Low noise road surfaces — A state-of-the-art review

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This article summarizes present knowledge concerning the design and performance of low noise road surfaces. As a background, noise generation mechanisms and mechanisms causing noise reduction by surface design are explained, as well as the currently best measurement procedures. Guidelines on how to design a surface for low noise characteristics are given, for example texture optimization. Low noise surfaces include types like surface dressings with very small chippings, exposed aggregate cement concrete and thin bituminous surfaces; also machine-ground cement concrete is mentioned. However, the type with the greatest potential for noise reduction is porous surfaces, both with bituminous and cement binders. It is shown that for these, the product of voids content and thickness is a good descriptor of noise reduction. Thicknesses of 40–50 mm and voids contents of 20% are the minimum required in order to obtain a reasonable noise reduction, but there is no point in going to extreme thicknesses, say beyond 100 mm. It seems that the best traffic noise reduction attainable with such surfaces is around 8 dB(A) in new condition, using small chippings in the top layer. A surface named Twinlay has been especially optimized to have a long acoustical lifetime for urban applications at speeds around 50 km/h, otherwise clogging of porosities by dirt is a serious problem in urban areas. In most cases, regular cleaning operations are required. In applications where speeds are 90–130 km/h, there is a significant self-cleaning of porous surfaces and the acoustic lifetime can be acceptable even without cleaning. The article reviews the experience with low noise surfaces in various countries and also presents some futuristic designs, like an acoustical multi-resonator pavement and pavements made mainly of rubber particles, the latter having a potential of 10 dB(A) of noise reduction. There is no doubt that road surfaces will be used frequently to reduce traffic noise and can give substantial effects. One shall, however, observe that this may mean serious economic trade-offs and some other problems, as well as the long-term noise reduction efficiency still is poor for most designs.

Keywords: Road surfaces, Noise reduction, Sound absorption, Road traffic noise

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1. INTRODUCTION

Vehicle noise emission is dominated today by the noise from the interaction of tire and road surface, so called tire/road noise, when vehicles travel at constant speeds of 50 km/h and higher. For cars, tire/road noise dominates even at constant speeds of 30 km/h and higher. Also at moderate acceleration and deceleration conditions, tire/road noise often dominates on modern vehicles. Noise from the remainder of the vehicle, i.e. power unit noise, dominates at accelerations from standstill up to 30–50 km/h; conditions which are common at light-controlled intersections or roundabouts and otherwise in stop-and-go traffic.

It follows that any effective vehicle noise emission reduction policy must address the problems of both power unit noise and tire/road noise. The responsibility lies with the following four parties:

• Power unit noise to be controlled by vehicle manufacturers (they also have a responsibility to select low noise tires for their vehicles)

• Tire/road noise, as influenced by tire construction, to be controlled by tire manufacturers
Tire/road noise, as influenced by road surface construction, to be controlled by road authorities and road constructing companies. In some cases also power unit noise can be controlled.

Vehicle noise to be controlled by drivers (quiet driving) and owners (purchase of low noise vehicles and tires, and proper maintenance of them).

This author believes that the potential for overall vehicle noise reduction is the greatest for measures aimed at tires and road surfaces and with equal potentials for each of them [Sandberg, 1993]. Neither of them shall therefore be neglected. However, this article concentrates on the third point above.

2. WHAT IS A “LOW NOISE ROAD SURFACE”?

When addressing the problem of road surface influence on noise, the term “low noise road surface” very often is used. What is this really? Well, first one should remember that it still remains to be proven that the road surface emits significant noise; it is the rolling tire that emits the noise. So, in terms of noise emission caused by a moving vehicle, ALL road surfaces are “low noise surfaces”. However, they no doubt influence tire/road noise emission a lot. As shown in [Sandberg, 1992] the influence of road surfaces on vehicle noise at moderate and high speed is equally large as that of vehicles, i.e. basically of tires. Some authors claim that the road surface influence is much bigger than the tire influence, but this view is often based on a very limited class of tires whilst including all possible types of road surfaces.

With a lack of definition, everyone is free to claim that a particular surface is “low noise”, in fact the big majority of surfaces would be “low noise” if one would use for example paving stones or laterally grooved cement concrete as references. There are examples of this in the literature. But since so many experts use the term “low noise road surface” we evidently need a definition. This author proposes the following definition of the term:

A “low noise road surface” is a road surface which, when interacting with a rolling tire, influences vehicle noise in such a way as to cause at least 3 dB(A) (half power) lower vehicle noise than that obtained on conventional and “most common” road surfaces.

This of course leads to another terminology and definition problem: Which surfaces are conventional and “most common”? This could be a little different in various countries, but it seems to this author that the type of surface being very common and conventional in most industrialised countries, in particular in densely-populated areas where noise problems are common, is dense asphalt concrete (DAC) with maximum chipping size between 11 and 16 mm. Another type of common surface, currently gaining world-wide popularity, is the stone mastic asphalt (SMA), in German called Splitt-Mastix Asphalt, with maximum chipping size between 11 and 16 mm. Fortunately, these surfaces “give” approximately the same vehicle noise emission (within approximately a 2 dB(A) range) and with just a minor influence of chipping size. Thus, it is suggested here that these are treated as one group as the reference case for assessing if a surface is “low noise” or not. An additional feature should be that the reference surface group includes only surfaces exposed to traffic for at least one year. See further Clause 10 of ISO 11819–1. Throughout this article the term “noise reduction” refers to the difference in A-weighted noise level between a low noise surface and one or more references of type DAC or SMA with a maximum aggregate size between 11 and 16 mm.

