The global experience in using low-noise road surfaces: A benchmark report

By Ulf Sandberg[1]
Sweden

Final report
16 February 2009

Report made in response to
Hong Kong Environmental Protection Department project No. AN 06-004
"Reviewing the Trial of Low Noise Road Surface (LNRS) in Hong Kong and Benchmarking the Experience on the Use of LNRS in Overseas Countries"

---

[1] Senior Research Scientist at the Swedish Road and Transport Research Institute (VTI), Linköping, Sweden, and
Adjunct Professor 2002-2008 at Chalmers University of Technology, Division of Applied Acoustics, Gothenburg, Sweden

List of contents

FOREWORD

This work has been conducted as part of the project "Reviewing the Trial of Low Noise Road Surface (LNRS) in Hong Kong and Benchmarking the Experience on the Use of LNRS in Overseas Countries" (No. AN 06-004) for the Hong Kong Environmental Protection Department (EPD). A report has been submitted earlier regarding the first part of the project, i.e. "Reviewing the Trial of Low Noise Road Surface (LNRS) in Hong Kong". This report intends to cover the second part if the project; i.e. "Benchmarking the Experience on the Use of LNRS in Overseas Countries".

In the contract it is written that the Benchmark report shall provide a benchmark/review of "the applications of LNRS materials (including the use of elastic porous asphalt) in some overseas countries, including USA, Japan, the Netherlands, Sweden, Denmark and UK and propose the possible way forward on trial of LNRS materials in Hong Kong".

This report therefore includes a rather comprehensive state-of-the-art review with regard to the global experience of low noise road surfaces, but with a clear focus on the mentioned six countries. In addition to the six countries, however, the author has chosen to review some of the research in Germany, Austria and Switzerland, since it has been considered to be of particular interest to the further work in Hong Kong. Unfortunately, there has not been time to do similar reviews for countries such as Canada, France, Italy, Spain and Portugal, simply since time has not been sufficient and the report has already become rather large.

Even for the countries treated in the report, the review can be seen as nothing but a snapshot, since there is such a wealth of information on the subject in each one of them and it is beyond the capacity of the author, given the time and budget constraints, to cover all but the most interesting things. When choosing "the most interesting things" the selection has been made with the assumed needs of the Hong Kong LNRS policy and ambitions in mind.

This means, for example, that this report attempts to look especially at low noise road surfaces applied in urban areas on low-speed roads. This low-speed and urban focus is so important for this report that it could even had been part of the title. Research on LNRS almost exclusively dealt with high- or medium-speed roads until about 2000 after which researchers and road engineers started to look for solutions also in low-speed cases. The bulk of literature therefore deals maybe to 90 % with high-speed cases and 10 % with low-speed cases. Therefore, in this report, often experience with regard to high-speed applications of LNRS are somewhat neglected and instead low-speed cases are lifted forward.

As required, this report attempts to evaluate the experience reviewed and based on this suggest how Hong Kong LNRS policy can be improved and go forward. Consequently, it includes a long list of recommendations.

It is hoped that the recommendations will be useful and lead to a more efficient LNRS policy in Hong Kong in the future. It is also hoped that the report may stimulate innovation and the willingness to test new technologies (new for Hong Kong), of which some undoubtedly will fail but hopefully a few will succeed and thus justify the efforts spent. Remember that research and trials that never fail will not be even close to cutting edge research.

The Author

ABSTRACT

This report provides a rather comprehensive state-of-the-art review with regard to the global experience of low noise road surfaces, but with the following focus areas:

- Experience in primarily USA, Japan, the Netherlands, Sweden, Denmark and UK; secondarily in Germany, Austria and Switzerland

- Relevant parts of large European research projects

- Experience related to low-speed roads (50 km/h or less) in urban areas

The information has also been collected and evaluated with the Hong Kong low noise road surface policy and its assumed future needs in mind.

Apart from review of research on low noise road surfaces, country by country, this report also includes a brief review of the particular policies in the mentioned countries with respect to selection of road surfaces and especially coupled to the impact on noise emission that this policy has.

Naturally, since one of the major noise-reducing tools that the road engineer has is to give the road surface a high air voids content, this review to a large extent deals with porous surfaces. Nevertheless, since in later years so-called thin layers have become very popular, not the least due to low-noise properties, this type of surface is also the subject of large parts of this report.

Based on the collected material and evaluation of its results, the author gives recommendations for implementation of certain findings in the Hong Kong low noise road surface policy, as well as suggests topics for further studies and development for the purpose of improving the same.

ACKNOWLEDGEMENTS

This work has been conducted as part of the project "Reviewing the Trial of Low Noise Road Surface (LNRS) in Hong Kong and Benchmarking the Experience on the Use of LNRS in Overseas Countries" (No. AN 06-004) for the Hong Kong Environmental Protection Department (EPD).

The author is grateful to the Hong Kong EPD for sponsoring this project and for all support given by the EPD as well as the Highways Department (HyD) during the course of the project. The author is particularly grateful to Mr Ping-sum Ng and Mr Alvin Tse of the EPD, as well as Mr Chun-wah Chow and Mrs Claudia Kan of the HyD who have been very helpful as expert guides during visits and for supplying information between the visits. Also the interest and support by Mr Elvis W K Au and Mr C W Tse, Assistant Directors of the EPD, is gratefully acknowledged.

In April-May 2007, the author was invited to take part in the study tours that Hong Kong officials made to the Netherlands, Germany, Denmark, California, Arizona and Japan, based on a proposal made by this author as part of the project. These tours were extremely interesting and enhanced this work substantially. The author is very grateful to the EPD for extending the project to allow this participation by myself.

It has been a true pleasure to work with the mentioned individuals as well as with several others in Hong Kong who have been involved and who have all so generously shared their knowledge and experience, in addition to offering their sincere friendship.

Most of all, the author is grateful to all research colleagues and others involved in road research and management in various countries, who have been so kind in supplying information for this report. The individuals assisting with this are so many that it is difficult to list them all. Common to everybody has been an openness to share information and doing their best to answer questions. It is really stimulating to be part of such a wonderful traffic noise research community.

The author is Senior Research Scientist at the Swedish Road and Transport Research Institute (VTI), in Linköping, Sweden, and was also Adjunct Professor at Chalmers University of Technology, Division of Applied Acoustics, in Gothenburg, Sweden during the 6-year term 2002-2008. However, this project was conducted independently by the author by special agreements. Nevertheless, the author is grateful to VTI and Chalmers for making this work possible.

The author welcomes comments related to this report; please send them by e-mail to ulf.sandberg@vti.se

The Author

LIST OF ABBREVIATIONS AND ACRONYMS

Road surface types

AR	Asphalt rubber surface – may be gap-graded or open-graded (rubber granules mixed into the binder or the aggregate)
ARFC	Asphalt rubber friction course – open-graded AR (term used in Arizona)
DAC	Dense asphalt concrete
DPAC	Double-layer porous asphalt concrete
HRA	Hot rolled asphalt (common surfacing in the UK)
OGAC	Open-graded asphalt concrete (common in Denmark and the USA)
OGFC	Open-graded friction course (essentially the same as OGAC)
PAC	Porous asphalt concrete (single-layer)
PERS	Poroelastic road surface (surface with high porosity made mainly of rubber) (in the Q-City project the term is used for AR surfaces)
PMFC	Polymer modified friction course (term used only in Hong Kong)
RAC	Rubberized asphalt concrete – essentially same as AR (term used in California)
SLPA	Single-layer porous asphalt concrete (term used only in the Netherlands)
SMA	Stone mastic asphalt (= Stone matrix asphalt in American English)
TLPA	Twin-layer porous asphalt concrete (term used only in the Netherlands)

Other items

AADT	Average Annual Daily Traffic (bi-direction traffic count for an average 24h day)
BASt	Bundesanstalt für Strassenwesen (German Federal Road Research Institute)
dB	Decibel, unit for sound level
CPX	Close-Proximity Method (method to measure noise characteristics of surfaces)
DoT	Department of Transport(ation)
DRI	Danish Road Institute
DWW	Road and Hydraulic Engineering Institute (DWW) (in 2007 renamed RWS - Rijkswaterstaat)
EPD	(Hong Kong) Environmental Protection Department
EU	European Union
FHWA	Federal Highway Administration (USA)
HyD	(Hong Kong) Highways Department
IPG	Innovatie Programma Geluid (Noise Innovation Programme for Road and Rail Traffic) - Dutch research programme
LNRS	Low Noise Road Surface(s)
PMB	Polymer-modified binder
PWRI	Public Works Research Institute (Japan)
Q-CITY	European research project (see special section with this name)
SILENCE	European research project (see special section with this name)
SILVIA	European research project (see special section with this name)
SPB	Statistical Pass-By Method (method to measure noise characteristics of surfaces)
SPL	Sound pressure level
VTI	Swedish Road and Transport Research Institute
WnT	Roads to the Future - Dutch research programme

1. THE NEED FOR TYRE/ROAD NOISE REDUCTION BY IMPROVED ROAD AND STREET SURFACES

A couple of years ago the following statement by The Staff of the American Concrete Pavement Association was published in Better Roads, Aug. 2003, "Special Concrete Section":

"The bottom line is that, now, tire-pavement noise really is a non-issue. To the extent it was ever a problem, the matter has been resolved. Decisions should be made towards making our highways and roadways safer for the American public. When thousands of lives are being lost on wet pavements, the industry's priority should be on safety – not on minuscule levels of tire-pavement noise."

This author thinks that there is total agreement that the first priority is safety but the part of the statement saying that tire-pavement noise (what this author calls tyre/road noise) is a non-issue is in sharp contrast to the problems facing many if not most road and street authorities. This is valid in most industrialized countries. An example is the U.K. in which economic compensation is paid to home owners whose homes are exposed to too high levels of traffic noise from new or rebuilt highways. It has sometimes occurred that such compensation for noise has exceeded the rest of the cost of the highway. Obviously, tyre/road noise is an extremely important issue in such cases.

A key point is that there is not necessarily any conflict between requirements on safety and noise. For example, countries such as the Netherlands and Japan already require the use of low noise road surfaces on all highways in noise-exposed areas, and the U.K. Highways Agency more or less banned cement concrete pavements based on noise concerns[2] and is replacing "noisy" pavements with "quieter" ones over a 10-year period. It goes without saying that they would not do so if this would jeopardize safety.

Tyre/road noise was a concern already 2000 years ago in ancient Rome in which possibly the first noise ordinances were introduced. The wheels of various types of carts and carriages made a lot of noise when rolling over the very uneven stone pavements. Also, about a century ago, there are several indications of tyre/road noise being a problem; for example, the king of the Swedish-Norwegian Union, Oscar II, required the use of a wooden block pavement on some locations in Oslo, Norway, to reduce noise (Fig. 1). One of these locations was the access road running into his castle where still today an area paved with wooden blocks remains. In the Hong Kong study tour to Denmark in April 2007, it was noted that such a pavement still existed also in an indoor driveway in Amalienborg; the former Danish Royal Castle, now the residence of the Crown Prince Frederik and his family. The Danish and Swedish royal families were well acquainted with each other; for example the Danish Crown Prince (later King) Fredrik VIII married in 1869 the Swedish princess Louise, and they or their advisors might have shared the ideas of this quiet pavement. It was also common that straw was used to dampen the street noise outside hospitals and other sensitive places. In 2001, the 100th anniversary of the death of the great Italian composer Guiseppe Verdi in Milan was commemorated by covering the street outside the still existing hotel where he spent his last weeks with straw, since this was what people did 100 years earlier to reduce the noise from the street surface.

[2] Whereas in fact also cement concrete pavements may be made quiet….

Today's tyre/road noise is also a matter of concern. In fact it is one of the major environmental problems of modern society and one which is not stabilized or "under control". Indications of the growing noise problem are social surveys and records of complaints to authorities. For example, in England and Wales, there are now more than double the number of domestic and transport related noise complaints to local authorities than there were ten years ago [Anon.; 2003]. In Germany, noise exposure from road traffic noise increased steadily during the 1990's [Fichtner, 2002]. In the latest Swedish property taxation, it was reported from one of the major regions that each fourth property owner requested depreciation due to road or railway noise, despite it was expressed on the forms that the proposed property values already took noise exposure into consideration. Yet, Sweden is one of the quietest countries in Europe. Other indications are the increasing public reluctance to accept new roads and motorways that authorities decide on; although the reasons often are attempts to bypass traffic in urban areas to solve the associated environmental problems.

