instead of 4 dB(A) for thin layers, in relation to conventional, dense asphalt concrete (Pipien & Bar, 1991). Recently (Stenschke, 1990) reported that a 500 mm thick structure reduced vehicle noise at coast-by and pass-by by 6-11 dB(A) depending on binder type and driving condition and 5-7 dB(A) for a stationary car. The latter indicates the big potential for improvement due to the third effect as stated in Chapter 6.3, i.e. sound propagation.

6.6 Influence of the Binder

Binders like pure bitumen, cement, “plastic”, bitumen added with fibers and bitumen added with rubber powder have been tried. Regarding cement as a binder, see 6.7 below. See also 7.8 below, regarding rubber added to the binder.

In those cases where a direct comparison have been possible between the binder effects, no influence on noise has been demonstrated. For example, this author has tried surfaces with and without 8 % of the binder being rubber powder and found no significant difference. Measurements on a commercial surface in Sweden including fibers have not indicated any increased noise reduction in relation to one with pure bitumen binder.

Results presented in (Stenschke, 1990) showed that for a 500 mm thick structure a cement binder gave approx. the same noise reduction as when using a bitumen binder. However, a "plastic" binder gave approx. one additional dB(A) of reduction. It is not clear how the plastic binder could improve the noise reduction of the surface.

However, when investigating the effect of the binder, it is important to consider also long-term effects. The binder could have some influence on how fast a surface gets clogged with dirt and thus have an indirect but rather important effect on traffic noise.

Another indirect effect of the binder is that certain binders may make it possible to design the surface texture and the porous structure in a way which is favourable to noise, i.e. the binder changes the texture which changes the noise.

6.7 Noise Reduction of Porous Cement Concrete

According to (von Meier, 1988), cement shows promising properties as a binder since the internal porosity structure may be favourably altered. However, later field tests with porous cement concrete have not yet been fully successful since such surfaces have become uneven and thus uncomfortable to drive on. More research is needed and there is even a special international working group (PIARC) on porous cement concrete. It is premature to draw final conclusions since there is not yet any experience on heavily trafficked roads, but the following is a summary of the current state-of-the-art.

Trials in the Netherlands with porous cement concrete have shown that such a surface can, in principle, obtain approximately the same noise reduction as a porous asphalt concrete (Onstenk, 1992). It is stated that "to obtain equal noise absorption characteristics the accessible porosity of porous concrete needs to be at least 25 volume % For motorways the thickness of the porous concrete layer needs to be about 40 mm. In order to avoid unfavora-
ble megatexture the maximum grain size of the aggregate of porous concrete should be about 10 mm". The problem is the latter hint regarding megatexture.

Evidently, megatexture (texture at wavelengths of 50-500 mm) has become too rough on cement concrete of this type in these early tests, which makes it uncomfortable to drive on such a surface. This author speculates that the reason may be that a cement concrete surface cannot be rolled in the way that an asphalt surface can be rolled at laying, in order to make the surface even. The rolling has the effect that the chippings will align themselves in such a way as to obtain the smoothest possible top profile and the vibrator substitutes which are used for cement concrete do not provide for the same efficient chipping alignment.

In France, for urban applications, a thickness of 150 to 400 mm is used in order to extend noise absorption down to low frequencies (Sommer, 1992-1).

In Japan, the area of porous cement concrete now exceeds 600 000 m². However, only side-walks and other public areas than roads have been surfaced in this way, so far. Trials are now being made to apply the technique also to roads (Matsuno, 1992).

6.8 Noise Reduction of New and Old Porous Asphalt Surfaces

6.8.1 Reference Surface for Comparisons

Some recorded noise reductions have already been mentioned. The word "reduction" directly implies a comparison, i.e. a noise reduction value of a road surface is always referred to a reference road surface. A problem with all "noise reductions" reported by various authors is that the reference surface often is different. Few results are therefore really comparable. Mostly, however, the authors refer to a conventional asphalt concrete of the dense type. Not even this is perfect, because a new surface of this type is quieter than an older surface. Also the chipping sizes may be rather different and thus influence noise.

This author suggests that the reference surface for estimating "noise reduction" be a:

Dense asphalt concrete essentially complying with the grading curves in Fig. 6 (broken lines). It means that the max. chipping size should be 10-13 mm. It should be at least one year old.

The essential advantages are that this type of surface

a) often represents the most common type in urban areas
b) in most cases is the closest "relative" to the most commonly used porous surfaces.

There are numerous studies of noise reduction of porous asphalt which have been conducted over the latest 20 years. The following presents some selected results from various countries. The review is far from complete; it just serves as an illustration of interesting features and trends.
6.8.2 Experimental Results

Sweden

The following table summarizes a 4-year experiment in Sweden with porous asphalt with maximum 12 mm chipping size (20-30 % initial voids content) with three different thicknesses, corresponding to 50, 80 and 110 kg/m². The total life-time before re-surfacing was approximately 5 years. Results for equivalent 2 hour average levels as well as peak pass-by levels (average peak levels for all vehicles) are presented. Measurements were made 10 m from the road centre. Speeds were constant in the range 60-100 km/h.

Table 1. Noise reduction relative to an old conventional dense asphalt.

<table>
<thead>
<tr>
<th>AGE OF SURFACE</th>
<th>NOISE REDUCTION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In $L_{eq}$</td>
</tr>
<tr>
<td>0 years</td>
<td>5-7 dB(A)</td>
</tr>
<tr>
<td>2 years</td>
<td>4-5 dB(A)</td>
</tr>
<tr>
<td>4 years</td>
<td>1-2 dB(A)</td>
</tr>
</tbody>
</table>

It can be noticed from the table that:

- The reduction in noise decreases with age
- The average reduction is around 3 dB(A)
- A bigger reduction is obtained for the equivalent levels than the peak pass-by levels. It can be explained by an extra reduction due to sound propagation over a "semi-absorbent" road surface at long distances.

Furthermore, it should be pointed out that:

- If the common reference would have been a dense asphalt surface of equal age as the porous surfaces, then the noise reduction value for the new surfaces would have been reduced by 2 dB(A), since this is approximately the difference between a new and old dense asphalt concrete.
- The reduction for trucks is approx. the same as for cars.
- Increased thickness was advantageous when the surfaces were new, but of little importance later.
- It has been noticed in other studies that the voids content should be as high as is possible with respect to durability. At least 20 % is required initially.