3. HISTORICAL REMARKS

The use of certain road surfaces to reduce traffic noise is nothing new. Already 100 years ago, an application of “low noise” surfaces was to replace cobblestones or other paving stones with wood blocks. This made the surface less uneven and softer, both of which resulted in lower tire/road noise. However, the advantage was won at the expense of durability and cost. In [Crocker, 1984] it is stated: “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.

The first time a porous road surface was reported as an unusually quiet surface was in USA by [Steere, 1973]. Then, although similar surfaces were tested in the U.K. in the early 70’s it was not until [Sandberg, 1979] and [Nilsson, 1979] that really “low noise surfaces” were reported. The first commercial
4. GENERATION AND PROPAGATION MECHANISMS

It is necessary to have a basic understanding of how tire/road noise is generated. Research on generation mechanisms has been conducted since the mid-70's and resulted in an extremely complicated menu of mechanisms and related phenomena, all of which have been demonstrated to have some influence. However, the most influential mechanisms are listed in the following table.

Furthermore, there are some phenomena closely related to the mechanisms, which influence the amplitude but which cannot be regarded as pure "generation mechanisms". These are also included in the table, since they are all related to the road surface. Figure 2 attempts to illustrate the mechanisms.

5. TEXTURE OPTIMIZATION FOR LOW NOISE

According to [Sandberg and Descornet, 1980] road surface texture influence on tire/road noise can be summarized as:
- Sound pressure levels at low frequencies (below a "cross-over frequency" $f_c$) *increase* with texture amplitude when considering texture within the texture wavelength range 10–500 mm
- Sound pressure levels at high frequencies (above a "cross-over frequency" $f_c$) *decrease* with texture amplitude when considering texture within the texture wavelength range 0.5–10 mm.

Consequently, the effects of texture on exterior noise are conflicting, depending on how the texture is composed. The cross-over frequency is approximately 1,000 Hz for car tires and 500 Hz for truck tires. It seems that there is an interaction between road texture wavelengths and the texture of the tire,

Table 1 Mechanisms of tire/road noise emission.

<table>
<thead>
<tr>
<th>Generation mechanisms</th>
<th>1 Radial vibration mechanism</th>
<th>1A Impact of tire tread blocks or other pattern elements on road surfaces</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1B Impact of road surface texture on the tire tread</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2A Pipe resonance</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2B Helmholtz resonance</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2C Pocket air-pumping (may also be a special case of 2B)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3A Stick/slip motions causing tangential tire vibrations (might give excitation to 2A and/or 2B)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3B Rubber-to-road stick/release (adhesive effect)</td>
<td></td>
</tr>
<tr>
<td>Special amplification or reduction mechanisms</td>
<td>4 The horn effect</td>
<td>4 The curved volume between the tire leading and trailing edges and the pavement constitute something similar to an exponential horn used to amplify sound</td>
</tr>
<tr>
<td></td>
<td>5 The acoustical impedance effect</td>
<td>5A Communicating voids in porous surfaces act like sound absorbing material, affecting source strength</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5B Same, affecting sound propagation to far-field receiver</td>
</tr>
<tr>
<td></td>
<td>6 The mechanical impedance effect</td>
<td>6A Pavement gives more or less reaction to tire block impacts depending on dynamic tire/road stiffness proportions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6B Some tire vibrations may be transferred to the pavement, possibly radiating as sound (speculation)</td>
</tr>
</tbody>
</table>
Fig. 2 Tire/road noise generation mechanisms. The left part summarises these that are based mainly on structure-borne tire vibrations, dominating at frequencies below 1,000 Hz. The right part summarizes the mechanisms related to air pumping or air resonances, dominating above 1,000 Hz.

The stiffness or the mechanical impedance of the road surface has not yet been convincingly demonstrated to affect noise emission significantly, but there are several indications (non-convincing when seen separately) that a stiffer surface gives more noise generation than a softer surface. This would explain why cement concrete surfaces with rather similar textures as asphaltic surfaces seem to give somewhat higher noise levels (something which is still arguable).

If one would measure the texture profile curve and make a spectral analysis of it, one would obtain a texture spectrum [ISO/DIS 13473-2]. Figure 3 shows a typical such texture spectrum for a dense asphalt concrete surface with 11 mm max. chipping size. What one would attempt to achieve when optimizing texture for low noise would be to try to
push down the range under the left arrows and lift 
up the range under the right arrows. One way of 
achieving this is by choosing a smaller max. chipp-
ing size, which would move the peak in the spec-
trum to the right, but this should be made without 
sacrificing the total texture, like in a fine SMA 
surface when one removes some of the finer material.

6. GENERAL GUIDELINES FOR 
NOISE REDUCTION RELATED TO 
ROAD SURFACES

A comprehensive collection of practical advice for 
design of low noise road surfaces, for example of 
how one may achieve a certain desired road texture, 
is presented in [Sandberg, 1996]. Here is a sum-
mary of general guidelines :

• Construct the wearing course with as high voids 
  content that is possible from a durability point of 
  view, an initial voids content of more than 20 % is 
  a minimum to achieve good noise reduction but 
  25–30 % would be ideal. The thickness of a 
  porous layer should be at least 40 mm, preferably 
  thicker, in order to achieve sound absorption at 
  relatively low frequencies also.