Fig. 1. Laying of "noise-reducing" wooden blocks in a street in Oslo, Norway, at the beginning of the previous century. Photo by courtesy of the Swedish Road Administration Museum.

A fundamental question is: will the traffic growth and increased noise be accepted at all? The traffic growth reflects a desire to expand commerce and increase personal travelling; in some areas such as Hong Kong it also indicates a growth in population and new residential areas. This is what one part of the population wants. Another part wants to cut down on traffic; irrespective of the mechanisms behind the traffic growth. This author believes that the traffic growth will be accepted *only* provided the environmental problems can be solved. In other words, the message is: Make quieter tyres or fewer tyres, make quieter roads or no roads. In practice, it means that a Road Administrator who does not have a sufficient competence in laying, managing and maintaining quiet road surfaces, or an Environmental Protection Department which lacks knowledge in how to use low-noise road surfaces as noise abatement tools, will not satisfy their customers - the public.

Lack of knowledge on the use of low-noise road surfaces (LNRS) does not apply to the responsible authorities in Hong Kong. In Hong Kong, trials to use low-noise road surfaces (LNRS) started in 1987 and a programme for resurfacing high-speed roads with such material has been in force since the early 1990's. Nowadays the use of LNRS on high-speed roads in noise-exposed areas is common practice, given certain traffic and road conditions. In 2002 a new programme started aiming at trying such surfaces also on medium- and low-speed roads and streets in urban areas.

In 2006, the Environmental Protection Department (EPD) of Hong Kong published a "Comprehensive Plan to Tackle Road Traffic Noise in Hong Kong" [EPD Plan, 2006]. An important part of this plan is an increased and widened use of low-noise road surfaces (LNRS) on low-speed roads and streets. In order to evaluate the LNRS programme, to review international experience and to obtain ideas and proposals for making the use of LNRS more efficient in the future it was decided to sponsor a project in which international expertise would be engaged to conduct reviews and evaluations. After a tendering procedure, the author was selected to conduct this project. The project results are presented in two reports, of which this is the second one.

2. PURPOSE, LIMITATIONS AND METHODS

The purpose of the work reported herein is to review the experience and results of the application of low-noise road surface (LNRS) materials in other countries than Hong Kong[3]. Furthermore, the practice and official policy with regard to the use of such road surfaces is reviewed. The report addresses the experience with both low-speed and high-speed roads and streets, although the major interest in this report is on low-speed roads, and it has been the ambition to especially focus on this so far under-researched part of the problem. Unfortunately, the majority of experience is with high-speed roads; thus the information related to low-speed roads is rather limited. As foreseen in the tender documents for the project, the review is focused on six countries, namely USA, Japan, the Netherlands, United Kingdom, Denmark and Sweden, but major experience with LNRS in other countries are also reviewed, albeit in less detail.

This study has been conducted in the following ways:

- Review of reports, articles and conference papers
- Experience from personal study visits to test sections with LNRS worldwide and active participation in international projects
- The study tours that Hong Kong officials and the author made to the Netherlands, Germany, Denmark, California, Arizona and Japan in 2007
- Discussions with colleagues and other experts at meetings and conferences
- Communication by e-mail with colleagues and other experts

During the last few years the interest in low-noise road surface materials and their use on roads and streets has accelerated and the trend is still increasing. The number of documents dealing with the low noise road surfaces has thus rocketed to an annual level which is no longer possible to review in full. Therefore, it must be pointed out that this review is far from complete; not even for the countries on which the study is focused.

The report deals with exterior tyre/road noise and traffic noise emitted from the vehicle/road interaction and propagating to the environment. It does not address interior noise inside vehicles. The reader should recognize that the relation between exterior and interior vehicle noise and the effects on these of various surfaces may not be very straightforward and clear.

3. STRUCTURE OF THIS REPORT

This report could be structured in two basic ways:

1. Review the experience country by country, with sub-sections by major subjects
2. Review the experience by subject, with sub-sections by country

The author has chosen the first alternative, plus a special section on international projects, and a supplementary section reviewing similarities and differences between countries by subject.

[3] The experience of LNRS in Hong Kong is already reviewed in the first report within this project.

4. BRIEF REVIEW[4] OF ROAD SURFACES USED FOR REDUCTION OF ROAD TRAFFIC NOISE

4.1 General overview - The role of the road surface

The role of the road surface is to provide a safe, economic, efficient, comfortable and environmentally friendly drive of the vehicles travelling on it and also to be economic and environmentally friendly when being constructed. Therefore, a number of surface characteristics must be favourable, such as skid resistance (both in dry and in wet weather), tyre wear, surface wear, durability, visual guidance, drainage, splash and spray generation, emission of particulates, rolling resistance and noise generation. It follows that the parameter of particular interest in this report, i.e. noise characteristics, is just one of many parameters to observe in the design and construction process.

In many situations the effect of the surface on noise emission is very important. The difference in road traffic noise for a range of road surfaces, given the same traffic and speed, may amount to as much as 10-15 dB(A)[5] in rare cases and 5-8 dB in common cases. This can be compared with the noise reduction of a noise barrier, which in the most favourable cases (covered roads excluded) may amount to around 15 dB(A) but as an average may be around 8 dB(A)[6] behind the barrier as seen from the road.

It must be pointed out that as far as we know, the road surface itself does not generate noise[7]. Therefore, in a physical sense, it cannot be "noisy". On the contrary, any road surface is always “silent”. It is the tyre which emits noise when running on the road surface. Even the tyre is absolutely silent when it does not roll. However, since the noise is generated in a tyre/road interaction process, and this noise is much influenced by the surface characteristics, it is common practice to speak about "noisy", "quiet", or "low-noise" surfaces, meaning that it is the traffic travelling on this road surface which may be "quiet" or "noisy", as affected by the road surface.

The following sections intend to give as an introduction a brief overview of both "noisy" and "quiet" road surfaces in rather general terms. If nothing else is noted, the terms "noisy" or "quiet" or any "noise reductions" refer to dense asphalt or SMA reference surface with a maximum aggregate size of 11 mm.

---

[4] This chapter is adapted from a similar chapter in the other report within this project [Sandberg, 2008-1]. It is essentially repeated here since it may be useful as a general overview before going into details in later chapters. Readers who have read this chapter in the other report, or who are familiar with low-noise road surfaces, may just neglect this chapter.

[5] The correct notation of the unit is "dB" and the relevant measure is "A-weighted sound pressure level". However, the notation "dB(A)" is very often used to make it clear without writing the longer term "A-weighted" that A-weighting has been used when processing the sound levels. ISO does no accept the "dB(A)" notation.

[6] A change of 10 dB in noise level is generally considered to correspond to a doubling or halving of the subjective perception; although some experts argue that even a 3-5 dB change may have such effects under certain conditions.

[7] One should also be aware of that "noise" is defined as "unwanted sound" and as such is not a physical parameter; instead it is a subjective parameter. However, it has become common practice in environmental engineering to use the term "noise" as a synonym for "sound" with the implication that this type of sound is unwanted by most people. Therefore, the term "noise" is used in this report to represent the physical parameter sound pressure, where it is understood that the sound is unwanted.

4.2 Road surfaces to be avoided

First it should be mentioned what kind of surfaces that one should avoid because of their noise characteristics. Some of them are actually among the most popular ones; mostly for durability and safety reasons. The following surfaces should be avoided; listed from the worst to the more moderate ones:

- **Paving setts:** Paving setts of the old types create of lot of tyre/road noise. They are justified mainly for historical and/or cultural reasons, and often on streets where there should be little traffic. Surfaces of this kind are frequent in old towns in Europe. See further [Sandberg & Bendtsen, 2007].
- **Transversely tined cement concrete (TTCC):** Cement concrete surfaces with transverse tines produced by dragging steel tines in a comb-like structure in the non-cured concrete are second in noise emission only to old types of paving setts. If the spacing between tines is not randomized, such a surface may create a whistling and extremely annoying tonal noise. Randomized tine spacing will not reduce the noise level but will reduce annoyance to some extent. Although the noise problem has been widely recognized since the early 1970's, these pavements are still used extensively in the USA but have been abandoned in Europe for noise reasons. The brushed concrete (see below) frequently used in Hong Kong, looks similar to a tined surface but is usually not as "rough" as is often the case in USA. See [Rasmussen et al, 2007].
- **Brushed cement concrete (BRCC):** Instead of using steel tines one can use a softer material (a "brush") to brush the concrete transversely to the driving direction while the surface is still uncured. Depending on the brush material and exact brushing technique used, these surface may range in noise characteristics from being equal to the noisiest SMA:s up to the "noisiness" of the TTCC. The BRCC was used in Hong Kong as the traditional paving material on high-volume roads and streets, but is not used any longer in new constructions.
- **Hot rolled asphalt (HRA):** The HRA has been widely used in the UK, but is now being phased-out due to noise reasons. A revision of the U.K. traffic noise prediction method, the CRTN, specifies a difference between HRA and SMA as large as 4-5 dB for high-speed highways and motorways [Abbot & Nelson, 2001].
- **Surface dressing with large chippings:** Surface dressings (chip seals) are unfavourable if maximum chipping sizes are above about 13 mm. These were very popular in Europe on low-volume roads in the 1970's, not the least in Sweden, but are nowadays rarely used on roads where traffic noise is a significant problem.
- **Very smooth surfaces:** Surfaces, in particular cement concrete, with a very smooth macrotexture are "noisy" due to the poor "ventilation" to air in the tyre/road interface which they provide. These should be avoided, anyway, for safety reasons.
- **SMA and DAC with large chippings:** Stone mastic asphalt (SMA) or dense asphalt concrete (DAC) with maximum chipping sizes in the range above about 13 mm. These are dominating on roads in the Scandinavian countries since they are highly resistant to the studs used on tyres in wintertime. However, SMA:s with smaller chippings and especially with optimized gap-grading features may be considered as relatively quiet surfaces.

4.3 Low noise road surfaces

The following surface types are useful for reduction of traffic noise (in order from moderate to the best):

- **Diamond grinding:** For existing cement concrete surfaces, be they transversely tined or very smooth-textured, diamond grinding which creates narrow longitudinal grooves is a useful measure. Durability is fine, except if studs are used on tyres in wintertime. Potential noise reduction: 1-2 dB in relation to a dense asphalt concrete, 3-5 dB in relation to a tined cement concrete.

- **Exposed aggregate cement concrete (EACC):** An alternative solution, for a new cement concrete, is to use the exposed aggregate technique, provided a maximum aggregate size of 8 mm is used. Swedish experience with this (e.g. wet friction, durability and noise) is very positive. On roads for medium and low speeds, this author would recommend a maximum aggregate size of 5 or 6 mm. Potential noise reduction (for 8 mm): 1-2 dB in relation to a dense asphalt concrete[8], 3-5 dB in relation to a tined cement concrete.

- **Small-aggregate surface dressings:** An alternative measure at medium and low speeds, either on a smooth cement concrete or a smooth asphalt surface, is to lay a surface dressing (chip seal) with very small chippings (preferably in the range 1-5 mm). There are several proprietary methods of this type, such as Shellgrip, Epoxygrip and Italgrip, many of which have the major object of increasing friction. For example, the Wisconsin DoT recently presented excellent improvements in accident rates in a trial with Italgrip [Hitec, 2004]. If, and only if, such surfaces are laid on a very smooth base without becoming depressed, they may almost compete with porous surfaces in terms of noise reduction. Potential noise reduction: 1-5 dB in relation to dense asphalt concrete or SMA 0/11.