Fig. 10 shows how frequency spectra are influenced typically.
The decrease of noise reduction with age may be a typical winter climate effect. Such impaired efficiency has not been noticed in for example Denmark, England (Nelson and Abbot 1990) and Hong Kong (Chan, 1990). There are reasons to believe that the efficiency of drainage asphalt can be better maintained in countries in southern Europe.

The previous data concerned free-flowing traffic on roads. How is the situation at interrupted-flow on streets where tyre/road noise is much less important? According to for example (Sandberg, 1984), drainage asphalt reduces also power-train noise. The reduction is around 3 dB(A) for new surfaces in relation to a totally reflecting surface; a value which has been confirmed by several later studies.

![Normalized Traffic Noise Spectra](image)

**Fig. 10** Frequency spectra (peak pass-by) for traffic noise of light and heavy vehicles travelling at 80-90 and 70-80 km/h, respectively, on an old, smooth, dense asphalt and a new porous asphalt surface.

This leads to the prediction that in urban traffic a reduction of at least 3 dB(A) could be obtained on new porous surfaces. Studies regarding the application of porous asphalt in urban areas is underway, e.g. extensive programs are going on in Norway and Germany; see further below.

Results from some other countries follow.

**Norway**

(Storeheier & Arnevik, 1990) reports a noise reduction of traffic noise in urban areas with 50 km/h posted speed with mainly free flowing traffic of:
o 1.5 dB(A) for 50 mm surfaces with 17-19 % voids
o 3.5 dB(A) for 50 mm surfaces with 21-22% voids
o 4.5 dB(A) for 2-layer surfaces (42+38 mm)

The values above concern new surfaces. After one year the noise levels had increased by 1.5 dB(A) in the first case and 2.6 dB(A) in the second case. Therefore, the remaining noise reduction is only 1 dB(A) in the second case (0 dB(A) in the first case). Then it should be observed that the reference surfaces were all the time a mix of new and old surfaces and it is possible that the new surfaces (being less noisy than the old ones) have biased the comparison by approximately 1 dB(A), so that a fair comparison probably would indicate 2 and 1 dB(A) reduction, respectively.

Trials with cleaning are reported in 6.12.

**Denmark**

Most investigations show that the noise reduction of porous asphalt decreases with time. An exception is the investigation of (Kragh and Jessen, 1991) where there was a slight improvement in noise reduction in relation to a dense reference asphalt during the first year of operation. The test surfaces were laid on a highway with mixed traffic running at approx. 80 km/h. See Table 2.

**Table 2** Noise reduction of porous asphalt surfaces in relation to a dense reference surface. Values processed from (Kragh and Jessen, 1991).

<table>
<thead>
<tr>
<th>Type of surface</th>
<th>$L_{Aeq}$ rel. to reference, in dBA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>New condition</td>
</tr>
<tr>
<td>Porous asphalt max. 8 mm, voids 18-22%</td>
<td>4.0 dB(A)</td>
</tr>
<tr>
<td>Porous asphalt max. 8 mm, voids &gt;22%</td>
<td>3.6 dB(A)</td>
</tr>
<tr>
<td>Porous asphalt max. 12 mm, voids &gt;22%</td>
<td>2.0 dB(A)</td>
</tr>
<tr>
<td>Dense asphalt max. 12 mm, (reference)</td>
<td>0.4 dB(A)</td>
</tr>
</tbody>
</table>
Another recent investigation showed that a newly laid porous asphalt (max. 8 mm) in a city street in Copenhagen (50 km/h, 10 % heavy vehicles) gave a noise reduction of 4 dB(A) in relation to a new, dense asphalt surface (Petersen and Kragh, 1991). It should be a little more in relation to an old surface. Other measurements, with one car and one truck, showed that the reduction in terms of L_Aeq was only slightly smaller at 20 km/h than at 60 km/h. The rather high noise reduction may be caused by the surrounding buildings making this site a multi-reflective environment in which case a sound absorbing surface should be extra effective.

Germany

The following table which comes from (Steven, 1990) summarizes some German results. See also 6.12 and 6.14 regarding other experiences with porous surfaces in Germany.

Table 3 Reduction of car pass-by noise-levels (7.5 m) on different German surfaces (DA=Drainage asphalt; AB 0/11=dense asphalt, 0-11 mm stones). The speed probably was 30-60 km/h in the residential areas and 60-120 km/h on the country roads

<table>
<thead>
<tr>
<th></th>
<th>number of test sites</th>
<th>surface</th>
<th>percentage of max. shipping size</th>
<th>difference of pass-by levels between DA and AB 0/11 in dB(A)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>min.</td>
</tr>
<tr>
<td>residential roads</td>
<td>3</td>
<td>DA 0/11</td>
<td>40-70</td>
<td>+0,5</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>DA 0/8</td>
<td>67-92</td>
<td>-1,0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>DA 0/5</td>
<td>100</td>
<td>-3,0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DA 0/3</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>country roads</td>
<td>6</td>
<td>DA 0/14</td>
<td>41</td>
<td>+0,7</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Belgium</td>
<td>64-70</td>
<td>-0,7</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>DA 0/11</td>
<td>50-60</td>
<td>-0,8</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>DA 0/8</td>
<td>70-95</td>
<td>-3,0</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>DA 0/8</td>
<td>50-60</td>
<td>-2,9</td>
</tr>
</tbody>
</table>
France

Fig. 11 summarizes some French results (Pipien & Bar, 1990) reported at the recent tyre/road noise conference.

In addition, tests with drainage asphalt in actual city streets have been conducted in Paris. The result was a reduction of 1-5 dB(A) depending on the proportion of heavy vehicles and the test site (Delanne and Lebret, 1988). These results are in line with those reported for Denmark above.

The Netherlands

In the Netherlands, a so-called TWIN-lay surface has been tried very recently (von Meier, 1991). It consists of:

- a top layer of (max.) 4-8 mm chippings, 25 mm thick
- a bottom layer of (max.) 11-16 mm chippings, 45 mm thick
The air voids content was 26% initially. Measurements with the statistical pass-by method have shown that the noise reduction was 4 dB(A) at 60 km/h and 5 dB(A) at 120 km/h for both cars and light trucks. The reference was another newly laid surface, but of "standard" dense construction.