• It is essential to construct the porosity in order to 
  prevent clogging by having rather wide channels.

• Minimize megatexture, especially around wave-
lengths of 50–100 mm. This can be achieved e.g. 
  by using uniform, not so large chippings and 
  having them packed close together.

• Avoid very smooth macrotextures ; instead maxi-
  mize macrotexture at wavelengths around 2–6 mm 
  for car tires and 4–8 mm for truck tires.

• The previous two points are easier to achieve if a 
  small maximum chipping size is used, ideally in 
  the range 3–6 mm, and if the chippings have sharp 
  edges, such as when they are crushed.

7. MEASURING METHODS

An ISO standard for measurement of road surface 
influence on traffic noise [ISO 11819–1] was printed 
in 1997. It is called the Statistical Pass-By (SPB) 
method and relies on a roadside measurement on a 
statistical selection of automobiles and heavy vehi-
cles passing-by the microphone (a minimum of 80 
vehicles of each category). The measurements are 
processed in regression analysis of noise versus 
vehicle speed, from which an index called “SPBI” is 
determined, which is the characteristic vehicle sound 
level at a chosen reference speed. This method is 

Work is underway in ISO to standardize a second 
measuring method for tire/road noise, called the 
Close-Proximity (CPX) method ; previously called 
“the trailer method”. In the CPX method, the 
average A-weighted sound pressure levels emitted by 
four specified reference tires are measured over an 
arbitrary or a specified road distance, together with 
the vehicle testing speed (50, 80 or 110 km/h), by at 
least two microphones located close to the tires. 
For this purpose, a special test vehicle, which is 
either self-powered or towed behind another vehicle, 
is used. In the latter case the test vehicle is a trailer. 
Reference tires are mounted on the test vehicle, either 
one by one, or a few at a time. Four uniquely 
different reference tires have been selected in order to 
represent the tire/road characteristics that are to be 
studied. Examples of test vehicles are shown in 
Figs. 4 and 5 below.

A committee draft [ISO/CD 11819–2] has been
proposed. The CPX method partly has the same objective as the SPB method but is useful in more general acoustic situations, with some sacrifice of representativity. The SPB and CPX methods are intended to supplement each other; SPB being more useful for "type testing" of pavements and CPX more useful for follow-up of individual road surfacing projects. An international experiment to test the CPX method and compare most of the trailers in-use today was conducted in the summer of 1998 in Europe (with Japanese participation), see the web-site http://www.geocities.com/CapeCanaveral/Lab/6594/cpxtest.htm. One problem with the CPX method is that it underestimates the sound absorption benefit of porous surfaces during propagation to the far field and thus it needs some supplementary procedure (see next paragraph).

Many low-noise road surfaces have significant sound absorption characteristics. For measurement of such characteristics in-situ, an ISO working group currently works-out two methods. One is a special "guard tube method" with Cepstrum signal processing which measures a relatively small spot, the other one is a free field method with either MLS or burst sweep signal processing, measuring a larger surface [Garai et al., 1998]. A draft for the latter one was recently submitted to ISO.

8. NON-POROUS LOW NOISE ROAD SURFACES

Already in [Descornet, 1979] it was noticed that a fine surface treatment with 1-3 mm emery chippings and a polyurethane binder gave a noise reduction of 3-4 dB(A) after two years of operation on a low-volume road. A similar surface with 4-6 mm chippings gave half of that reduction. These are typical "texture-optimized" surfaces; the first one probably very close to what is practically achievable. This was also realized in 1989 in Austria as a surface dressing on ("noisy") cement concrete surfaces, called EP-Grip. It utilized 3-4 mm chippings bound with epoxy; later a cement binder was developed for it [Sommer, 1992]. A similar surface, "Epoxy-Durop", was used in the above-mentioned CPX test.

Another surface treatment suitable for cement concrete is longitudinal grinding by a machine. This creates an even surface (reduces megatexture) but also creates narrow longitudinal grooves, which in favourable cases can give noise reductions up to 3 dB(A) relative to a reference case discussed above, but much more in relation to typically "noisy" cement concrete surfaces [Sandberg, 1998-2].

A third way of reducing traffic noise on concrete surfaces is to use the exposed aggregate technique. One term sometimes used for this surface is "whisper concrete". This was reported several years ago by [Sommer, 1992] to give considerable noise reduction (similar to a medium-aged porous asphalt) provided max. 8 mm chippings were used, although experiments had been conducted in Belgium much earlier to test the same principle but bigger chippings. Later successful experiments have been reported by [Abbott and Phillips, 1996]. However, chippings should not be bigger than 8 mm in which case approx. 3 dB(A) of noise reduction can be achieved in favourable cases [Sandberg, 1998-2]; experiments with smaller chippings are recommended. See also a review in [Sommer, 1995].

Finally, some thin bituminous surfaces with somewhat "noise-optimized" texture have appeared in recent years. There are "thin" (20-25 mm thick), "ultra thin" (12-18 mm thick) and "micro surfacings" (6-12 mm thick). Often they have modified binders, use max. chipping sizes in the range 4-8 mm, and are marketed commercially, with names such as Novachip (=Safepave in the U.K.), Microville, UL-M, Miniphone, Citychape and Colsoft. The reader may find more information by searching on Internet. The latter two contain some rubber in order to get a better texture and softer surface. Usually, these surfaces are not tested for noise characteristics in a professional way (at least not reported) so it is difficult to say what the noise reduction is, but usually it is 1-3 dB(A) in relation to our reference case.