- **Thin layers (AKA "thin surfacings"):** Thin layers, or thin surfacings, as they are often called in the U.K., are proprietary systems (belonging to a certain company) in which a hot bituminous mixture is machine-laid onto a bond or tack coat to form a textured wearing course generally less than 40 mm in thickness. Since the 1990's, various categories of thin asphalt surfacing systems have gained a major share of the market in countries such as France, the U.K. and the Netherlands. These thin layers require greater use of high-specification aggregates than traditional materials. There is now a multitude of thin surfacings offered on the market; most of which have good acoustic characteristics. In the EU projects SILVIA[9] and SILENCE[10] such surfaces have appeared to reduce noise by 3-6 dB in new or fairly new condition in comparison to dense asphalt concrete with medium aggregate size [Bendtsen & Andersen, 2005]. Part of these favourable values is due to a moderate porosity in new condition, part is due to macrotexture being optimized for low noise. What the performance is when they become older is not yet sufficiently tested, but it is clear that they will gradually become noisier with time, almost like porous surfaces. Thin surfacings are most useful on low- or medium-speed roads and streets, presently being widely applied in for example the UK, France and the Netherlands, but some of them may also be used on motorways. Potential noise reduction: 3-7 dB in relation to dense asphalt concrete when new; gradually reduced with time.

---

[8] The reference here is a mix of dense asphalt concrete (DAC) and SMA with max. 11 mm chippings
[9] See http://www.trl.co.uk/silvia/
[10] See http://www.silence-ip.org

- **Asphalt rubber friction course (ARFC):** In Arizona, and also in California, Texas and some other US states with warm climate (but also in Portugal and Japan), adding a large proportion of rubber particles obtained from recycled tyre rubber to the binder and applying a very high content of binder to a dense asphalt mix has been reported to give excellent noise, friction and durability properties. There are two variants: one with a low air voids content ("gap-graded") and another one with a high air voids content ("open-graded"). A pilot program in the US is underway to evaluate these surfaces for a possible wider use [Anon., 2005]; although they have been in successful use already quite a long time and on a large scale in the Phoenix valley in Arizona [Donavan et al, 2005]. Potential noise reduction: 2-5 dB in relation to a dense asphalt concrete, 8-12 dB in relation to a tined cement concrete. The noise reduction effect seems to deteriorate somewhat with time [Donavan et al, 2005]. Recent research in Sweden has shown that the noise reduction is not primarily due to the rubber, the rubber inclusion has only a marginal effect.

- **Single-layer porous surfaces:** This is the “traditional” low noise road surface, being tested for noise purposes since the late 1970’s, the first report on this by the author was published in 1979. Noise reduction in new condition is excellent provided the air voids exceed about 20 % and thickness exceeds about 40 mm. However, the problem is the reduced efficiency due to clogging. The pores are “self-cleaned” in the wheel tracks for high-speed traffic in wet conditions. Potential noise reduction: 1-7 dB in relation to a dense asphalt concrete, diminishing by about 1 dB per year; but faster on low-speed roads. Some road authorities consider this surface type as approximately 50 % more expensive as conventional dense asphalt surfaces over a life-cycle. In Japan, Italy, Hong Kong and the Netherlands this surface type is very widely applied. In Hong Kong, the commonly used variant is called Polymer Modified Friction Course (PMFC).

- **Double-layer porous surfaces:** By putting a second porous layer with smaller chippings on top of a first porous layer with large chippings the acoustic efficiency is increased further. These surfaces are currently under trial in several countries; most of all in the Netherlands. For example, an ongoing motorway trial in Sweden has indicated excellent performance during the first three years of operation, which is remarkable in the Swedish climate. Yet, the maximum chipping size in the Swedish top layer is 11 mm; whereas many countries make attempts with much smaller chippings, such as a maximum aggregate of 4 mm. A Danish experiment on a 50 km/h city street has also been very favourable for one of the three tested variants; namely the one with the largest chippings [Bendtsen et al, 2005a]. A German experiment has indicated that it is in principle possible to obtain very favourable effects also with porous double-layer cement concrete [Sliwa, 2005], although those attempts so far have stumbled over problems with friction, which are believed to be possible to solve by further research. Part of the favourable acoustic effect comes from the increased thickness by applying two layers, part of it from the combination of narrow and wide pores in the layers. The unfavourable side is the high cost of this surface type; it is substantially more expensive than the single-layer surface. A recent state-of-the-art paper gives more information [Goubert et al, 2005]. Potential noise reduction: 4-8 dB in relation to a dense asphalt concrete.

Finally, it shall be stressed that different road surfaces change characteristics with time and wear in different ways. It means that a surface which is very good in new condition might be poor after a few years of operation. One shall, therefore, study the noise characteristics over the lifecycle of the surface.

5. RECENT OR ONGOING RESEARCH PROGRAMMES AND TRIALS RELATED TO LNRS WORLDWIDE

5.1 *Multinational European projects*

5.1.1 CALM

The European Commission supports a project called "CALM II – Coordination of European Research for Advanced Transport Noise Mitigation". CALM II which runs until the end of 2007 aims at an enhanced and cross-sectoral coordination of the European transport noise research, involving the most relevant stakeholders. It intends to facilitate the networking of organisations, the coordination of activities and the exchange and dissemination of knowledge.

The overall objective (as cited from the website[11]) is "the synchronisation and encouragement of European transport noise research through a holistic system approach involving all related research areas. Based on intensive networking, the main aims of CALM II are

- optimising research efforts
- identifying synergies between noise research and development in the different transport modes
- strengthening the coherence of future noise research objectives
- identifying new technology requirements and remaining research needs."

On the website there is a very comprehensive list of European projects in the area of noise, which is searchable by subject, type of project and country. CALM II also organizes a few conferences per year, coordinates research efforts and identifies the needs for new research. The project structure is presented in Fig. 5.1.

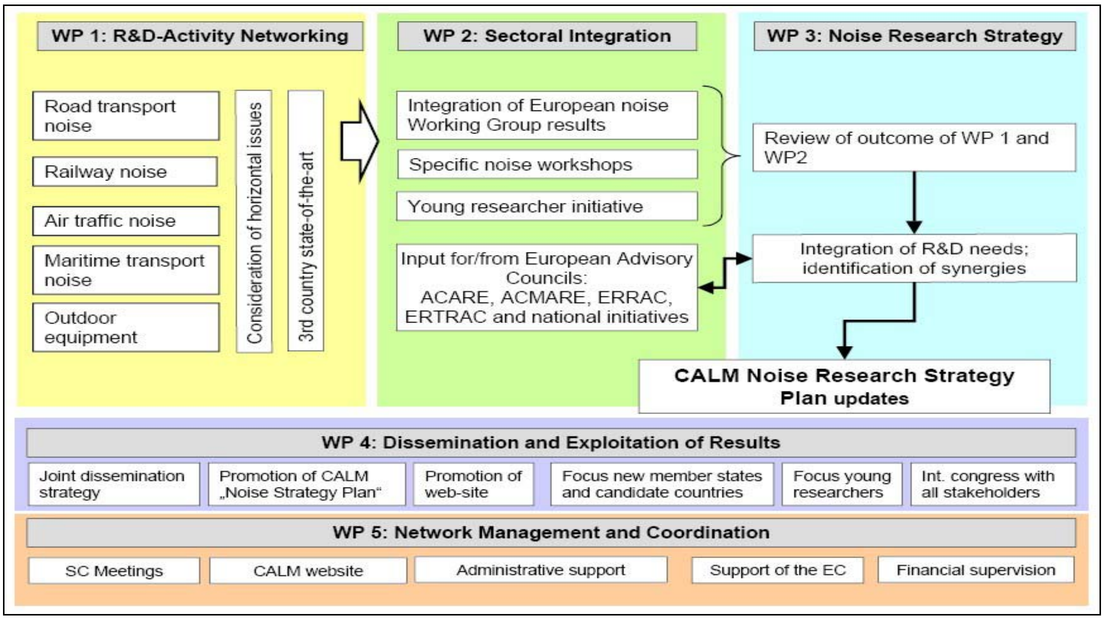


Fig. 5.1. Outline of the CALM II project (http://www.calm-network.com/calm2_general.pdf)

[11] Website of CALM: http://www.calm-network.com

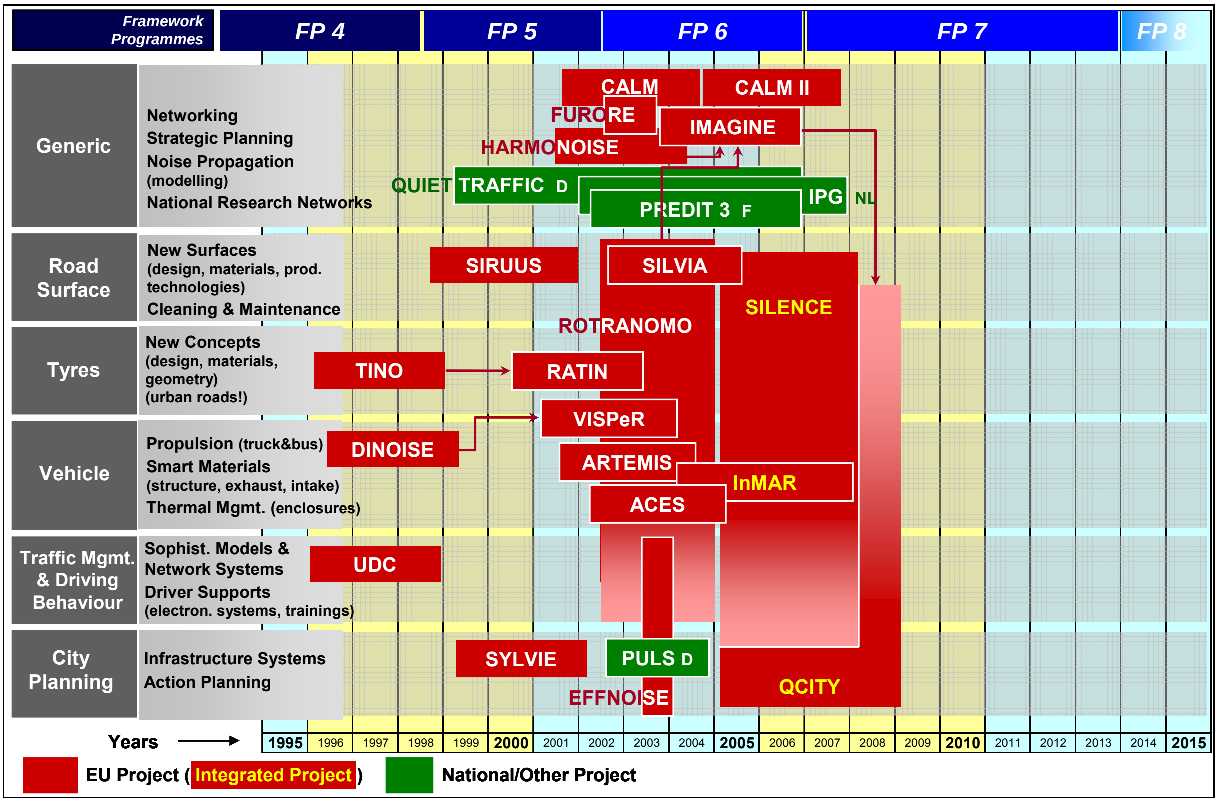


Fig. 5.2. Overview of past and current European projects, both at national (green) and multinational levels (red) and according to main focus. FP means Framework Programme, which means the consecutive research programmes of the European Commission. From http://www.calm-network.com/prep06_02.pdf

An overview of the recently completed and ongoing research projects of major importance is presented in Fig. 5.2. The subject of most interesting here is "Road Surface" and as can be seen there, the projects dealing with this are SIRUUS, SILVIA, ROTRANOMO, SILENCE and Q-CITY. The latter three cover also other subjects. They are described below, except ROTRANOMO which did not deal so much with road surfaces (it developed a vehicle noise prediction model in which the road surface is one parameter). CALM has produced a "Blue-Book 2006" which is a survey of European Research projects in the field of environmental noise and based upon the CALM project database; the booklet was issued in mid-May 2006 and can be accessed via the internet (http://www.calm-network.com/index_bluebook.htm). There is also a "Strategy Paper" at http://www.calm-network.com/SP_2020_final07.pdf .