Measurements in city traffic in the town of Breda have confirmed these results. 0.5 dB(A) higher reduction than stated above was achieved, but then the reference was a mix of dense, mostly aged, asphalt surfaces. The average speed was approx. 50 km/h (von Meier, 1992).

It is interesting to note that the binder includes rubber granulate 0.15-1.0 mm. Approximately 1 kg/m² of rubber is applied which amounts to somewhat more than 16% of the binder weight. However, there are no ways to determine how much of the noise reduction effect which is due to the rubber granulate, if any. See further Chapter 7.8 below.

United Kingdom

The noise reduction of porous surfaces has been monitored in the U.K. for several years; in fact longer than anywhere else. The most recent data (Nelson, 1992) indicate the following long-term behaviour in relation to non-porous surfaces:

- The first year of operation, the reduction was 3-6 dB(A) with the higher reductions for light and lower for heavy vehicles.
- During the next 4 years, the reduction was quite stable at approx. 4 dB(A).
- At the age of 5-6 years, the reduction has finally decreased somewhat to 3 dB(A).
- In recent years, the effect is equally good for heavy as for light vehicles.

These results are very encouraging since they suggest that the "acoustical lifetime" may be several years, at least in certain conditions.

6.9 Poroelastic Surfaces

A road surface composed of rubber granulate made of used tyres and bound by polyurethane has been tested in Sweden and Norway (Zetterling and Nilsson, 1990) and (Storch, and Arnevik, 1990). It reduces vehicle and traffic noise by 5-10 dB(A) in relation to a conventional, dense asphalt surface. However, problems with wet friction, inflammability and adhesion to the base have resulted in trials being interrupted after 2-4 months. It is also expensive but it could, nevertheless, be motivated in many cases as an alternative to noise screens, provided the mentioned problems can be solved. There are many problems with screens which can be avoided if a poroelastic surface could be used instead. Research and development regarding this surface will continue in Sweden in 1992.

Since a poroelastic surface has not yet been tried over a long period of time, it is not possible to say that it is a durable surface. However, it has the potential of being long-lasting in at least two respects:
1. It is resistant to wear from studded tyres, since the rubber is resilient to the stud impacts.

2. Due to its resilient properties, it is likely that clogging may be a smaller problem than on conventional porous surfaces. The dirt which accumulates will probably never get stuck in the porosities, since the rubber layer is all the time moving when a tyre rolls over it.

Therefore, if other porous surfaces fail to have a long-lasting noise reduction effect in urban areas with low-speed traffic, the poroelastic surface may well be the only effective alternative, provided its major problems can be solved.

6.10 Porous Surfaces on Sidewalks and Parking Areas

In large urban areas, a big proportion of the total ground area is covered by non-pervious materials such as dense asphalt and concrete. This is, of course, a big problem for water run-off and capacity during rain storms but it is also a big problem for the general water balance in the urban area. A solution to this problem is to use porous instead of dense pavements whenever possible.

Generally, there are less durability and wear problems on sidewalks and parking areas than on streets and it is then easier to apply porous asphalt on such surfaces. This is used to a considerable extent in Tokyo (Bendtsen, 1988). Also, porous cement concrete surfaces are largely used in Japan in such areas (Matsuno, 1992). Although these Japanese surfaces are not intended for noise reduction, and not tested for noise (?), they should have a measurable effect on noise. An acoustically absorbent surface should reduce noise due to the sound propagation over semi-soft ground instead of hard ground or due to absorbing effects in the multireflective volume contained within streets surrounded by buildings.

6.11 Porous Surfaces in Tunnels

The portals of tunnels are often significant sources of traffic noise. Also, due to multi-reflections inside tunnels, noise inside tunnels can reach very high levels which annoy the vehicle users, unless sound absorbing materials are mounted. A better solution may be to use a porous road surface in the tunnel. This would reduce noise emission as well as the build-up of a reverberant field in the tunnel. This principle has been used in Belgium, but noise effects are not yet reported as far as this author is aware of.

6.12 Cleaning of Porous Surfaces which Have Become Clogged

Trials to clean porous surfaces which have become clogged with accumulated dirt have been made the latest years. It is reported in (Bendtsen, 1988) that in Japan high-pressure water jets have been employed to clean porous surfaces. The effects on noise were not reported and probably not measured. Similar studies have been conducted in Sweden without significant success. It is reported in (Steven, 1990) that cleaning with high pressure water jets have improved noise reduction by 1.6-2.0 dB(A), given as a before-after comparison. However, the method was not economical.
The best description of the artificial cleaning technique this author has found so far is in (Weyringer, 1991). Special equipment used by Pyhrn Autobahn AG, which uses two parallel water jet units (110 Bar) and suction devices with a total operation width of 2 m, can clean 5000 m² per hour. The device recycles the water. This cleaning will cost only approx. 10 Pfennig per m² (equal to US $ 0.06 per m²). The equipment itself costs around DM 250,000.

It is stated that two cleaning operations on a 3-year-old surface have brought the noise reduction back to almost the original; however, this positive result is also stated not to be "general". It is also recognized that it is important to separate and take care of the solid material which is sucked-up since it contains some environmentally non-desirable substances. In 5 hours, 350 kg of such material was collected from 16,000 m² of porous surface.

Cleaning in 1990-91 of the Oslo test roads mentioned earlier have been successful in the respect that a somewhat improved air voids content has been recorded, mainly in the top surface (down to 10 mm). The difference was certainly visible. The cost for doing this is reported to be comparable to that of de-icing during a winter. It can thus be economical if employed at a larger scale. Extremely high water pressures were used (120-160 Bar). The noise reduction improved roughly 1 dB(A) by this cleaning (Storeheier, 1991).

Similar trials with cleaning have been going on in the Netherlands, but according to several verbal sources, this has not been as successful as one would wish. Therefore, a new concept has been tried recently especially designed to avoid the clogging effect in cities, when a "TWIN-lay" surface (see chapter 6.8.2 above) has been constructed. Here, the top layer with fine chippings is porous and is designed to act as a "filter" to prevent big particles to come down to the porous layer underneath which uses bigger chippings and thus have wider channels.