A surface which is somewhere "in-between" of these thin surfaces and "normal" DAC are SMA surfaces, see Fig. 6, of which the ones with maximum 8 mm chippings seem to reduce noise somewhat. In fact, the ISO 10844 surface which is generally considered to reduce noise by about 2 dB(A) is more or less an SMA 8 mm surface. See further the section about porous cement concrete.

9. POROUS LOW NOISE ROAD SURFACES

9.1 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-textured asphalt, open-graded asphalt, open-graded friction mix, porous friction mix, etc.

In this paper, the term porous surface is used consistently, although it is recognized that pervious may be a more relevant term than porous. 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. This author proposes that it is required that a surface has at least 15% of open voids in order to be called porous. In the following, the term “semi-porous” is used for surfaces which have an air voids content around 10–15%.

9.2 Construction

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

- 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 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, fibres, 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, we have 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 that could be bound by any binder, including asphalt. Cement concrete surfaces have different proportions of the ingredients above as compared to the asphalt concrete surfaces.

To get a porous mix, the proportions of stones, sand and filler are changed radically, mainly implying that the “medium sized” fractions are reduced (sizes approx. 1–4 mm in the case of Fig. 6). This will cause a lack of material to fill out the space between the larger chippings and will result in the air voids increasing substantially. Typically one aims at a porosity in the range of 15–25% by volume, although even higher porosities are desired from the drainage and noise point of view. However, it is always a balance between durability and drainage.

9.3 Acoustical Reduction Properties

Besides texture, porosity (expressed here as residual air voids content) is the most important parameter in order to create a low noise surface. One aims at a high sound absorption coefficient which would reduce not only tire/road noise but also power unit noise of the vehicles, especially if the sound can propagate for a long distance close over a porous surface. A high porosity will, however, be in conflict with the required mechanical strength and durability. Therefore high quality binders have been used in an attempt to compensate the loss of mechanical stability. The porous surface exhibits four major properties of importance to vehicle noise
reduction:
1. Its porosity will eliminate the compression and expansion of air entrapped in the tire/road interface when tires are rolling over the surface. "Air pumping and air resonant tire noise" will then be reduced (No. 2 in Chapter 4).
2. Its porosity will also reduce the amplifying effect of the acoustical horn existing in the space between the curved tire tread and the plane road surface (No. 4 in Chapter 4).
3. The porosity will give the surface an acoustical absorption, which will influence the reflection and propagation of the noise. This will influence not only tire/road noise but also other types of vehicle noise (No. 5 in Chapter 4), especially multireflected noise emitted or propagating underneath the body.
4. Finally, it is important that the surface with which the tire is in contact be as smooth as is possible, in order to reduce megatexture and large-scale macrotexture and thus reduce the radial vibration mechanism (No. 1B in Chapter 4). This can be achieved (1) by using small chippings (but not too small, otherwise porosity will suffer), (2) by rolling the surface several times after laying (but too much rolling will reduce porosity) and (3) by making sure that the larger chippings come close to each other.

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 Hamet, Attenborough, Bérengier, Storeheier and von Meier in [INTROC 90, 1990] for further information. A more recent paper on the subject, specialized on propagation effects, appears as [Bérengier et al., 1997].

For a certain porosity the acoustical absorption can be optimized. The design goal is to obtain the maximum amount of sound absorption \((a=1)\) at a frequency of \(f_{\text{max}}=1,000\) Hz for high-speed roads and of \(f_{\text{max}}=600\) Hz for low-speed roads [von Meier, 1992]. However, in [van Blokland, 1997] it is indicated that for cars it is better the lower the peak frequency is, within 500–1,100 Hz. In addition, the frequency spectrum bandwidth of the absorption coefficient should be as broad as possible. Porosity and flow resistance govern the bandwidth. According to [von Meier, 1992] the optimum flow resistance is in the range 20–50 \(\text{kNsm}^{-4}\) for high-speed roads and 12–30 \(\text{kNsm}^{-4}\) for low-speed roads.

Such a flow resistance is optimum, i.e. has the widest possible absorption bandwidth, if a maximum chipping size of 10–11 mm is employed, again according to [von Meier, 1992].

For heavy vehicles, the sound absorption should be designed for a maximum at one or two third-octave bands lower frequency than for cars. This is because they have their acoustic power more concentrated at lower frequencies. In practice, traffic noise is composed of noise from both cars and trucks in most situations. When there is no clear preference (cars or trucks), a general recommendation is to use the optimization for cars but to try to adjust somewhat in a "truck-related" direction.

9.4 The Importance of Air Voids and Thickness
As mentioned earlier, it is desired to obtain an air voids content of 15–25%, preferably at the higher end of this scale. An air voids content of 15–20% is supposed to correspond to average sound absorption coefficients of around 0.20–0.30 over the important frequency range. However, it has been shown that an average sound absorption coefficient in the range 0.10–0.20 also affects the noise [Sandberg, 1992]. However, such pavements give only 1–2 dB(A) of noise reduction and they are usually getting clogged within a short time.

The thickness of a porous surface influences noise reduction. Generally, the effect of increased thickness is to move the frequency of peak sound absorption to lower values and to move secondary peaks, which exist at 3 and 5 times the lowest frequency peak, into the most interesting range. At the same time, the absorption versus frequency dependence is smoothed out from a very "peaky" curve at small thickness (say 30 mm) to a much smoother curve at high thickness (more than 100 mm). This gives a possibility to optimize noise reduction by tailoring the thickness, since the fit between sound absorption frequency spectra and that of the emitted noise can be improved. When voids are partly filled with water, effects similar to that of increased thickness have been observed [Shima et al., 1994].