5.1.2 SIRUUS

A project with the title SI.R.U.US. - "SIlent Road for Urban and extra-urban USe" was conducted in the period 1998-2002. The partners were Argex (BE), BRRC (BE), INRETS (FR), LNEC (PT), Pavimental (IT), SACER (FR) with Autostrade (IT) as project co-ordinator. The main aim of the SI.R.U.US. project was to develop low noise multi-layer pavements with different surface and structural functions, so as to permit full scale implementation of innovative solutions capable of controlling road traffic noise mainly by optimising the texture, roughness, hydraulic conductivity and sound absorption characteristics; seeking a balance between their structural and acoustical performance over time and their life-cycle costs.

In researching the current main alternatives for low-noise pavements, the SI.R.U.US. project involved not only improved mixes but also new structures designed to implement the innovative concepts for the surface and lower layers. The most promising solutions of pavements, deriving from different raw materials (e.g. introducing also a light expanded clay aggregates), mixes and concepts, were tested using appropriate traditional acoustical, mechanical and physical measurement methodologies, at both reduced scale in the laboratory and full scale on short road sections under traffic. The results are reported in Sub-Chapter 6.2. The project had no website.

5.1.3 SILVIA

The EU project SILVIA[12] - "Sustainable Road Surfaces for Traffic Noise Control" was conducted in 2002-2005. The acronym SILVIA stands for SILeo VIA[13] ("road to be noiseless"). The project budget was approximately EUR 3.6 million in total. The main objectives were:

- The first objective was to develop a classification procedure for road surfaces combined with a conformity-of-production (COP) testing method.
- The second objective was to evaluate and specify road construction and maintenance techniques that would achieve satisfactory durability of the acoustical performances of low-noise surfaces while complying with other requirements of sustainability, i.e. safety, pollution, fuel consumption, structural durability and costs.
- To address the latter aspects, a third objective was to develop a procedure for cost/benefit analysis of noise abatement measures.
- As a result of the above, the fourth objective was to issue a "Guidance Manual on the Utilisation of Low-Noise Road Surfacings". This helps decision-makers to rationally plan noise abating road construction and maintenance taking into account low-noise surfaces and full life-cycle costs of the different solutions.

The partners were the following:

• BASt	Germany	• M+P	Netherlands
• BRRC	Belgium	• SKANSKA	Sweden
• CROW	Netherlands	• TØI	Norway
• DTF	Denmark	• TRL	Great Britain
• DWW	Netherlands	• TUG	Poland
• INRETS	France	• TUW	Austria
• ITALGRIP	Italy	• VTI	Sweden
• LCPC	France	• M+P	Netherlands

VTI was more or less involved in all activities except the CBA part; with a main focus on low-noise road surfaces (the second objective above).

The main results are reported in Sub-Chapter 6.3 in this report.

12 Website of SILVIA: http://www.trl.co.uk/silvia/

13 This is Latin. Originally it was assumed that it should read SILenda VIA, but silenda means secret, not silent.

5.1.4 SILENCE

The EU project SILENCE[14] is a research project funded by the Sixth Framework Programme of the European Commission, which aims to develop an integrated methodology and technology for improved control of surface transport noise in urban areas. The project runs from 1 February 2005 until 31 January 2008 and has a budget of approximately EUR 16 million. There are 42 official partners, but in practice there are more since one of the partners is FEHRL[15], which in turn consists of eight sub-partners. The co-ordinator is AVL LIST GmbH in Austria. VTI is one of the partners within the FEHRL consortium and is active in SP C, SP F and SP H. Chalmers University in Sweden is involved in SP C.

Issues that will be covered, include noise control at the source, noise propagation, noise emission, and the human perception of noise. "Integrated methodology" means the combined consideration of city authorities, individual traffic (on road) and mass transport (on rail and road) with a holistic treatment of all traffic noise facets: urban noise scenarios, individual noise sources (vehicles), traffic management, noise perception and annoyance. See Fig. 5.3 for the project structure.

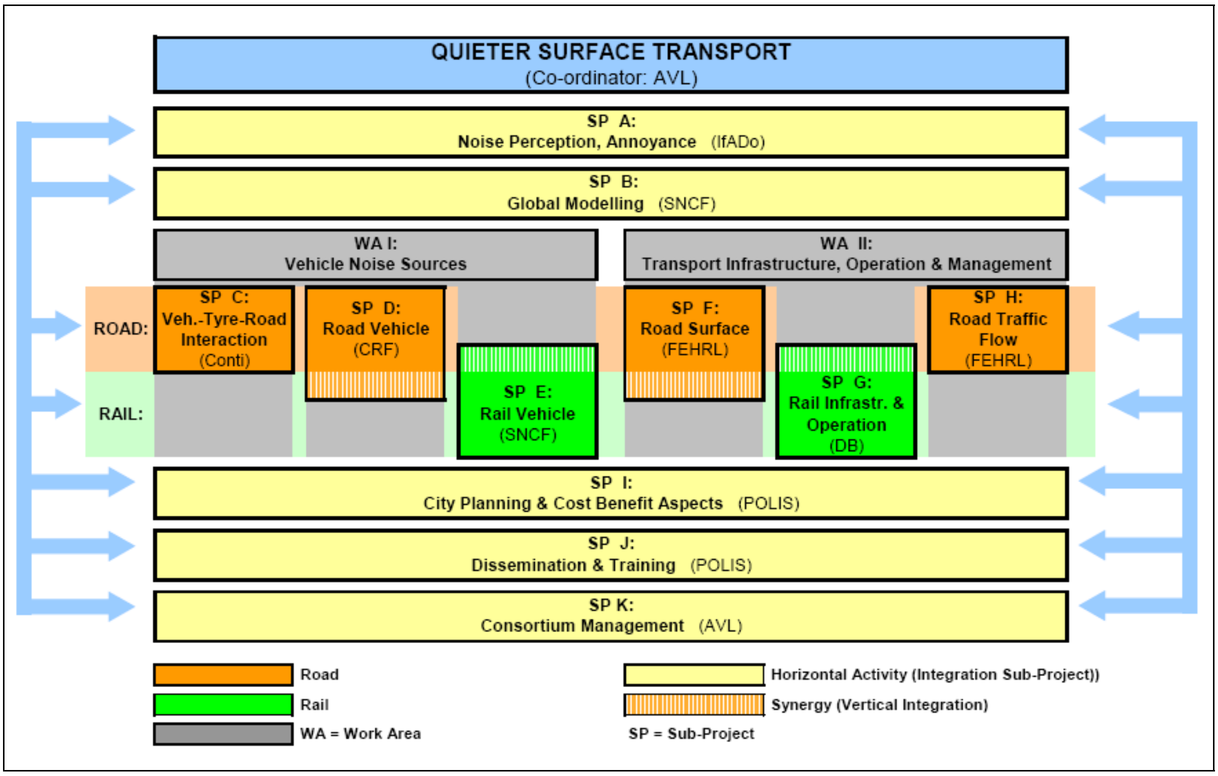


Fig. 5.3. The structure of the SILENCE project, with its Sub-Projects (SP) from SP A to SP K. Responsible organizations are indicated too. From http://www.silence-ip.org/

SILENCE will provide relevant and world-leading technologies for efficient control of surface transport noise, innovative strategies for action plan for urban transport noise

[14] Website of SILENCE: http://www.silence-ip.org/
[15] FEHRL = Forum of European National Highway Research Laboratories (www.fehrl.org)

abatement and practical tools for their implementation, and will bring about a significant reduction of people's exposure to noise, especially in urban conditions.

On this basis, the activities are developed and integrated into a unique system of noise abatement technologies and tools and methodologies for noise reduction and policies. The essential categories of urban traffic vehicles are considered like cars, light duty trucks, buses, trams, metros, trains, etc. The key results and deliverables of SILENCE are first a noise abatement technology platform for road and rail vehicles, urban transport infrastructure and traffic flow aspects, and second; tools, methodologies and input data for decision support systems, urban action plans and future noise scenarios. Fig. 5.4 attempts to illustrate how SILENCE will carry out and implement the results into an integrated approach for noise reduction in urban areas.

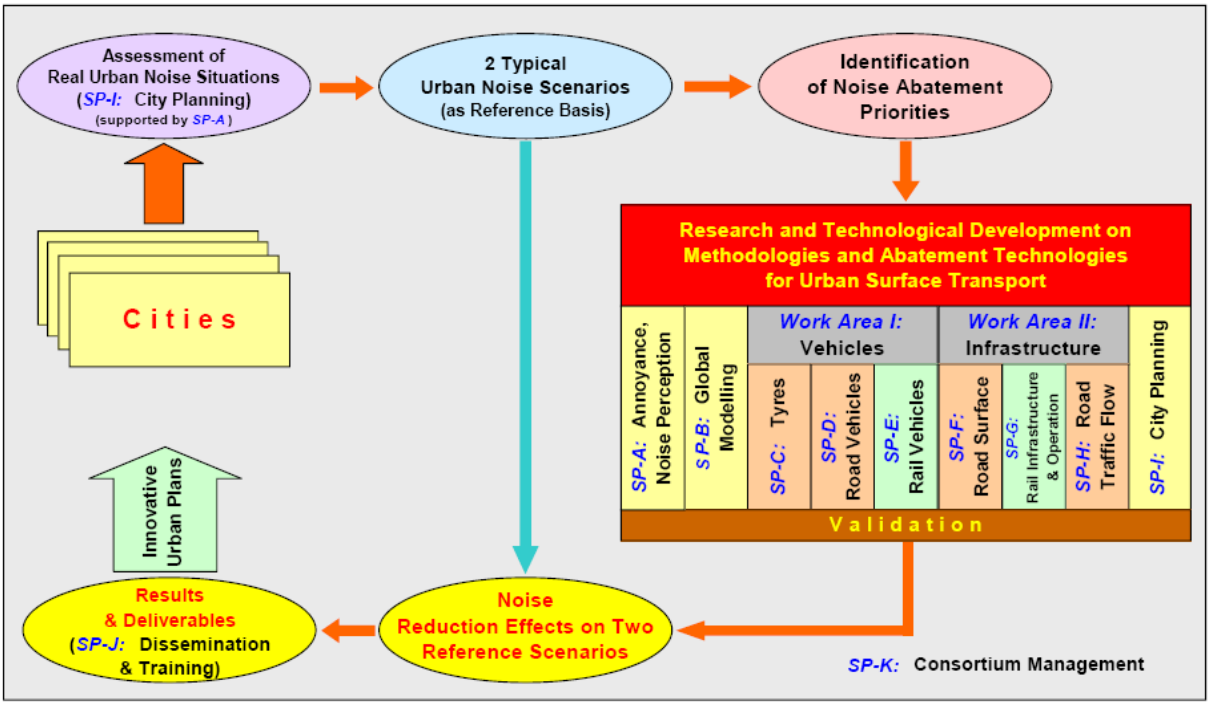


Fig. 5.4. Illustration of the integrated approach of the ongoing SILENCE project. From http://www.silence-ip.org/

For this report, the Sub-Project of interest is SP F "Road Surface". SP F considers the integral design and maintenance of low-noise road surfaces in urban areas. Particular attention is given to surfacing technologies that are appropriate for congested streets with road features such as inspection covers or streets that suffer from frequent interventions due to sub-surface street works. New surface types will also be developed for use on roads for medium to high speed traffic (50 to 100 km/h), which are typical for city ring roads and city arterial roads carrying heavy traffic close to often densely populated living areas. The sub-project also includes the development of technologies ensuring that low noise surfaces maintain their cost-effective acoustic performance throughout their lifetime.

5.1.5 QCITY

QCITY[16], "Quiet City Transport", is a project running in parallel with SILENCE (although continuing until 2009) and is of a similar type. The project runs from 1 February 2005 until 31 January 2009 and has a budget of approximately EUR 14 million. There are 27 partners, of which the co-ordinator is at Acoustic Control AB in Sweden.