It is believed that it will be rather easy to clean this top layer with high pressure water and that the particles released from it will not fill the bottom layer since they are enough small to be easily drained away. The fine top layer provides a smooth ride and gives low noise as reported above. This test is now taking place in the city of Breda (Anon., 1991).

It must not be forgotten that traffic may have a self-cleaning effect on porous surfaces. It is reported from several researchers that the general observation is that:

a) at high speeds, porous surfaces preserve their porosity better
b) this is especially pronounced in the wheel tracks
c) at low speeds, the self-cleaning effect seems to be small

The clogging effect may make the use of porous surfaces questionable in those urban areas where the speeds are less than (say) 70 km/h.

In summary, it is still an open question whether clogged surfaces can be restored or not, or if one has to accept the sometimes quick deterioration with time.
6.13 Recycling

When a porous asphalt has become totally clogged, it can be recycled, according to (Weyringer, 1991). An experiment in France is mentioned where the recycling was done with an addition of 6-8% pre-coated chippings 6-10 mm and 0.3-0.8% binder. It is stated that the experiment was successful and was made on totally 20 km.

6.14 Safety

One of the main purposes with a porous surface is to provide drainage of water away from the surface. It is obvious that this is in line with safety requirements. It is concluded in (Sandberg, 1987-II) that there is no general conflict between low noise and safety.

There is one problem, however. If water freezes on the surface, it may make the surface extremely slippery at some times. Normally, this is handled by de-icing with salt. On a porous surface, however, more salt is required since some of it is pouring down into the porosities and has no effect on the surface. Also, the different thermal effects in a porous layer as opposed to a dense layer may require an earlier action with salt. Finally, after a rainfall or after becoming wet for other reasons, it may take longer until the surface is dry. If freezing occurs then, this type of surface may have a disadvantage.

Road maintenance authorities can handle this problem, as is pointed out in (Ohlsson, 1990), once they are aware of it and have gained experience. However, some experiments with porous surfaces have been interrupted due to poor knowledge of this.

It should also be noted that on a porous surface the sound absorption effect is reduced during wet conditions. Consequently, some of the noise reduction does not occur fully during rainy conditions and for some time afterwards. It is still to be investigated how much the latter delayed drying effect reduces the overall efficiency of porous surfaces, and it is a problem which must be addressed soon.

The experience in Germany with the quite extensive use of porous asphalt has not been entirely positive. Articles in newspapers in 1991 have reported that certain local road authorities have become so disappointed with the results in urban areas that they will interrupt the trials and go back to conventional surfaces. The clogging has been reported to be total after only two years and there have been problems with slipperiness.

It is important to point out that the safety problems with porous surfaces in news media often focus on just the negative features (which mostly are possible to control if previous experience is practiced). In total, the effect of removing water from the surface is generally enough positive to outweigh the possible negative effects.

6.15 Economy

There are different views as to whether a porous surface is more expensive in production than a dense one or not. An advantage is that it may require less bitumen than a conventional one. However, more care must be observed during construction, for example with the base being even, with ambient and mixing temperatures, etc.
There may be increased maintenance costs due to the different de-icing policy required. A somewhat shorter life-time (in certain cases, for example when maximum noise reduction is desired) may also increase the total costs. If cleaning of accumulated dirt is required the costs will increase also.

The Swedish Road Administration, as a very rough rule, currently considers porous surfaces as being in total approximately 50% more expensive than dense surfaces. According to Austrian experience (Breyer, 1990), increased costs of between 30 and 100% have been reported.

One should observe that in urban areas, water drainage systems may be a very expensive part of building and maintenance costs. The use of porous surfaces will reduce the requirements on such systems, since there is a natural accumulation capacity in porous surfaces. If such effects can be utilized, this could possibly waive the increased costs as mentioned above and turn it into an overall cost advantage.

Experiences from extensive use of porous asphalt in the city of Gothenburg are reported in (Ohlsson, 1990). It is stated that "The alternative to porous asphalt in Gothenburg is to use split mastix, a gap graded hot mix. Comparing porous asphalt with this alternative the price per square meter is just about the same. However the great difficulty is to place a value on noise reduction, accidents caused by skidding or poor visibility, etc, versus decreased resistance to abrasion".

6.16 Public Response

In many cases where porous surfaces have been laid in order to reduce traffic noise, the road authorities have been surprised about the positive public response, which has been better than expected from pure objective measurements. As far as this author is aware of, this has been investigated more systematically only by (Mezgailis, 1990) where it was stated that "The surveys and political responses indicate overwhelming public support for open-graded asphalt surfacing".

It should be followed-up better by investigators how the subjective reactions really are. It could be noted for example, that noise barriers usually suffer from a "penalty" of around 5 dB(A) just to compensate for the negative reactions to their appearance, prevention of sight, etc (Krell, 1984). Porous surfaces would not suffer from such an effect which could make them more competitive to barriers than indicated by pure noise reduction values.
7. ASSESSMENT OF VARIOUS OTHER SURFACES

7.1 Asphalt Concrete (dense)

Even within a group of surfaces like dense asphalt concrete there may be a large variation in traffic noise levels. This depends on the different macrotexture that a surface can obtain by selection of the grading curve and by wear. Practical experience in Sweden indicates that it generally differs around 3 dB(A) between such surfaces on actual roads in Sweden if overall traffic noise is considered. The surfaces with large chippings (up to 16 mm) are the noisier ones and surfaces with small chippings (8 mm) less noisy. However, more important than the chipping size is how dense the surface may become and how well the areas between the large asperities are filled with smaller particles. As open texture as possible is preferred.

See further Chapter 7.7 regarding a special low noise surface of this type.

Another effect, which has already been mentioned is that a new asphalt concrete surface is less noisy than one which has been exposed to traffic for one year and more. The difference is usually around 1-2 dB(A), see page 3:18 in (Sandberg, 1987-I). It is not clear what the reason is for this.