Several of the papers in [INTROC 90, 1990] show the 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 mm total...
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 researchers have also experimented with super-thick porous structures; in some cases up to 700 mm. Results indicate a total noise reduction of appr. 7 dB(A), instead of 4 dB(A) for thin layers, in relation to conventional, dense asphalt concrete [Pipien and Bar, 1991]. A 450 mm 4-layer structure (top chippings<8 mm) 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 [Stenschke, 1990]. The latter indicates the big improvement potential due to mechanism SB in Chapter 4, i.e. sound propagation.

Thus, for a low noise road surface one should aim at high air voids contents and relatively high thickness. Figure 8 shows the relation between noise reduction and the combined effect of air voids and layer thickness, which is an “equivalent air thickness”. To achieve a noise reduction of about 3–5 dB(A), 25% voids are required for a thickness of 40 mm (which is a common pavement thickness). The relation in Fig. 8 is highly significant ($R^2 = 0.72$), despite all other variables which are present but not considered, like max. aggregate size, reference surface and temperature. If aggregate size could also be introduced into the analysis it would probably show that most points above the curve refer to surfaces with small chippings and points below the curve to large chippings. It indicates that porosity and thickness combined explain 70–75% of the total variation, that it is no point in making the surface too thick (at least when new), but it also shows that it seems impossible to achieve more than about 8 dB(A) of noise reduction, and the latter will probably require a very small chipping size.

Figure 9 presents some typical frequency spectra. It shows that the range of noise reduction fits reasonably well with the range of sound absorption for a 40–50 mm thick pavement (Fig. 7). The upper part of Fig. 9 is a surface which is becoming a little bit clogged, displacing the noise reduction to lower frequencies at the expense of its amplitude. The lower part refers to a surface that is a little bit thinner but still open, thus it has a substantial peak reduction due to sound absorption around 1–1.2 kHz but no absorption at lower frequencies. It should be noted, however, that it is not uncommon that porous surfaces with medium or large chippings display increased levels under about 800 Hz, unless they are very well rolled to provide an even tire/road contact surface [Sandberg, 1979].
rubber powder have been tried. In those cases where a direct comparison has 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 rubber powder added to the binder and found no significant difference. Measurements on a surface in Sweden with fibres in the binder did not indicate any increased noise reduction in relation to one with pure bitumen. 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 studying 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 and thus have an indirect but rather important effect on traffic noise. Another indirect effect of the binder is that certain binders make it possible to design the surface texture and the porous structure in a way which is favourable to noise, e.g. a higher porosity with the same durability may be achieved if a modified binder is used.

9.6 Noise Reduction of Porous Cement Concrete

In Japan, the area of porous cement concrete exceeds 600,000 m². However, only sidewalks and other public areas than roads have been surfaced in this way, so far, and the purpose has not been noise reduction. According to [von Meier, 1988], cement shows promising properties as a binder since the internal porosity structure may be favourably influenced by the designer. This is supported by [Dalziel, 1992] who found a higher sound absorption acting over a wider frequency range for laboratory samples. However, later field tests with porous cement concrete have not always been fully successful since such surfaces sometimes have become uneven and thus uncomfortable to drive on.

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%. For motorways the thickness of the porous concrete layer needs to be about 40 mm. In order to avoid unfavourable megatexture the max. grain size of the aggregate of porous concrete should be about 10 mm". 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 a similar way as an asphalt surface can be rolled after 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.

A recent report from tests in Belgium [Caestecker, 1997] showed a 5 dB(A) noise reduction of a porous cement concrete (44 mm thick, 19% voids, 4–7 mm max chipping size), but very surprisingly a dense "fine concrete" with 4–7 mm max chipping size and
having an extremely low megatexture showed the same noise reduction! Especially the latter surface is certainly worthwhile to follow up. The porous concrete layer was 40% more expensive than a normal wearing course (+25% for modified binder).

More information on porous cement concrete surfaces may be obtained in [PIARC, 1995].

9.7 Clogging and Restoration of Clogged Surfaces

The acoustical optimization guidelines have so far only considered new porous surfaces. Optimization might look a little different if one would consider the entire lifetime of a porous surface, since after some time the clogging has made the communicating channels more narrow and much fewer and the assumptions regarding the structure in new, unclogged condition are no longer valid. This author considers it as most urgent to re-assess all optimizations for the case where some clogging has occurred and see how the optimization might change. A porous surface must be optimized for its entire lifetime, not only for its new condition.

Clogging might occur because there are deposits in the voids of dirt from the road surroundings, from wear products from the pavement itself and from tires. Furthermore, the surface is somewhat compacted by the traffic and the compaction occurs at the expense of the voids. The dirt particles might interact with some bitumen to form a "mortar" which may be quite difficult to remove.

The most effective cleaning process is the one which takes place during heavy rainfall and when vehicles travel at high speed on the surface. The removal of water at the leading edge of the tire/road interface, and the suction of dirt water up from the pavement at the trailing edge, may occur with very high pressure gradients and will give an efficient self-cleaning effect.