The aim is to develop an integrated technology infrastructure for the efficient control of road and rail ambient noise by considering the attenuation of noise generation at source at both vehicle and infrastructure levels. The activity will support European noise policy to eliminate harmful effects of noise exposure and decrease levels of transport noise creation, especially in urban areas, deriving solutions that will ensure compliance with the constraints of legislative limits.

A major objective is to provide municipalities with tools to establish noise maps and actions plans (as required in EU Directive 2002/49/EC) and to provide them with a broad range of validated technical solutions for the specific hot-spot problems they encounter in their specific city.

Table 5.1. The work packages in QCITY and the main tasks of them. From [Mercier-Handyside, 2005]

SP1 - Noise Maps & Modelling	Analysis of hot spots in city noise-maps. Detailed analysis with the aid of residential oriented analysis and measurements
SP2 – Human perception of vehicle noise sources	Classification of vehicle types, including handling with respect to their subjective perception characteristics.
SP3 – Vehicle/-infrastructure interface	Validation of pertinent tools for noise control such as usage of low noise vehicles, traffic control, interchange between different transportation systems, etc.
SP4 – Propagation & receiver parameters	Reduction of rolling noise at the source. This includes new rail and railway wheel types including retrofit measures. New low-noise road surfaces and tyre types. Quantification and R&D on parametric influence for both wheel/rail and tyre/road noise.
SP5 - Design and implementation at validation sites	Development and validation of new methods that work on sound propagation (such as new screen concepts landscape effects etc) and receiver parameters including town planning.
SP6 – Consolidation – Action plans - Dissemination	Final detailed design of all solutions retained

It is within SP3 (Sub-Project 3) where the interesting parts related to low-noise road surfaces lie. This SP has a Work Package 5, which contains the following work items (copied from http://qcity.org/content_frame.php?inc=subprojects3):

[16] Website of QCITY: http://qcity.org/ .

Work Package 5: Refine and optimise the road surface

- In previous projects it has been found that road surfaces which are poroelastic (i.e. both display permeable communicating pores in the surface and substantially increased elasticity) can be very quiet (12-14 dB).
- Problems with wear still have to be tackled. A new technique for pre-coating the rubber with bitumen has though shown promising characteristics.
- Other means for creating poroelastic road surface characteristics will also be tested such as using a twin layer technique where the upper layer is made as a rather conventional open graded asphalt mix, while the lower layer is designed to display a high compliance.
- Another challenge is to achieve acceptable wear characteristics with as small stone sizes in the mix as possible. It has e.g. been found that 5 mm typical max. stone size will give 2-4 dB more noise reduction as compared to a mix with 8 mm typical max. stone size.

5.1.6 HARMONOISE AND IMAGINE

The HARMONOISE project[17] was conducted in 2001-2004 and developed methods for the assessment and management of noise from road and rail traffic. HARMONOISE is an acronym for "Harmonised, Accurate and Reliable Prediction Methods for the EU Directive on the Assessment and Management of Environmental Noise". The total budget was EUR 2.6 million. The main outcome was a traffic noise prediction model named HARMONOISE which is intended to become common to all EU countries and be implemented as obligatory under the EU Environmental Noise Directive and will thus find a wide use for purposes of noise planning, mapping, zoning, noise abatement measures and strategies and for compliance checks.

The IMAGINE project was a direct continuation of the HARMONOISE project; and was conducted 2004-2006 and had a budget of EUR 4.4 million. IMAGINE is an acronym for "Improved Methods for the Assessment of the Generic Impact of Noise in the Environment". For the production of strategic noise maps as required under the EU Directive 2002/49/EC, improved assessment methods for environmental noise will be required. Noise from any major source, be it major roads, railways, airports or industrial activities in agglomerations, needs to be included in the noise mapping. For road and rail, improved methods were developed in the HARMONOISE project. These methods were adopted in IMAGINE for also aircraft and industrial noise. The IMAGINE project also developed guidelines for noise mapping that will make it easy and straightforward to assess the efficiency of action plans. In summary, IMAGINE provided the link between HARMONOISE and the practical process of producing noise maps and action plans.

The main results are reported in Sub-Chapter 6.1 in this report.

[17] Website of HARMONOISE: http://www.imagine-project.org/artikel.php?ac=direct&id=289

5.2 Bilateral projects

There are some Franco-German activities related to tyre/road noise under the umbrella project called "Deufrako"[18]. The platform DEUFRAKO has been in existence for 25 years now and has served as the basis for initiating several joint projects. In 2003 a new DEUFRAKO Working Group on Silent Traffic was established to give guidance and advice on transport noise reduction in both countries [Heinzelmann, 2006].

One project within the DEUFRAKO platform, which deals with low-noise road surfaces, is named "Prediction and Propagation of Rolling Noise (P2RN)". The duration is two years starting in April 2006 [Anfosso, 2007]. The partners are:

- on the German side: BAST, Müller-BBM
- on the French side: LCPC, INRETS, ENPC, Colas, Eiffage-TP

French and German institutes headed by the "Laboratoire Central des Ponts et Chaussées" (LCPC) in Nantes in France, and the "Bundesanstalt für Straßenwesen" (BASt) in Bergisch Gladbach in Germany will cooperate in this two-year project [Auerbach, 2006]. The theoretical approach is based on the SPERoN ("Statistical Physical Explanation of Rolling Noise") hybrid model developed by one of the partners (Müller-BBM) and already implemented and tested in Germany on a large set of measurements carried out on the Sperenberg test site near Berlin; which is a former Soviet military airport. A second model named HYRONe will also be used; this one has been developed by INRETS during two national "PREDIT" projects in France, involving all the present French partners.

In a first stage, the SPERoN model has been validated for different kinds of French road surfaces. In a second stage, the model has been applied as an adapted tool to design new textures for low-noise road surfaces, which will be constructed and tested. Finally, in a third stage, the results obtained with SPERoN will be used as an input for outdoor sound propagation models developed in France and Germany in order to estimate the effect of the optimised low-noise pavements in the far field, close to the façades of residential buildings. A comparison with other, more common German and French low-noise pavements will also be performed.

French and German data of SPB levels for a number of road surfaces as well as a number of topographical situations, have been introduced into a common database “DEUFRABASE”, making it possible to calculate the effect of a certain road surface at an arbitrary position beside a road. Table 5.2 shows a list of the present road surface SPB data. It appears that the quietest surfaces are French thin layers and French porous asphalt with max. 6 mm aggregate.

There is no web site for P2RN at the moment. Recent summaries of the project appear in [Auerbach & Bérengier, 2008] and [Berengier et al, 2008].

In a way, one can also consider the participation of the Danish Road Institute in the IPG program (see later) as a kind a bilateral cooperation [DRI-DWW, 2005]. There were, likewise, a significant cooperation between Germany and the Netherlands in certain parts of the IPG project.

[18] Website of DEUFRAKO: http://www.deufrako.org/

Pavement	PC LAmax (90 km/h)	PC LAmax (110 km/h)	HT LAmax (80 km/h)
TAC 0/6	72.7	75.3	-
PA 0/6	72.8	75.4	80.3
VTAC 0/6 – type 2	73.4	76.0	81.4
UTAC 0/6	74.1	76.7	83.5
PA 0/10	74.2	76.8	82.0
VTAC 0/6 –type 1	74.9	77.5	82.8
TLPA 0/8	*75.2*	*76.9*	*80.6*
VTAC 0/10 – type 2	75.3	77.9	82.6
PA 0/14	76.1	78.7	83.9
PA 0/8	*76.2*	*77.8*	*83.9*
VTAC 0/8 – type 1	76.2	78.8	82.6
TAC 0/10	77.6	80.2	85.6
SMA 0/5 ln	*78.0*	*80.3*	*87.5*
DAC 0/10 (F Ref)	**78.0**	**80.6**	**85.4**
SMA 0/8 ln	*78.3*	*80.3*	*85.6*
UTAC 0/10	78.3	81.0	84.4
SD	78.5	81.1	-
SD 6/8	78.6	81.2	-
CASS	78.6	81.2	85.3
SD 4/6	78.9	81.5	-
VTAC 0/10 – type 1	79.0	81.6	85.2
SD 6/10	80.0	82.6	85.9
DAC 0/14	80.0	82.7	86.2
SMA 0/8 S	*80.1*	*81.9*	*85.9*
GA 0/5 ln	*80.1*	*82.2*	*86.6*
VTAC 0/14	80.4	83.0	86.2
SMA 0/11	*80.8*	*82.9*	*86.9*
CC 0/16 Kamm	*80.9*	*82.7*	*87.9*
CC	*81.0*	*82.9*	*90.6*
EAC	*81.1*	*83.0*	*89.1*
CC	81.2	83.8	87.5
SMA 0/11 S	*81.4*	*83.4*	*87.5*
German Ref (Calc)	***81.5***	***84.1***	-
CCST	*81.6*	*83.6*	*89.7*
GA 0/5	*81.8*	*83.3*	*87.6*
EAC 0/5	*82.1*	*83.6*	*90.4*
SD 10/14	82.1	84.7	86.4
UTAC 0/14	82.1	84.7	-

Acronym	National Acronym	Meaning
TAC	BBM	Thin Asphalt Concrete
PA	BBDr/*OPA*	Porous Asphalt
VTAC	BBTM	Very Thin Asphalt Concrete
UTAC	BBUM	Ultra Thin Asphalt Concrete
TLPA	*ZWOPA*	*Two-Layer Porous Asphalt*
SMA	*SMA*	*Stone Mastic Asphalt*
DAC	BBSG	Dense Asphalt Concrete
SD	ES	Surface Dressing
CASS	ECF	Cold-Applied Slurry Surfacing
GA	*GA*	*Gussasphalt*
CC	BC/*ZB*	Cement Concrete
EAC	*WB*	*Exposed Aggregate Concrete*
CCST	*ZBKR*	*Cement Concrete treated with Synthetic Turf*

Table 5.2. The road surface SPB data in the DEUFRAKO database. The LAmax data are L_{veh} levels according to the SPB method (ISO 11819-1) where PC means Passenger Cars and HT means Heavy Trucks. The legend for the road surface (pavement) acronyms is shown at the bottom of the page. Table from [Berengier et al, 2008].

Explanations:

Lines in normal style are French road surfaces

Lines in italic style are French road surfaces

The line in **bold letters**, normal style, is the French reference road surface

*The line in **bold letters**, italic style, is the German (virtual) reference road surface*

5.3 *National projects and research programmes*

5.3.1 PREDIT in France

Since 1990 there has been a national research and innovation programme in land transportation in France called PREDIT[19]. The programme is supported by the ministries in charge of research, transports, industries, environment, the Ademe and the Anvar. The present programme is called PREDIT 3 and is built on three general objectives [Duhem, 2003]:

- To ensure the sustainable mobility of people and goods ;
- To increase the security of transport systems ;
- To improve the environment and contribute to the objectives to reduce greenhouse effect gases.

PREDIT 3 has a special focus on goods transportation and energy and environment issues (the greenhouse effect in particular) as well as a diversified research on safety. The budget is about 300 million Euros in public funds, but this is to cover all the areas of which most do not deal with noise issues.

5.3.2 QUIET TRAFFIC in Germany

In Germany there is a Research Network Quiet Traffic (in German "Forschungsverbund Leiser Verkehr")[20]. This has been active since 1999 and is still active. Total project costs so far amount to about EUR 35 million. The newest and for this report most relevant part of the program is called "Leiser Strassenverkehr 2 - LeiStra2".

Overviews are presented in [GStLV, 2003], [Krieger & Schmidt, 2003], [Würzel, 2006], [Lorenzen, 2007] and [Lorenzen, 2008]. The focus of the network activities is on the attenuation at the source of road, rail, and air traffic noise and quieter operational procedures. Vehicles and infrastructure are not dealt with separately but as an interaction. Five subject areas have been established:

- Effects on humans;
- low-noise road traffic (tire-road interaction, noise at expansion joints);
- low-noise trains and tracks;
- low-noise transport aircraft; and
- common technologies & methodologies (noise sources, propagation, prognoses)

Technical network activities include among other things low-noise tyres, low-noise road surfaces and low-noise bridge joints. Partners from academia, industry, operators, and agencies are cooperating in the network, which is supported by the German government. Fig. 5.5 gives an illustration. The short-term objective of the project was to reduce tyre/road noise by 3 dB within three years through optimisation of the total tyre-road system. In addition and as a long-term objective, it was intended to design a tyre-road-vehicle-system which would be at least 5 dB quieter through the use of tyre/road noise models [Krieger & Schmidt, 2003].