7.2 Cement Concrete (dense)

It is concluded in (Huschek and Springborn, 1989) that cement concrete surfaces are no noisier than asphalt concrete surfaces having the same texture. This is based on a very large number of measurements. However, the statement is based on measurements with just one special tyre (the PIARC ribbed reference tyre) and by the trailer method.

This author does not share this view. Measurements reported in (Sandberg, Ejsmont & Gustavsson, 1990) show that, no matter what tyre types (out of 5) or speeds (50-90 km/h) that were used, the noise penalty was approx. 2 dB(A) in relation to a smooth asphalt concrete. Furthermore, in (Sandberg, 1987-I, page 7:39) evidence is given that, texture being comparable, there is some noise penalty for cement concrete in relation to bituminous surfaces.

Transversal grooving of cement concrete surfaces may result in extremely annoying noise. On some roads, the authorities have had to install special road signs as a warning to the drivers that the noise they hear is due to tyre/road noise and is "normal". See Fig. 12. Public reaction to such noise is sometimes so extensive that the authorities have had to change their re-surfacing policy to avoid grooved cement concrete. In any case, periodic grooving must be avoided since the tonal noise resulting from this will be very annoying. The spacing of the grooves should be randomized.
Another factor to consider is when there are joints in cement concrete surfaces. The joints may not necessarily increase the average sound level very much, but the periodic and very pronounced impact sound may annoy people much more than any objective measure describes.

7.3 Low noise treatments for cement concrete

It is possible to reduce traffic noise on cement concrete surfaces by special techniques. Very recently, a workshop was organized with the objective to review these techniques (Sommer, 1992-I). The most important are:

* Porous cement concrete
* Longitudinal texturing
* Exposed aggregate
* Thin overlays (Surface dressings)

These are discussed briefly in the following, with the exception of porous cement concrete which is treated in Chapter 6.

Longitudinal texturing

According to (Breyer, 1990) new techniques have been tested in Austria with some success. For example, longitudinal texture may be created by using a burlap drag. According to (Sommer, 1992-II), a burlap drag longitudinal finish reduces noise by 2 dB(A), as compared to a transverse finish produced by a broom (horse hair).
The most common method in Europe seems to be to use a longitudinal smoother in combination with a burlap and/or a plastic brush (or comb) (Sommer, 1992-I). It is difficult to give any appropriate noise reduction values here, since it depends on which the reference surfaces are, but several dB(A) have been achieved in relation to a new surface built according to "old concrete" technique. In (Sommer, 1992-II), a longitudinally grooved surface obtained with a "Plastic Comb" reduced noise by 4 dB(A) in relation to an old type cement concrete.

Measurements in Sweden on motorways have shown that longitudinal grinding reduces noise of both old and new surfaces. The grinding produced longitudinal grooves, with a lateral periodicity of approx. 5 mm and each 2 - 3 mm wide. See Fig. 13. Using the "Old, smooth" cement concrete as a reference, it can be seen that directly after grinding this old surface, the noise level decreased 0.5-3.0 dB(A) (the range is due to different tyres and test sections). One year later, including studded tyre wear, there was no significant change; i.e. the reduction effect is still there. When comparing the old smooth surface with a newly laid and ground surface, the noise difference is 3-4 dB(A). However, when this new surface has been worn for one year, the noise is similar to that on the old and smooth surface. The grooves produced by the grinding simply were worn out after only one year. This is due to that the grinding was done mainly in the relatively "soft" mortar on the top of the new surface. When grooving is made in an old surface, it is mainly made in the much harder aggregate which will maintain the grooves for a considerably longer time. See Fig. 14.

![Fig. 13](image-url)

Fig. 13 Tyre/road noise measured with the trailer method on different road surfaces. Average for two tyre types. Speed 70 km/h. The two upper lines in each bar show the recorded range for this surface type.
Fig. 14 Cement concrete surface after grinding of new surface (left) and old surface (right). There is one groove per 5 mm (each one 2 - 3 mm wide).

Exposed aggregate

The following is mainly cited from a summary made by this author in (Sommer, 1992-I):

The exposed aggregate finish can be used on new, reconstructed or recycled cement concrete roads and is presently considered to be perhaps the most advantageous method in order to obtain low noise on cement concrete surfaces. However, it is not a very easy technique to apply. The constructor will find it difficult to obtain an optimum texture from the very start, he will need to learn the technique.

It is important that an optimum macrotexture and low megatexture is obtained. A low megatexture can be obtained by using:

* a longitudinal smoother (before exposing the aggregate)
* a maximum aggregate size which is as small as possible

According to the theories of (Descornet and Sandberg, 1980) and to the recent Austrian experience, the aggregate to be exposed should preferably have grain sizes 4 - 7 mm (or 4 - 8 mm) in order to give optimum macrotexture. The mortar should include sand 0 - 1 mm, with 0 - 2 mm being less desirable but also possible.

The aggregate is exposed by either of two principles:

1. Simultaneously watering and brushing the fresh concrete surface by means of a rotary brush. This is an old technique, not preferred today.
2. Spraying an appropriate setting retarder on the fresh concrete immediately after concreting. After hardening of the concrete (24 - 30 hours after laying), the surface is mechanically brushed so as to remove the mortar that has not set. A minimum of water is used.

Experienced Belgian methods with 0 - 32 or 0 - 20 mm chippings are easy to apply, but not as effective for noise reduction as new Austrian methods with smaller chippings. In Austria, recycling of old cement pavements is normal and can make use of the addition of a top layer of 30 - 40 mm with exposed aggregate.

Experience in the Netherlands with max. 20 mm chippings, the results of which had been compared to Belgian exposed aggregate surfaces, indicated that great gains in noise reduction are obtained when going from 32 to 20 mm max. aggregate size.

With an "optimum texture", according to the Austrian experience for two different test sections (see above), noise reductions of 5 - 7 dB(A) compared to "old concrete" and 0 - 2 dB(A) compared to a longitudinally textured surface have been achieved. See Fig. 15. The noise level is then claimed to be comparable to that of medium-aged porous asphalt. The porous asphalt would probably be more efficient when it is new but rather quickly loses much of its advantage.