Many attempts to clean porous surfaces with water jets and following suction of dirt water have been reported in the literature — some of them successful (see Fig. 10) but also many not very successful. The most promising procedure is the investigation reported in [Matsuda et al., 1998]. This Japanese study concluded that the best cleaning process was a combination of water jet blasting, dirt water suction and vibrations transmitted by a "plane of water" between the water blasting and suction.

Whether a porous surface should have double or just a single layer (for the same total thickness) is not so important in the new condition, but very important in used condition; see further about Twinlay.

The reader is recommended to study a proposed management and maintenance program for porous surfaces presented in Fig. V.8 in [OECD, 1995]. It is suggested that two years after laying and then periodically every two years, the surface should be cleaned, including road shoulders.

9.8 The Double-layer Concept ("Twinlay")

With regard to the most effective low noise surface considering the full acoustical lifetime, there are basically three schools:

(1) Small max. chipping size (4–6 mm) and a high porosity shall be utilized. The initial reduction is very high although inevitably clogging will occur in the relatively narrow channels, but seen over many years the efficiency is acceptable. Mainly German and French sources favour this principle.

(2) Large max. chipping size (16–20 mm) and a high porosity shall be used. Since the voids channels will be relatively wide, it will take a considerable time until they become clogged. The initial noise reduction is traded in favour of a moderate reduction preserved over a longer time. This principle is favoured by mainly British sources. It also
has support in the results of [Sandberg, 1997].

(3) Double-layer: One shall combine the two principles into one, using the first principle in a top layer in contact with the tires, and using the second principle in a bottom layer. This is a principle tried in France quite early but mostly employed nowadays in the Netherlands. The latest design in the Netherlands has been named Twinlay referring to the double layer, see below. This surface is claimed to have a long acoustical lifetime, provided it is cleaned regularly.

The last principle may need some explanation.

The original Twinlay surface consists of:
- a top layer of max. 4-8 mm chippings, 25 mm thick, 26% voids
- a bottom layer of max. 11-16 mm chippings, 45 mm thick, 26% voids

It is interesting to note that the binder includes rubber granulate 0.15-1.0 mm in order to resist ageing and allow the unusually high binder content of 6.5%. 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 is due to the rubber granulate, if any.

The Twinlay concept is especially intended to avoid the clogging effect in urban areas. The idea is that the upper layer acts as a "filter" with rather small but many channels (pores) between the small chippings in which dirt would be accumulated (a "sieve effect"). Due to the small chippings and with appropriate rolling, it is relatively easy to get a smooth megatexture, which results in low noise at low frequencies. The layer underneath has bigger chippings and wider channels. The size of the chippings has no negative effect here. When a cleaning machine sprays water on the surface there is plenty of discharge volumes under the clogged top layer through which the water/dirt mix can escape and be sucked up (see Fig. 10). It is claimed that the top layer can be efficiently cleaned and that the particles released from it will not fill the bottom layer since they are enough small to be easily drained away. A cleaning frequency of once per year keeps the acoustic efficiency at approximately the initial level. First tests took place in 1990 after which several sections have been laid. A problem experienced was that it may be troublesome to get enough bonding strength between the two layers, and skilled asphalt laying operators are needed in order to lay the thin top layer satisfactorily.

A refined design called Twinlay M has been presented, with the purpose to increase friction and resistance to wear at road intersections. It is the same as the old one except that the top layer is only 15 mm thick with chippings of max. 2-4 mm. It means a lower total thickness. Test sections were laid first in 1996 and followed by several others. The town Breda alone has >10,000 m² of Twinlay.

Recently, a drain suitable for draining water and dirt away from the road in urban applications where there are kerbstones or other obstructions at the roadside has been presented ("Keradrain"). It is produced to supplement the Twinlay or other porous surfaces at such locations.

The acoustic efficiency is claimed to be very good, even for low speeds. Measurements on the original Twinlay with the SPB 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 Twinlay M is approximately 2 dB(A) more efficient and is claimed to give a significant traffic noise reduction even at 30 km/h.

Most of the information above comes from [Heerkens and Bochove, 1998]. See also [van Blokland].

Some comments: The fine top layer should become clogged fairly soon and thus need frequent cleaning, although cleaning may be efficient. However, the acoustic efficiency may stay good even with a somewhat clogged top layer since it will create some type of Helmholtz multi-resonators with narrow necks at the top and large volumes underneath, which should give a sound absorption over a wide frequency range including rather low frequencies. The total thickness is 80 mm which seems to be close to an optimum (see Figs. 7-8) and the voids times thickness product is also near the maximum efficient one according to Fig. 8. Low megatexture should further improve noise reduction.
9.9 Concluding Remarks

Some special issues not mentioned before will be mentioned here. First, low noise surfaces would be especially beneficial on bridge decks, because noise propagation from bridges is a difficult problem. A first study on this was reported in [Hakamada et al., 1998] although the noise testing was not yet made. In another study, including only dense pavements, no low noise surface durable enough for a bridge was found [Sczyslo, 1995] but continued studies were planned.

Another item of interest is the combination of a porous surface and noise barriers. Few field tests seem to have been made, but scale modelling has suggested that a porous surface 5 dB(A) less "noisy" than a reference dense surface will give a little lower reduction when combined with a screen [Bérengier and Anfosso-Lédée, 1998]. Depending on the receiver position the road surface reduction effect will be 2-5 dB(A). A similar study in Japan, also indicated that one cannot simply add the effects of a low noise surface and a barrier [Berengier and Anfosso-Ledee, 1998]. The total effect is somewhat lower.