[19] Website of PREDIT: http://www.predit.prd.fr
[20] Website of Leiser Verkehr: http://www.fv-leiserverkehr.de

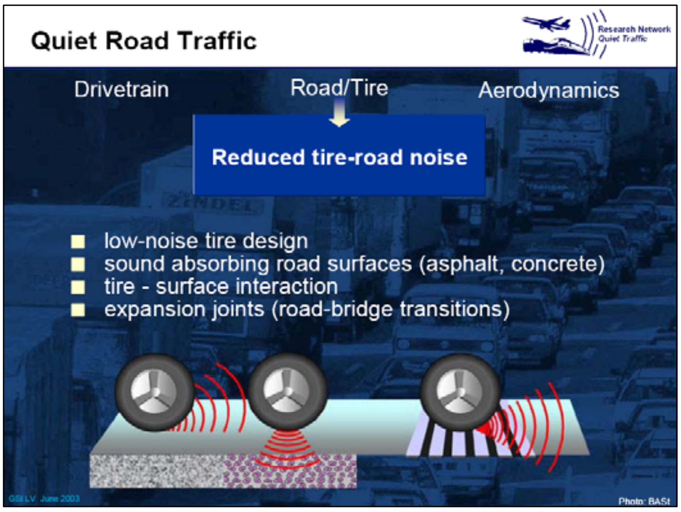


Fig. 5.5. Illustration of the road traffic part of the German Quiet Traffic network. From: http://www.fv-leiserverkehr.de

Low-noise road surfaces is one of the few subjects that still is active within the programme, namely until June 2008; see Fig. 5.6 (although later information states that it will continue into 2009). One active topic there is bridge expansion joints.

Further information about the programme is presented in Section 11.2.1.

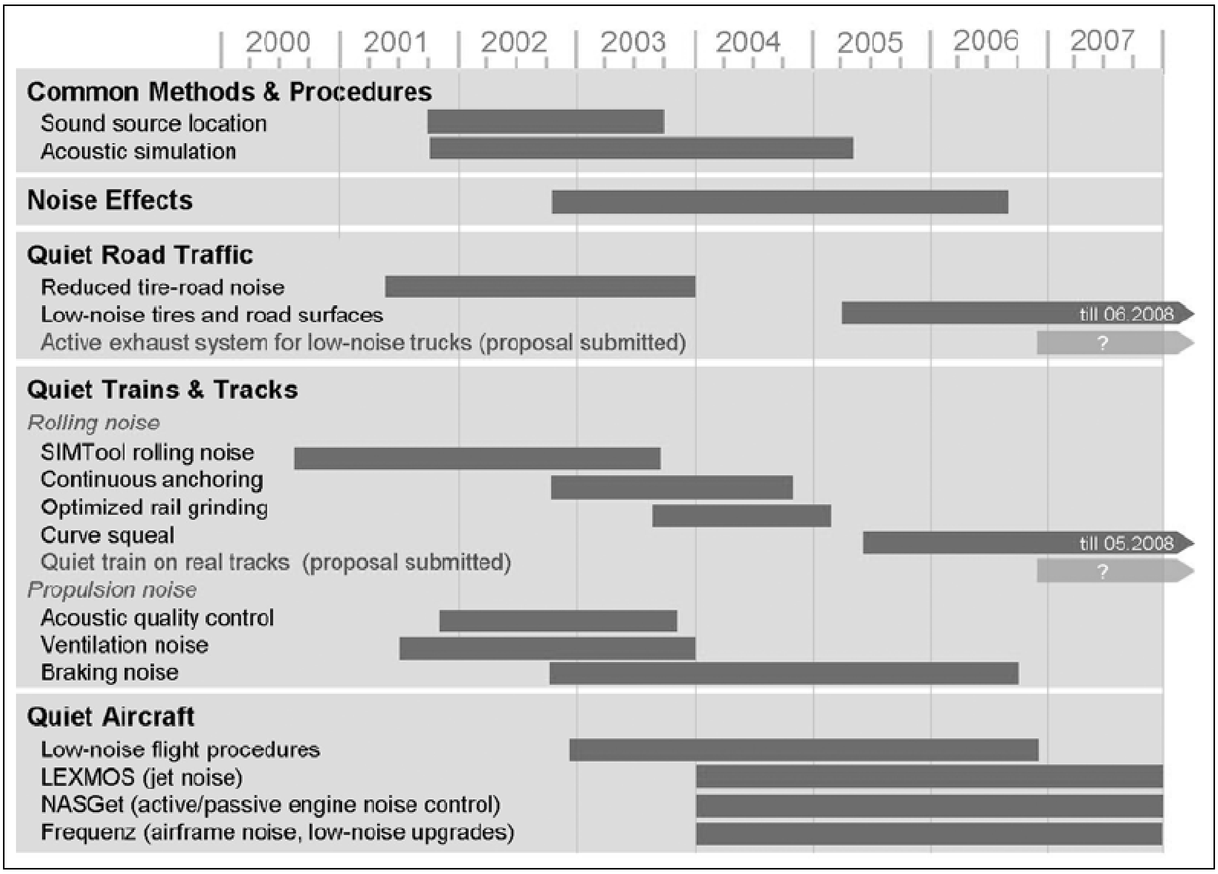


Fig. 5.6. The subjects and time scale of the German Quiet Traffic network. Diagram from [Würzel, 2006].

The remaining part of the programme, "Integrated improvement of porous asphalt", begun in 2005 and has the following focus areas [Rodehack & Beckenbauer, 2006]:

Work Package 1 "Polymer-Nanotechnologie zur Modifizierung von Poreninnenwandungen" (Polymer-nanotechnology for modification of inner walls of pores), conducted by the University of Stuttgart. By means of polymer-nanotechnology one shall attempt to modify the inner walls of the porosities to make them hydrophobic (water repelling) or alternatively strongly hydrophilic (hydrogen bonding). The idea is that this may reduce the clogging.

Work Package 2 "Untersuchung der Strömungsverhältnisse in offenporigen Fahrbahndecken (Study of the flow conditions in open-porous road surfaces)", conducted by the Technical University of Munich. This project will analyze and simulate the flow process in porous asphalt, how dirt particles get stuck and cleaning possibilities.

Work Package 3 "Umweltanalytik und Verbesserung des Schallabsorptionsvermögens von offenporigen Fahrbahnbelägen (Environmental analysis and improvement of sound absorbing capacities of open porous road surfaces", conducted by the consultant company Müller-BBM. This project deals with optimization of the geometrical properties of the voids, but will also deals with cleaning materials and methods.

Work Package 4 "Strukturkennzeichnung von Asphalten mit besonderen geräuschmindernden Eigenschaften (Structure characteristics of asphalts with special low-noise properties)", conducted by the Bundesanstalt für Materialforschung und -prüfung (BAM, Federal Institute for Material Research and Testing), Berlin. This project will rely much on computer tomography (see further Denmark).

5.3.3 WnT and IPG in the Netherlands

The Dutch "Noise Innovation Programme for Road and Rail Traffic" (Innovatie Programma Geluid - IPG)[21] is a programme focusing on national roads and railways and is intended to make more solutions available to tackle noise nuisance and to halve the costs of the necessary noise measures. After testing new noise-reducing measures on vehicles, roads and railways, the second important step is to quickly implement the innovations. Implementing the new measures must result in a clear reduction in noise and a 50 % reduction of the existing costs. The IPG is a collaboration between VROM (Ministry for Housing, Spatial Planning and the Environment), V&W (Ministry of Transport, Public Works and Water Management), ProRail and DWW (Directorate-General for Public Works and Water Management).

The project ran over the time period 1 Jan. 2002 - 31 Dec. 2007 (with some parts extending into 2008) and had a remarkable budget. The road research part of the IPG programme had a total of EUR 54 million for the total programme until its end in 2007/2008. In 2006 the budget was EUR 14 million, which is the largest annual budget. The railroad sector had another EUR 24 million. Then there is also an air pollution part which has approximately an equally large part, bringing the total for the IPG programme to EUR 110 million. Then there is a budget for implementation which is large and is additional. The IPG even has an own flag, see Fig. 5.7.

[21] Website of IPG: http://www.innovatieprogrammageluid.nl/

The basic idea behind the programme is that by reducing noise at the source and by improved noise barriers and spending a large amount on research and development, the total costs of reducing noise immission in the Netherlands will be much lower than if one would just use conventional methods; i.e. mainly noise barriers and tunnels. If only the conventional, known technology would be used, an investment of about EUR 2 billion in noise reducing measures would have been necessary during the first decade of the 21st century. This dilemma, increased mobility accompanied with huge investments in noise reducing measures, was the reason for the Ministry of Environmental affairs and the Ministry of Transport to initiate the IPG Program and to implement new cost effective noise measures as soon as possible [Hofman & van der Kooij, 2003].

There were goals in terms of noise reduction set-up for the IPG programme. Table 5.3 summarises the expected noise reduction effects in terms of generic technologies and products. These figures were derived based on an average fleet composition on the main road networks in the Netherlands.

Finished products:	
Road surfaces	4 dB(A)
Tyres and vehicles	2 dB(A)
Barriers	2 dB(A)
Total reduction	**8 dB(A)**
Demonstrated products, but further work needed before implementation:	
Road surfaces	6 dB(A)
Tyres and vehicles	3 dB(A)
Barriers	3 dB(A)
Total reduction	**12 dB(A)**

Table 5.3. IPG noise reduction goals as expected to be reached at the end of 2007 (first half) and a few years later (second half). From [IPG,2006]. Note that the reference surface is a "virtual" DAC 0/16.

Fig. 5.7. The IPG flag.

Fig. 5.8 shows the structure of the road traffic noise part of the IPG programme as it appeared in 2006. Note that "Project Cluster 2" (columns 2 and 3) is the part which deals with LNRS.