*Note: Since the trailer method was used, there is considerable concern as to whether this method would correctly measure the noise reduction of porous surfaces. When making the comparison with porous asphalt one shall also have in mind that the latter reduces not only tyre/road noise but also power-train noise, which is not the case for exposed aggregate concrete.*

Finally, the additional costs for the exposed aggregate procedure are rather small; approximately 10 % increase of the total pavement cost according to [Sommer, 1992-I](#). The risks are more or less limited to the "loss" of this extra cost.

**Thin Overlays (Surface Dressings)**

More than 10 years ago (Descornet and Sandberg, 1980) provided the basic understanding for how the texture of a road surface could be optimized by texture "design". It was stated that the texture at texture wavelengths above 10 mm should be as low as possible and the texture at wavelengths below 100 mm should be as high as possible. One of the most quiet surfaces tested there was a slurry seal which had pronounced texture at very short wavelengths.

Consequently, in order to reduce noise on smooth cement concrete surfaces, one way is to put thin overlays on top of such surfaces. The easiest way is to use a surface dressing with chippings as small as possible with respect to wear and drainage. This has been tried by [Sommer, 1992-II](#) with good results.
More than 300,000 m² of cement concrete has been covered with a surface dressing with 3 - 4 mm chippings which have been bound with epoxy. Such a surface has proven to give low noise. See Fig. 15 where it can be seen that it gives equally good noise reduction as the exposed aggregate surfaces and a medium-aged drainage surface. However, please read the note regarding the measuring method in the previous section.

In countries with extensive use of studded tyres in winter-time, such a surface may be impossible to use, because the studs will probably wear these small chippings away rapidly. It will be very interesting to follow-up the Austrian experiment, which so far (up to 3 years) has been successful, since they have some studded tyres in the winter season.

Three new types of cement-bound surfaces are also being tested:

* "Rough" surface. This consists mainly of 2 - 4 mm chippings (12 kg/m²) bound with a mortar of cement, sand and epoxy. This surface obtains a rather fine but pronounced texture.

* "Structured" surface. Like the above surface but somewhat thicker mortar layer and rolled with a structured roller afterwards.

* "Micro-drainage" surface. The material is similar to the first one, but instead of first spreading out the mortar of sand, cement and epoxy and then chippings on top of this, all is mixed together before spreading.

Fig. 15 Comparison of tyre/road noise (measured with the trailer method and the PIARC rib tyre) on cement concrete surfaces. Altbeton = Old concrete, Washbeton = Exposed aggregate (with 7 resp. 8 mm max. chippings), EP-Grip = Surface dressing with 3 - 4 mm chippings bound with epoxy. From (Sommer, 1992-II).

7.4 Surface Dressings (Chip Seals)

Regarding surface dressings (or chip seals as they are also called) the noise effects largely depend on the chipping size:
a) Chipping sizes of max. 12-20 mm:

Such surfaces generally increase tyre/road noise by 1-3 dB(A) compared to smooth, dense asphalt concrete. The increase is only for cars. For trucks, noise may even decrease! Therefore, for total traffic noise the situation is not clear-cut.

b) Chipping sizes less than 8 mm:

Such surfaces may be very quiet. In (Sandberg, 1987-1) it is concluded that such a texture would be very appropriate for noise reduction, and it is also shown that one of the quietest surfaces measured there was a resinous slurry with small chippings, a surface which in principle is similar to a surface dressing.

See also "Thin overlays" above.

In summary, surface dressings with very small chippings may be almost as quiet at porous surfaces! However, note that they will be effective for reduction of tyre/road noise only. In interrupted-flow urban traffic they will not be effective since they do not provide any absorption.

c) Double layer surface dressings:

Double layer surface dressings with (say) 12-16 mm chippings in the bottom layer and 4-8 mm on top are less noisy than single layer surfaces with the same maximum chipping size. Truck tyre/road noise may be reduced by such surfaces while there may be a penalty for cars, at least at low speeds.

When surfaces of this type are worn, they appear more and more like smooth and dense asphalt concrete. Noise emission also approaches that of a corresponding asphalt concrete surface.

7.5 Block Surfaces

In old towns and cities, traditional paving stones is still a common type of surfacing. In (Meschik, 1990) there is a review of the effect on noise of such surfaces. The noise increase is 1.5-8 dB(A) according to this.

In this case there is obviously a conflict between environmental and cultural ambitions. Paving stones are mainly used today because cultural values must be preserved.

In some types of streets, paving blocks of modern types have been introduced. Although the traffic usually is not intense on such streets, there have sometimes been some concern over the increased noise they cause. This has been investigated by (Samuels and Sharp, 1985) who did not find any consistent noise increase due to the blocks.
Another investigation of modern paving block surfaces showed that 7 types gave noise emission equal to that of an asphalt concrete 0/11 mm while 5 types gave 2-5 dB(A) higher noise levels (Pauls, 1992).

7.6 The Pavetex Surface

It was reported at the recent tyre/road noise conference by (Iwai et al, 1990) that a new surface called "Pavetex" could reduce tyre/road noise as much as a porous surface. The Pavetex surface is a very peculiar surface, since it is similar to a very complex semi-soft carpet, see Fig. 16.

One could doubt that such a surface be durable. However, according to the Japanese authors it has resisted 16 months of traffic without problem...

![Image of Pavetex surface structure]

Fig. 16 The structure of the Pavetex surface. From (Iwai et al, 1990).

7.7 The ISO Test Track Surface

The working group ISO/TC 43/SC 1/WG 27 has had the task to develop a test track surface for use during vehicle noise homologation tests according to ISO 362 and 7188. This surface shall be as quiet as possible, without being sound absorptive (Sandberg, 1991).

The final result of the work is (ISO/DIS 10844, 1992). This draft standard specifies a surface which is basically a dense asphalt concrete surface with maximum 8 mm chippings and with threshold values for sound absorption, air voids and texture depth. It has been shown that this surface reduces tyre/road noise by around 1-3 dB(A) in comparison to "normal" asphalt concrete surfaces. It could be suitable in urban areas when speeds are not too high. It is not yet known how it performs after years of very intensive traffic.