During wet weather, in general, one can say that a porous surface will have approximately the same efficiency as in dry weather. There are data indicating possibly a little lower effect [Sandberg, 1985] but also higher effects, see e.g. [PIARC, 1993] and [Shima et al., 1994]. This is because the surface is usually kept relatively dry also in wet weather; however, the sound absorption effect around 1 kHz is lost since the voids are filled with water [Shima et al., 1994]. The drying process may take several days, impairing noise reduction efficiency for a considerable time after a rainfall.

The reader will find a most comprehensive and impressive report on the use of low-noise surfaces, mainly porous, in a French book unfortunately written only in French [Bar and Delanne, 1993]. A few years ago, the World Road Association issued a textbook on porous surfaces in general [PIARC, 1993]. Nordic experiences regarding porous surfaces are reported in [Sandberg et al., 1993].

10. EXAMPLES OF CURRENT USE AND EXPERIENCE OF POROUS SURFACES

In Italy, currently 10% of the 3,000 km of motorway network is surfaced with porous asphalt concrete. Clogging is recognized as a problem but is efficiently managed by regular cleaning operations. Nowadays all new porous surfaces are cleaned after two years [Luminari, 1998].

Nordic results have shown that in urban applications (50 km/h), a “normal” porous surface will become clogged already after one year so that its acoustic efficiency is almost totally lost, see [Sandberg et al., 1993] and [Bendtsen, 1998]. An exception was a “Duradrain” which worked well in an urban area also after one year [Sandberg, 1997]. In extraurban applications, even without cleaning efforts, most of the noise reduction effect may be kept for about 6 years [Bendtsen, 1998] although serious stripping occurred in the 7th year. Both the Swedish and Danish road administrations consider porous asphalt surfaces as about 50% more expensive than dense. Danish estimations indicate that a double-layer pavement like Twinlay would cost 2.7-3.5 times a dense pavement [COWI, 1998]. The Nordic experience is that in wintertime de-icing with salt requires more salt and the operations must be better predicted. Road stations being experienced in this are able to manage friction problems fine.

Porous asphalt surfaces have been used extensively in France for about a decade, mostly in extraurban areas but also in urban areas. To-date the area covered with porous surface is 45 million m², the major part of this is on toll motorways where 15% of the network length (1,500 km) is covered with porous asphalt. The most important objective is to reduce water spray and wet skidding. In urban applications there is widespread disappointment re. the acoustical lifetime and winter operation problems. Although the use of such surfaces has not been equally extensive in Germany, the disappointment seems even bigger there. In both countries, few porous surfaces have been laid recently.

The Dutch government enacted a law several years ago, requiring roads on the entire highway network carrying traffic above a certain limit to be resurfaced by and by with porous asphalt; i.e. using a porous surface each time a highway needs normal resurfacing. This has now resulted in most of this high-volume road network being covered with porous asphalt. Mostly, a single layer with 16 mm max chipping size has been utilized. It is acknowledged that clogging is a problem. They have also recorded friction problems which seem to be inherent of this surface type [Jutte and Siskens, 1997].

Hong Kong has a most interesting resurfacing programme in which they have resurfaced 10.3 km
of high-speed roadways and will resurface another 0.85 km with porous asphalt. Currently, porous surfaces are used as standard material on new (non-inclined) highways with speeds > 70 km/h. The type used is a 50 mm polymer modified asphalt, comprising a 20 mm polymer modified cushion course material as the base and 30 mm friction course material as the top layer. It contains 18–25 % air voids and aggregate size is < 10 mm. The experience indicates that noise reduction is about 5 dB(A) initially, but deteriorates fairly uniformly with time and is down to about 1 dB(A) after 5 years. The first section was laid in 1987 and re-overlaid in 1993 since they normally resurface these road sections every 5 years in consideration of noise benefit and cost issues [Yeung, 1998].

Porous asphalt is used on the majority of the New Zealand motorway system (300 km) and high-traffic-volume divided carriageways. On the State Highway system it is estimated that there is approximately 1,200 lane km of porous asphalt surfacing. By far the majority uses a 14 mm maximum aggregate size with a total air voids content of 20–22 %, although there is some use of a 20 mm aggregate size mix laid 40–50 mm thick, again with approximately 20 % air voids. The latter has been used on roads where water cannot drain to the sides, e.g. on hills, and a larger storage capacity is required. Polymer modified binders have been used in areas of high stress [Patrick, 1998]. Note: Having inspected many New Zealand roads recently and studied the specification, this author thinks that the max. aggregate size is more like 8 mm instead of 14 mm.

Porous concrete pavements have been used recently on a trial basis in France, Spain, Netherlands, Belgium and Germany. For urban roads up to 40 cm of thickness has been tested in France [PIARC, 1995]. A 15 cm thick surface was said to be equally good as the best porous asphalt surfaces and was the most quiet cement concrete surface recorded in France.

11. CURRENT USE OF OTHER LOW NOISE SURFACES

Exposed aggregate cement concrete surfaces have gained high popularity in recent years in countries such as Australia, Austria, Belgium, U.K. and Sweden where they are now more or less standard treatment of a cement concrete surface. In Japan, some trials have been made also [Shimeno et al., 1998]. Thin wearing courses are used to a great extent in France, Sweden and the U.K. and are tried also in USA. Surface dressings (chip seals) with only very small chippings are used on a limited basis in Austria, Germany, Netherlands and the U.K. and probably in some other countries.