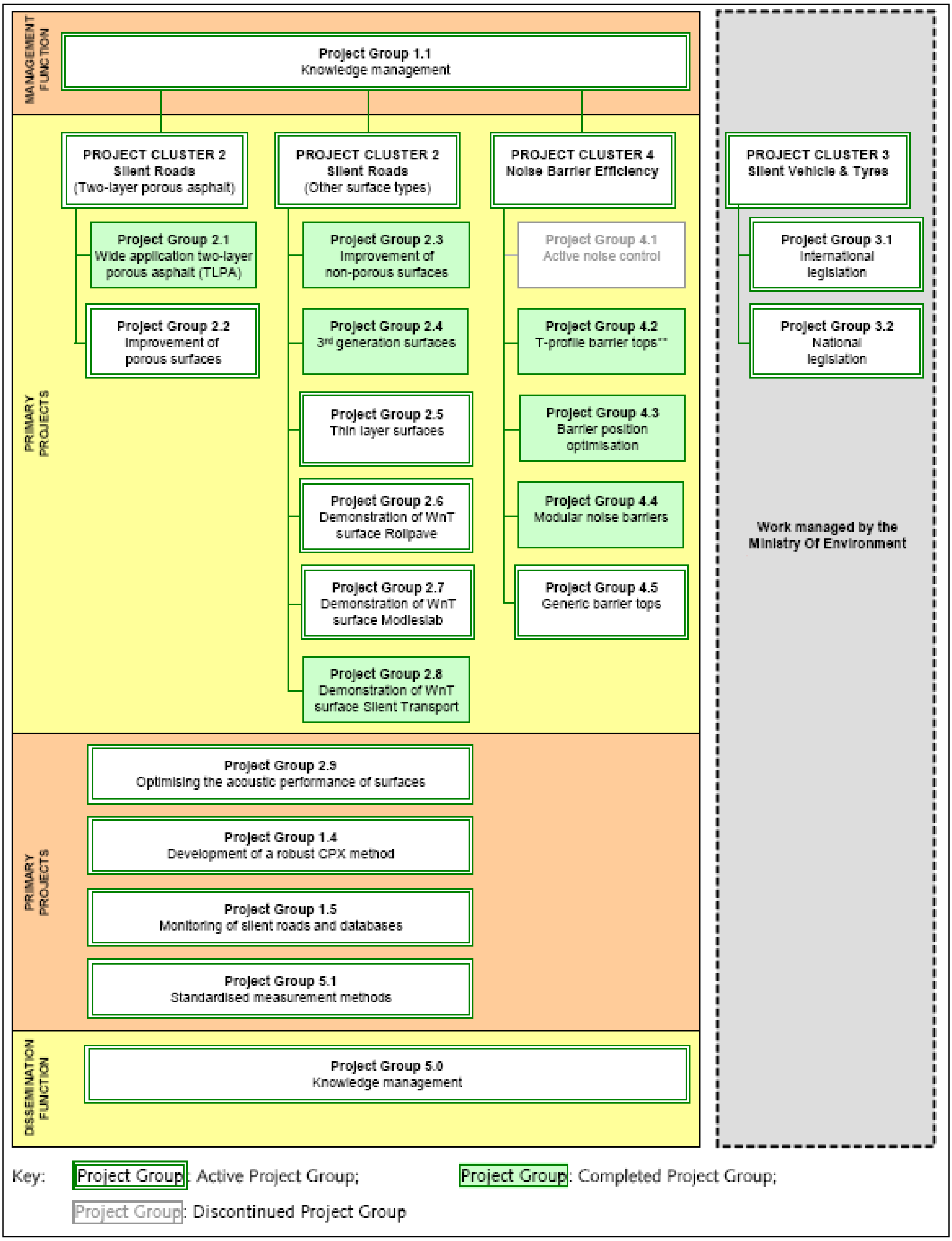


Fig. 5.8. The structure of the road traffic noise part of the IPG programme as of 2006. Diagram from [IPG, 2006].

A sub-project within the IPG aims at producing an "Acoustic Optimization Tool (AOT)"; which will be a program for estimating before constructing a surface, and aiding in the design, the noise characteristics of low noise road surfaces from an input of road surface type, aggregate size or grading, as well as sound absorption and texture values. To this end, very comprehensive experiments were conducted on a test track with 41 test sections at Kloosterzande in southern Netherlands, and on some road surfaces too, the results of which were used to calculate all kinds of relations between noise emission and design and performance parameters (Fig. 5.9). The test track, which was originally an access road to a ferry terminal, later replaced with a bridge and then unused for traffic, will be abandoned after the IPG program has finished. The results of the AOT project have been reported in 2008 [van Blokland, 2008]. The IPG was formally closed with a final seminar in 2008 [IPG, 2008].

Fig. 5.9. A few of the many test sections on the Kloosterzande test track in southern Netherlands. The number of test sections was 41 in the middle of 2007.

The IPG was preceded by a "Roads to the future program" (WnT) within which very silent pavements were designed and constructed. While IPG focuses on the short term and on the most silent roads currently available, the WnT focused on the long term and on very silent roads preferably laid with innovative fast construction techniques [Hofman & van der Kooij, 2003]. WnT was the innovation program of the Ministry of Transport to challenge the market to propose innovative solutions for the problems, and to be implemented within 30 years. During the years 2000-2003 within the WnT much effort was spent on innovative concepts for noise reduction.

The results of both the IPG and WnT programmes are reported elsewhere in this report. The major summarizing and final reports in English are [Morgon, 2008-1][Morgan, 2008-2].

There will not be any major continuation of IPG after the present work finished at the end of 2007, with a final seminar in June 2008. However, there are a couple of follow-up projects in order to continue work with some aspects of the IPG, in a project called Super Silent Road Traffic (Super Stil Wegverkehr - SSW) and another one called Maintenance Innovation Programme (Innovatie Programa Wegbeheer - IPW). The SSW will run for 4 years and have a budget of (at least) 5 million EUR. It will focus on the "4th generation" of low-noise road surfaces for high-speed roads and the target noise reduction is 8 dB in relation to the Dutch reference surface which is a "virtual" DAC 0/16.

5.3.4 USA

5.3.4.1 Concrete Pavement Surface Characteristics Program

The National Concrete Pavement Technology Center at Iowa State University, Federal Highway Administration, and the American Concrete Pavement Association have joined financially and technically to conduct a Concrete Pavement Surface Characteristics Program. Concrete pavements around North America have been evaluated for not only noise and texture, but also smoothness and friction. The broad objective of the study, which is not yet finished, is to optimize concrete pavement surface characteristics that address noise without compromising smoothness, friction, and other functional elements of the pavement [Rasmussen at al, 2006]. To meet this objective, this effort calls for the:

- Evaluation of key findings from the joint FHWA-American Association of State Highway and Transportation Officials (AASHTO) Quiet Pavements International Scan conducted in 2004
- Development of time history data for various texture and grinding alternatives.
- Development of improved construction practices that will lead to cost effective and repeatable noise solutions.

The technology developed and evaluated under this effort serves as a key component in a broader goal of assessing pavement surface characteristics. When coupled with the results from other research efforts, the result will be the design and construction of smoother, safer, and quieter pavements in the United States.

The experimental part of the project is conducted by The Transtec Group, Inc., based in Austin, Texas. For the latest results, see [Rasmussen et al, 2007].

5.3.4.2 “Tire/Pavement Noise 101” Workshops

Sponsored by the FHWA, a series of workshops called "Tire/Pavement 101" have been organized all over the United States starting in 2005 and still going on. Originally, the objective was written as follows:

> "The objective of this task order is to develop a workshop, lasting a maximum of six sessions, including a pilot session, on tire/pavement noise fundamentals to raise the level of awareness of tire/pavement noise for the pavement engineering community and the environmental/noise community." [TOPR, 2004].

However, the workshops turned out to become so popular that the original six sessions have been multiplied, and by March 2007 no less than 29 states and two Canadian provinces had been or were scheduled to be visited; some of them even twice [Rasmussen, 2007]. The lecturing is made by The Transtec Group, Inc., from Texas, in collaboration with Purdue University, and the lecturing material is to some extent based on the Tyre/Road Noise Reference Book [Sandberg & Ejsmont, 2002]. This author has contributed to the development of the material and also lectured at one of the workshops. The special logotype is shown in Fig. 5.10.

Fig. 5.10. The logotype of the Tire-Pavement Noise 101 workshops.

A typical workshop outline is shown in Fig. 5.11. A workshop generally runs for a full day approximately 08:00-16:00 and the objectives are listed as:

- To educate noise practitioners on the fundamentals of pavements
- To educate pavement practitioners on the fundamentals of noise
- To understand tire-pavement noise and how it fits into a larger framework
- To understand the fundamentals of measuring and interpreting tire-pavement noise
- To examine current practices for designing and constructing quieter pavements
- To learn of research and policy directions related to tire-pavement noise

5.3.4.3 Quiet Pavement Pilot Program (QPPP)

As a result of input from the general public, as well as results from studies conducted during the 1990's, Arizona Dept. of Transportation (ADOT) got permission in 2003 from the FHWA to implement a Quiet Pavement Pilot Program (QPPP); specifically to use asphalt rubber friction courses (ARFC) on selected freeway segments in the Phoenix area to reduce noise. Based on similar public concerns and tyre/pavement noise studies, the California Department of Transportation also conducts a QPPP in California. See further [FHWA, 2005].

The QPPP's are intended to demonstrate the effectiveness of quiet pavement strategies and to evaluate any changes in their noise mitigation properties over time. Current knowledge on changes over time of ARFC and other potential quiet pavements is considered by the FHWA as extremely limited. Thus, the programs will collect data and information for at least a 5-10 year period (starting from 2003 in the Arizona case). Provided the outcome of the studies is sufficiently positive in terms of durable noise reduction, safety and durability, the FHWA may allow the use of quiet pavements as a means for noise abatement; but then only on a State-specific basis.

- INTRODUCTION
  - *Welcome*
  - *Review of agenda and housekeeping*
  - *Team and self introductions*
  - *Workshop objectives*
- SETTING THE STAGE
  - *Pavement surface characteristics overview*
    - Pavement types
    - Texture
    - Smoothness
    - Safety (friction, splash & spray)
    - Noise
    - Durability, maintenance, and cost considerations
  - *International activities*
    - EU directives
    - European scan on quiet pavement systems
    - Other international activities
  - *Domestic policy and regulations*
    - Federal
      - FHWA noise policy – TNM and mitigation measures
      - FHWA pavement policy
      - Truck noise controls
    - State and local
  - *Domestic initiatives*
    - FHWA QPPP
    - FHWA PSC program
    - Purdue SQDH roadmap to quiet highways
    - CP Road Map – SC Track
    - NCAT research
    - State DOT and NCHRP research
- NOISE FUNDAMENTALS
  - *Basic terminology*
  - *Sound levels*
  - *Frequencies*
  - *Sound generation and propagation*
    - Vibrations and waves
  - *Basic sound measurement*
  - *Basic sound analysis*
    - Time vs. frequency domain
    - Filtering
  - *The listening experience – psychoacoustics*
- PAVEMENT FUNDAMENTALS
  - *Pavement types and materials*
    - Asphalt
    - Concrete
  - *Pavement specification and design*
    - Materials specifications
    - Texture specifications
  - *Pavement construction*
    - Quality control – Variability control
  - *Pavement preservation and rehabilitation*
    - Preservation techniques
    - Overlays
- TRAFFIC NOISE
  - *Sources*
    - Powertrain
    - Aerodynamic
    - Tire-pavement interaction
  - *Contributing factors*
    - Traffic mix
    - Speed / braking / acceleration
    - Roadway geometrics
  - *Mitigation techniques*
    - Conventional (noise barriers)
    - Quiet pavement pilot program (QPPP)
- TIRE-PAVEMENT NOISE
  - *Tire basics*
  - *Generation mechanisms*
  - *Amplification mechanisms*
  - *Pavement factors*
    - Texture
    - Materials
  - *Changes over time*
  - *Other factors*
    - Speed
    - Tire effects (type, condition, and forces)
    - Wet surfaces
- MEASUREMENT TECHNIQUES AND MODELING
  - *Measurement fundamentals*
    - What to measure
    - Where to measure
  - *Wayside (pass-by)*
    - Statistical pass-by
    - Controlled pass-by
    - Coast-by
  - *Near field (close proximity)*
    - CPX sound pressure method
    - CPX sound intensity method
  - *Interior (vehicle) noise*
  - *Laboratory drum*
  - *Material properties*
    - Acoustic absorption
      - Impedance tube
      - Impulse response
    - Complex modulus
    - Permeability and porosity
  - *Modeling*
    - Relating and predicting various noise measures
    - Fundamental modeling of tire-pavement noise
- QUIET PAVEMENT BEST PRACTICES
  - *Asphalt alternatives*
    - Porous friction courses
    - Rubberized asphalt
    - Stone matrix asphalt
    - Optimized conventional hot-mix asphalt
  - *Concrete alternatives*
    - Conventional texturing variations
    - Diamond grinding
    - Exposed aggregate surfaces
    - Porous concrete
  - *Selecting viable alternatives*
- CONCLUSION
  - *Summary of key concepts*
  - *Future trends in research*
    - Pavements
    - Noise
  - *Future trends in policy*
    - Pavements
    - Noise
  - *Discussion*
  - *Adjourn*

Fig. 5.11. A typical Tire/Pavement Noise 101 workshop outline

5.3.4.4 Tire/Pavement and Environmental Noise Research Study for Colorado

Like Arizona and California, the state of Colorado has an ambition to be allowed to use quiet pavements as a noise abatement method, but has not so far been granted a QPPP. To prepare for a possible policy change, Colorado DoT (CDOT) has started a project to study the noise characteristics of a large number of pavements in Colorado, with a certain emphasis on their long-term performance. The study is performed by the Transtec Group, but also Volpe Center is involved, and even this author is a consultant in the project.