Measurements have been conducted recently with the statistical pass-by method on a test track (!) in the Netherlands (von Meier, 1991). The results showed that the ISO surface was 1-2 dB(A) less noisy than the reference asphalt surface (both were newly laid).
In 1991, a surface which appears to meet the requirements of ISO/DIS 10844, has been laid on 20 km highway near VTI in Sweden. This surface was a split-mastic asphalt with max. 8 mm chippings, called Viakotop 8. Measurements conducted with the trailer method, using 5 tyres, showed that this surface emitted less tyre/road noise than the conventional dense asphalt concrete with 0/12 mm chippings. The average improvement was 2 dB(A). It shows that the "ISO surface" can be applied also to highways and streets under normal traffic and is useful not only for test tracks for which it was originally designed.

7.8 Rubberized Asphalt

It is claimed that "Asphalt-Rubber" is an effective means of reducing traffic noise (ARPG, 1990). Scrap tyres could be used as the raw material in such surfaces. References are given to lots of investigators and the noise reductions are claimed to be very high. However, when checking all the references, it is clear that they all refer to comparisons of porous surfaces in relation to dense surfaces but where the porous surfaces have included some rubber. All the noise reductions can, in fact, be due to the porosity and not the rubber, according to this author's view. There is nothing which shows that it is the rubber in the surfaces which is causing the noise reduction. Therefore, the suggestions of using rubber for noise reduction have no support.

This author has investigated the effect of adding 1 - 4 mm rubber granulates in a dense asphalt concrete, so called "RUBIT", see (Sandberg, Ejsmont and Gustavsson, 1990). The proportion of rubber by total weight has been 3-6 %. The result was that it was not possible to trace any noise reduction to the effect of rubber. The rather open texture obtained can also be achieved with split mastic asphalt. The rubber content in the surface probably has to be much higher in order to be effective.

Similarly, the effect of adding rubber to the binder has not yet been demonstrated to have any significant effect, see Chapter 6.6. The only possible exception may be a laboratory investigation in which it was shown that when adding rubber to the bitumen binder, a so-called "configuration factor" in the mix could be increased, which changed the absorption coefficient favorably (von Meier, 1985). However, no comparable field experiments which can isolate the rubber effect are known to this author. See also 6.8.2 (regarding the Netherlands).

However, when using rubber as the main ingredient of the surface the effect on noise can be dramatic. See Chapter 6.9.

7.9 Wet Roads and Streets

Water on roads and streets increases the noise by 1-10 dB(A). By designing street and road drainage properties in a proper way traffic noise can be reduced. The best effect is obtained with porous surfacings.
8. THE IMPORTANCE OF PROPER MAINTENANCE OF SURFACES

If drainage wells and man-holes are located in the street there is a risk that vehicles will hit these sources of unevenness which may cause bump noise and rattling noise of loose goods. Maintenance may increase or decrease such noise depending on whether the surface level differences are reduced or not when a new surface is laid.

Maintenance also affects rutting in the surface, and thus water depths in wet weather and consequently traffic noise.

The longitudinal unevenness is influenced by road and street maintenance which affects bump and rattling noise according to the above, but also the so-called megatexture (texture wavelengths 50-500 mm) influences tyre/road noise at low frequencies.

Finally, newly laid asphalt pavements appear to be more quiet during their first year than the following years. This noise difference is generally:

- For dense asphalt concrete: 1-2 dB(A) lower noise the first year rel. to later years.
- For porous asphalt concrete: 1-2 dB(A) lower noise the first year rel. to the second year.

Also, a way of reducing noise of smooth cement concrete surfaces, as well as to make them more even which is most often the main objective for this operation, is to grind them longitudinally with close and narrow grooves, as is reported elsewhere in this paper. However, this grinding should be made at intervals of just a few years since the grooves loose their effect due to wear.

In summary, a poor maintenance of a road and street network in urban areas influences traffic noise in many, additive ways. Frequent re-surfacing may reduce the time average noise level in the order of one dB. However, the subjective effects may be bigger than expected from the objective measures, since people notice a sudden noise change but may not notice a gradual noise increase afterwards.
9. OPTIMIZATION OF THE TYRE/ROAD SYSTEM

As has been stated earlier, the noise characteristics of road surfaces are not independent of
the tyre. For example, for truck tyres larger chipping sizes can be accepted (for low noise)
than for car tyres. For smooth-patterned tyres, increased texture usually means higher noise
levels, while for rough-patterned tyres the contrary seems to be true.

Unfortunately, this means that the matter is very complicated. In any case, there must be
room for optimizations of the tyre/road system with respect to noise. There may be certain
tyre/road combinations which are better than others. The only systematic study of this so far
has been made in the Netherlands. In (von Meier, 1990) the basics for this are outlined
while the results are given in (von Meier, Blokland and Bochove, 1991). It is not easy to
identify clear conclusions there, since the matter is rather complicated. A "best" tyre is
identified, but the differences are rather small and the range of textures of the surfaces and
range of tyres may be too small to display the possible optimization problems. More
research on this is needed.

10. DEFINITION OF A "LOW NOISE ROAD SURFACE"

In analogy with vehicles, it would be desirable to be able to define a "Low Noise Road
Surface". Once this definition is decided it would be possible for road and environmental
authorities to encourage the use of such surfaces with certain favours or simply to require it
in some cases.

Such a definition should preferably be based on functional properties, not on design. A
design definition would not encourage development and not make possible optimizations
which take also other characteristics into consideration.

What should a definition look like? It is still premature to give a final recommendation, but
this author would suggest (tentatively) that it is based on these two principles:

1. The sound absorption coefficient. Data indicate that a sound absorption coefficient
averaged over the range 400-1600 Hz is the most relevant value and that noise
is influenced when the coefficient exceeds approximately 0.10. However, in order to
have a long-lasting and significant noise reduction the coefficient needs to be
considerably higher.

2. The macrotexture. A rough macrotexture will create tyre/road noise of the type
described as mechanism No. 1B in Chapter 2.3 and may thus counteract the noise
reduction by absorption.

Possibly, a macrotexture requirement could be provisionally supplemented or replaced by a
design limit, e.g. that the max. chipping size be 12 mm or less. This design limitation
would not be severe enough to prevent development and alternatives.

Another problem is how to handle the impairment of the porosity and sound absorption
from initial high values to lower values when the surface has become worn?
As has been argued before, even though a surface can not preserve its high initial noise reduction, the public will still notice a considerable improvement and may not react so much to the slow, gradual increase of noise. So, possibly, the problem of ageing must be left aside at the moment.