12. FUTURISTIC SURFACES

12.1 The Poroelastic Road Surface

A poroelastic road surface consists of granules or fibres of rubber (or similar elastic material) bound together with a binder of e.g. bitumen or polyurethane. The same binder may also be used to bind the surface onto a base course. Rubber may come from scrap tires. In some variants, a poroelastic road surface may contain also sand and/or stone material. Poroelastic road surfaces manufactured and tested so far have had a voids content 30–40 %. The elasticity of the surface is beneficial to “vibrational-excited” tire/road noise. Thus, the poroelastic road surfaces tested so far have all been very effective for reduction of road traffic noise—the effect being around 10 dB(A) compared to conventional dense asphalt surfaces. This is the best result recorded for any low noise road surfaces.

This means that this type of surface may compete with conventional traffic noise reduction measures such as building of noise screens or exchange to special noise-insulating windows. It has been estimated that the road area on which low-noise road surfaces would be beneficial, i.e. where noise reduction measures are required, is as large as 70 km² only in Japan.

However, to-date there are no poroelastic road surfaces which have left the experimenting status and serious problems still remain unsolved, like adhesion to the base layer and friction properties. The poroelastic road surface was invented and developed in Sweden in the late 70's and early 80's. Development then concentrated on obtaining an acoustically very effective surface but did not put great efforts in getting it durable and safe. Field tests in Sweden and in Norway at the end of the 80's consequently failed with regard to durability.

Two projects are on-going: One in Sweden in which a mix of sand and stones supplement the rubber granules, the latter of which come from scrap tires. The other project is conducted in Japan, using factory-made rubber mats glued on cement
base courses. Extensive tests of many types have been conducted in this Japanese project and the results so far are promising. For example a test section has been in operation two years now. One of the remaining problems is to find a binder that effectively binds the surface to an asphaltic base course. Another is to get more economic binders.

Regarding literature, the reader is referred to the first paper by the Swedish inventor [Nilsson, 1979], to several papers/articles by Japanese authors which are summarized in another article in this journal, by Dr. S. Meiashi, and to a recent state-of-the-art review by this author [Sandberg, 1998-2].

12.2 The Pavetex Carpet and Topping with a Rubberized Mix

An interesting “topping” for existing cement concrete pavements is a surface called GPUX, after the inventor Mr. G. Potter. This is an elastic, truly flexible surface consisting of 1/3 of rubber mixed with a stone aggregate, sand and polyurethane binder. Successful trials (so far) have been made to apply it to cement concrete blocks. Although the surface was made primarily for obtaining ice-free roads in winter climate, there seems to be a noise benefit too. Results are not yet published, but this author has received information via personal communication with Graham Potter Associates in the U.K.

A somewhat related idea was presented in a paper by [Iwai et al., 1990] at the International Tire/Road Noise Conference in Sweden in 1990 where a 6 mm thick “Pavetex” carpet was presented which was claimed to reduce tire/road noise levels down to those on porous surfaces.

12.3 The Euphonic Pavement

Around 1990, trials were made at VTI to check how background noise in trailers used for noise testing of tires and roads could be checked. One idea was to eliminate the noise from the test tire by using extremely “quiet” tire/road combinations. For this purpose, a pavement was used which consisted of Helmholtz resonators underneath a perforated, plane aluminium structure. This “pavement” was developed at the University of Goettingen in Germany during a scholarship period there by J. A. Ejsmont, Technical University of Gdansk. This type of pavement was found to be approximately as quiet as a soft carpet for homes (unpublished).

The same concept has been employed by Italian researchers in the construction in 1992/93 of a so-called Euphonic Pavement, [OECD, 1995] and [Luminari, 1998]. It consists of a 40–60 mm thick layer of porous asphalt on top of a continuously reinforced concrete slab with resonators of about 500 cm³ each, distributed over the entire surface in a manner shown in Fig. 12. Scale models have been tested and the pavement has been scheduled for further refinement and full-scale implementation within and as a major part of the new European SIRUUS project, probably to be field tested in 2001. It is meant to be used in extrarural areas. For urban areas, the SIRUUS project will develop a new pavement also utilizing some type of resonators between layers in a double-layer (?) construction [Luminari, 1998].

13. INCENTIVES FOR USING LOW NOISE ROAD SURFACES

In the EU Green Paper on “Future Noise Policy” it was suggested that when it is feasible “the Commission will promote the use of low noise surfaces for road projects in noise sensitive areas receiving Community funding.” The idea is interesting but the restriction that low noise pavements shall be supported only in projects which obtain funding from the Community, implies that the effect of such support will be very limited on a global scale.

Another example is that the Twinlay surface qualifies as a low noise surface under the Dutch Noise Control Legislation act “Wet Geluidshinder”. It probably gives this surface some advantage or even requires such a surface.

A third example concerns the U.K., where proposals are being worked out to develop a new type approval procedure called HAPAS to be operated by the British Board of Agrément [Phillips, 1998]. This will include an optional noise test using the
SPB method, although no noise limits are set. Because of noise concern the Highways Agency specifies that no roads carrying more than 75,000 veh./day are allowed to be laid with cement concrete unless the exposed aggregate technique is used.

Finally, some traffic noise prediction methods include corrections for road surface influence, which indirectly encourages the use of low noise surfaces. The most sophisticated road surface correction scheme, worked out by this author, appears in the Nordic method [TemaNord, 1996].

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