11. INFORMATION SEARCH (BIBLIOGRAPHY)

At present, more than 800 papers or other documents with relevance to tyre/road noise are available (INFORMEX, 1991). A large proportion of this number deals with road surface influence on the noise. With such an extensive literature available, it is natural that each new research project should be started where others finished, i.e. one should begin with conducting a literature survey.

The most comprehensive single source available at present is the proceedings of a recent conference (INTROC 90, 1990). At least half of the papers deal with the subject of road surfaces. Some of the information provided there is briefly mentioned in this paper.

Tyre/road noise investigations have been reported at least since 1925. The number of publications in this field grows so fast that it is not possible to handle all of them without a modern data base system. General bibliography data bases which are available world-wide are not detailed enough in their keywords to help with a search for particular problems related to tyre/road noise and they are also very incomplete. In order to handle this, a computerized bibliography has been presented recently where all known tyre/road noise papers are classified based on 70 keywords specialized on the subject (INFORMEX 1991). This bibliography is also possible to edit and supplement by the users themselves. See the figure below for a typical printout.

<table>
<thead>
<tr>
<th>Search</th>
<th>Supplement</th>
<th>Edit</th>
</tr>
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<tbody>
<tr>
<td>Record Number: 544</td>
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Author(s): Pottinger, M.G., Marshall, K.D., Lawther, J.M., Thrasher, D.B.
Title: A Review on Tire/Pavement Interaction Induced Noise and Vibration
Source: The Tire Pavement Interface. ASTM STP 929. Edited by M.G. Pottinger and T.J. Yager
Type of document: DISCUSSION S-O-A BOOK
Comments: Excellent review

Keywords (primary keywords written in upper case)
GENERAL REVIEW, VIBRATIONS, TIRE NONUNIFORMITIES, bibliography, external t/r noise, internal t/r noise, public reaction, general mechanisms, vehicle vibrations, tire influence, road surf influence, road characterization, operating parameters

Fig. 17: Typical printout of a bibliography record in the TRN database (INFORMEX, 1991)
12. CONCLUSIONS

The paper has provided a review of how vehicle noise emission is influenced by road/street surface design and how this factor may be controlled.

It is concluded that:

- Porous asphalt is a type of surfacing which may be effective for noise reduction on highways and in some urban areas. Up to 5 dB(A) could be obtained on high-speed roads. In some countries these surfacings deteriorate rapidly with time, in other countries they continue to work well. On low-speed roads it is more common that reductions of 2-4 dB(A) are obtained initially, but by using multi-layer surfaces or extremely high void contents, 5 dB(A) can be obtained even at low speeds.

- Most commonly, however, the noise reduction efficiency is reduced very quickly with time, due to clogging. Already after the first winter season the reduction may be halved relative to the initial one. After some more years there is no reduction left.

- The clogging effect is most pronounced in urban areas with low speed traffic. High speed traffic will give a "self-cleaning" effect which usually is best in the wheel tracks.

- Cleaning of porous surfaces with high-pressure water have so far had limited success. However, in Austria, Norway and Germany some tests have proven worthwhile.

- A special type of porous surface is the poroelastic road surface made of rubber granulate from scrap tyres. It can reduce traffic noise by 5-10 dB(A), i.e. have the same effect as a noise barrier. However, there are severe problems which have to be solved until this surface type can be used at a larger scale and with acceptable durability.

- The use of rubber as just a small fraction of the mix has not been shown to be successful for noise reduction. The same effect could probably be obtained without rubber.

- Porous surfaces may be useful for urban noise reduction also when laid on sidewalks and parking areas due to the absorption it provides, especially in reverberant spaces.

- Porous surfaces are also recommended on roads in tunnels.

- Poor maintenance of roads and streets may to a large extent increase traffic noise. On the other hand, frequent re-surfacing may reduce traffic noise.

- Conventional asphalt concrete road surfaces are usually less noisy when they are new. By special design of the grading curve, low noise variants can be obtained also with such a type, such as the "ISO Test Track" Surface.
- Surface dressings may both increase and decrease noise emission, depending on the size of chippings. Very small chippings may result in a very quiet surface, in some cases almost as effective as a porous one.

- In Japan, a new surface called "Pavetex" has been tested with apparently good results. It needs more testing.

- Standardization in order to have uniform method(s) for classification of road surfaces with regard to noise properties is underway.

- Cement concrete road surfaces are often considered as rather noisy. However, methods to treat the surfaces of such pavements to obtain less noise are being developed. The most promising treatments are longitudinal grinding, surface dressings with small chippings on top of existing surface and the exposed aggregate technique using small chippings. In some cases, it is possible to obtain noise characteristics which are claimed to be almost as good as for medium-aged porous asphalt.

As a concluding remark, it is necessary to point out that the noise reduction effect of the appropriate road surfaces which are available today shall not be exaggerated. Most tests conducted and presented so far have been done on new surfaces. Experience has shown that the reduction generally deteriorates with time. Consequently, most investigations presented so far have given results which are not really representative of a long-term evaluation. The reader is advised to put special weight on those investigations which focus on long-term effects.

However, even though initial noise reductions of (say) 5 dB(A) may be reduced to 0 dB(A) at the end of the lifetime of the surface, the average noise reduction is enough big to motivate the use of low noise surfaces in many cases since alternative noise reduction measures may not exist or may at least be more expensive.

Low noise road surfaces are often useful as a noise reduction tool not only on country roads but also in urban areas. However, it must never be the only tool, since they do usually offer just a partial solution to the noise problem. Actions to reduce the noise emission by tyre and vehicle design are also necessary to reduce the overall emission of traffic noise.
13. REFERENCES


ARPG (1990): "Noise Reduction with Asphalt-Rubber". Asphalt Rubber Producers Group, Phoenix, USA.


DESCORNET and SANDBERG (1980): See SANDBERG and DESCORNET in this list.


KRAGH, J. (1990): "Vejbelaegninger og vejtrafikstøj - En opdateret litteraturgennemgang (Road surfaces and road traffic noise - An updated literature review)". Notat No. 9, Danish Road Data Laboratory, Herlev, Denmark. (In Danish).