5.3.4.5 Use of Lightweight Aggregate for Tire-Pavement Noise Reduction

The FHWA in the beginning of 2007 commissioned the Transtec Group to conduct a project to study the possibilities to reduce noise by using lightweight aggregates. Lightweight aggregates – including expanded clay, shale, and slag aggregate, among others – have been used for decades. When used for pavement surfaces, they have been reported as durable and cost-effective, both in the US and abroad. The benefits touted include their ability to provide a safe, skid-resistant surface. In the end, the emphasis was not on lightweight aggregate for noise, but instead alternate surfacing materials.

5.3.5 United Kingdom

The information provided below was obtained from [Stait, 2007].

The UK is currently undertaking two research projects, sponsored by the Highways Agency, that are investigating the acoustic properties of low noise surfaces.

The first is the feasibility of using double-layer porous asphalt on the road network. This project is near completion (December 2007) and has reviewed other countries experiences of double-layer porous asphalt and will provide recommendations to the UK Highways Agency on how the surface could fit in with existing maintenance and noise policies. The intention was to investigate all aspects; e.g. noise, skid resistance, durability, whole life costs, resource use, laying times, and water runoff.

The second project is examining the acoustic performance of thin surfaces over time. This will cover 6 mm, 10 mm and 14 mm surfaces (max. aggregate size), together with other common surfaces (e.g. Hot Rolled Asphalt) found on the UK road network. The project is due to run from October 2007 until January 2010 and will cover both new (<1 year old) and old (>5 years old) surfaces. This project will also trial the SILVIA classification methodology on several of the test sections.

In addition, the use of 6 mm thin surfacing on the road network is being studied in more detail by a separate project, and noise measurements have been undertaken on some test sections as part of this project. All the test sections for thin layers are on high speed roads, and any trials with double-layer porous asphalt would almost certainly also be on a high speed road. The work is for the Highways Agency which controls very few low or medium speed roads; thus the focus will be on high speed roads in the projects mentioned above.

5.3.6 Other large national projects

5.3.6.1 Norway

A large project is running 2004-2008 in Norway with the title Environmentally friendly road surfaces. The objective is to obtain a reduction in noise exposure along Norwegian roads and streets and to obtain a better air quality in urban areas [Milford, 2006]. The air quality issue is mainly related to generation, distribution and propagation of small particles worn off from the tyre/road interface by mainly studs in winter tyres.

The background of the project is that the Norwegian Parliament has decided that the noise exposure shall decrease by 25 % before the year 2010 in comparison to 1999, and that this requires, among other things, the use of road surfaces with lower traffic noise emission.

The total budget is approximately EUR 1.3 million (2.3 million if including the pavement costs). The project includes the construction of 25 test surfaces and measurements on another 43 surfaces; the latter of which are conventional Norwegian road surfaces. There is a possibility that the project will be extended until 2011, which would include a lot more field testing of road surfaces [Milford, 2006].

5.3.6.2 Finland

HILJA was a project running 2001-2004, co-ordinated by the Laboratory of Highway engineering at Helsinki University of Technology (HUT), where also most of the research work was done[22]. But also the Automotive Laboratory of HUT, Suomen Akustiikkakeskus (Acoustic Centre of Finland) and the VTT Technical Research Centre of Finland were working for the project.

The aim of the project was that the asphalt companies would develop silent asphalt products which also would have good durability and a reasonable price. The mix design was confidential; only the companies knew the proportioning. There was also a need to prepare functional quality criteria for those kinds of asphalts and define how their properties should be measured.

At the beginning, a literature research was done. It was important to collect knowledge from other countries, because there was not much experience of silent asphalts in Finland. Some test trials had been done before this project, but especially the durability properties of those asphalts were quite poor. After the literature research, after an inventory of ideas, altogether 50 test sections were built on seven different roads. These were tested and the results are reported later in this report.

[22] Most of this information is downloaded from the website: http://akseli.tekes.fi/opencms/opencms/OhjelmaPortaali/ohjelmat/Infra/en/Dokumenttiarkisto/Viestinta_ja_aktivointi/Julkaisut/HILJASUMMARY.doc

5.3.6.3 Italy – Trials with expanded clay and asphalt rubber

As reported above, the FHWA in USA intended to make trials with lightweight aggregates in pavements in a research project (but later abandoned the idea). It can be mentioned that Italy is already making such experiments. In fact, such materials have been tried before in Italy; at least since the late 1980's. A paper reporting substantial noise reductions of an expanded clay surface was presented already at the International Tire/Road Noise Conference in Gothenburg, Sweden, in 1990 [Canale et al, 1990]. The expanded clay surface trialled then was reported to give a similar noise reduction as an "open-graded" surface (early type of single-layer porous asphalt). See further 6.2.2.

What they work with presently in Italy is a wearing course based on an expanded clay aggregate; either entirely or in smaller proportions. For example, work is conducted by Prof Canestrari at the Institute of Hydraulics and Transportation Infrastructures of the Università Politecnica delle Marche in Ancona. A paper related to the mechanical performance of innovative asphalt mixes, including dense graded asphalt concrete with 27 % of the mineral aggregate volume replaced with expanded clay was presented in June 2007 [Canestrari et al, 2007]. A second paper has been submitted to the ISAP 2008 Symposium that will be held in Zurich. The acoustic advantage of the expanded clay (with the limited proportion tried) seems to be in the order of 2 dB initially. At the moment they are working on a trial section related to the use of expanded clay in a hot mix open-graded micro-surfacing [Canestrari, 2007]. Another researcher who works with this type of surface is Dr Pietro Leandri at the University of Pisa. He is involved in studying a trial section with 15 % of expanded clay in a DAC.

It is considered by the Italians that expanded clay surfaces not only reduce noise but also provide a surface with good strength in curves and at intersections. Thus, they should be of interest in urban areas, although the Italians presently seem to try them primarily for highway use.

The noise-reducing properties of expanded clay may come from either a softer surface (i.e. lower mechanical impedance) exhibiting high damping, or an aggregate with micro-porosity; the latter of which may reduce air-pumping. The latter characteristics are already considered useful for acoustic absorption in building materials [Vašina et al, 2005].

Italy will also make trials with significant amount of rubber granules in asphalt pavements. The project is called Leopoldo. It is intended to set up guidelines for the design, construction, monitoring and maintenance of road pavements on rural roads that fall under the responsibility of the Region of Tuscany, with the aim of improving durability of pavements as well as both road safety and environmental sustainability [Leandri, 2007]. Prof Canestrari is involved in a present trial section near Florence with rubber added to the asphalt, both in gap-graded and open-graded variants [Canestrari, 2007]. Dr Leandri is also involved in studying a trial section with asphalt rubber where they are using the dry process, adding 2-6 mm granules of rubber to the aggregate at a proportion of 4-5 % by weight. This is quite unique, although it resembles the Swedish tests with a similar surface called RUBIT in the 1970's; in USA called PLUS-RIDE.

6. SELECTED RESULTS FROM EUROPEAN PROJECTS

6.1 HARMONOISE

6.1.1 Virtual reference for comparing noise on various road surfaces

HARMONOISE (and later IMAGINE) accepted a new concept developed by this author within the project, which specifies a common reference for all road surface (noise) comparisons. A problem in the past (and still) is that various studies comparing noise characteristics of different road surfaces usually report a "noise reduction". But a reduction always means a comparison between two or more values, of which one must be a reference against which the "reduction" is calculated. Since this reference surface tends to be different in most studies or reports, even within a country or within an organization, one can never, without great care and expert knowledge, compare the results of any two studies with each other. One study may report a noise reduction of 3 dB for surface type "bestintheworld" but another study made for exactly the same surface "bestintheworld" may arrive at a reduction of 10 dB, just because of different reference surfaces. Only within Europe, there might be a difference of 5 dB between "common" types of surfaces used as references in such studies; where the Swedish SMA 0/16 in used condition may be one of the worst ones (a British HRA[23] may be even worse) and a German SMA 0/8 in new condition may be one of the "quietest" ones. In the USA, where transversely tined cement concrete is often used as a reference surface in similar studies, one might report a 7 dB noise reduction, if a TTCC of poor construction was the original surface, which in Europe might be reported as 0 dB, due to the use of an SMA 0/8 in new condition as a reference. Table 5.2 highlights the problem where it appears to be more than 3 dB difference between the references used in France and Germany, where the German reference is a mix of several rather “noisy” surfaces.

If a common reference is not used it is almost meaningless to compare results from various countries or organizations.

A recent paper [Sandberg, 2006], produced after the HARMONOISE project was finished, describes the virtual reference surface concept. It is recommended that the virtual reference surface be a mix (an "average") of DAC and SMA surfaces with a maximum aggregate size of 11 mm (1/2" in USA) and with grading curves similar to those which are specified in national or European standards, and with the additional condition that maximum 10 % of the binder may be rubber or similar flexible material. In the paper it is described how one can normalize noise data collected on a certain surface within a defined "reference cluster" to that of the nominal virtual reference surface. This allows the use of one or more surfaces within such a defined range of surfaces when collecting data for noise prediction models or for comparisons with assumed "low-noise" surfaces, while after corrections yet referring to one well-defined and universal virtual reference surface.

The virtual reference, and the range of surfaces that may be used for normalization of collected data to the virtual one, have been chosen to be universally acceptable; i.e. they are common in most if not all countries of the world. The use of this concept in the future for normalization of measured results will for the first time provide a possibility to directly compare the “noise reduction” for a certain surface from study to study and over time and

[23] DAC = Dense asphalt concrete, SMA = Stone Mastic asphalt, HRA = Hot Rolled Asphalt

location. The term "noise reducing surface" will finally mean the same to everybody. Maybe even more important is that the noise predictions by traffic noise models will be more accurate and repeatable when they are based on a relatively well-defined (virtual) surface and data collection on a range of surfaces can be normalized to such a virtual reference surface.

The following points describe the concept of the virtual reference surface, based on [Sandberg, 2006].

 # 1: Definition of the virtual reference

The virtual reference surface (pavement) is an "average" of a DAC and an SMA surface, with equal weights, having a maximum aggregate size of 11 mm. This point in the procedure is illustrated in Figure 6.1 as the central circular symbol between the two vertical scales. In USA, 11 mm aggregate size would correspond to the average of an aggregate size of 3/8" (9.25 mm) and of ½" (12.2 mm). However, having had the opportunity to study the texture of a lot of HMA:s and SMA:s in the USA, this author thinks that the average of an HMA and an SMA with a ½" aggregate would be the best choice in USA; i.e., most similar to European 11 mm aggregate surfaces, since the proportion of the largest chippings is often rather low in the US case. The aggregate gradation should be close to the gradations recommended in the European standards EN13108-1 and EN13108-5, which is close to those recommended by the national road construction authorities. The age of the virtual reference is assumed to correspond to an "average" service life. An additional condition is that maximum 10 % of the binder may be rubber or similar flexible material since some studies report a noise-reducing effect of larger proportions of rubber. So-called "thin surfacings" or "thin layers" shall also be disqualified.

 # 2: Selection of an actual reference when making measurements

When conducting data collection for a noise prediction model or for comparison of surfaces, e.g. checking or monitoring a "low-noise" surface, choose one or more surfaces within the following group (cluster) as an actual reference surface for the experiments:

- DAC with a maximum aggregate size from 0/8 to 0/16 mm. In USA this would correspond to an HMA with a maximum aggregate size from 3/8" to 5/8"
- SMA with a maximum aggregate size from 0/8 to 0/16 mm. In USA this would correspond to a maximum aggregate size from 3/8" to 5/8"
- The age of the surface (i.e. the time passing since it was laid) should be at least one year, and not be at the end of its service life either. A surface in new condition can also be accepted in cases where a comparison of surfaces of equal age is desired, including the new condition. However, then a correction to a "medium service life" is recommended; leaving the "new condition" as a supplementary option.
- Maximum 10 % of the binder may be rubber or similar flexible material.
- So-called "thin surfacings" or "thin layers" shall be disqualified, since they often have a more "noise-optimized" texture than DAC or SMA surfaces.

The two first points of the procedure are illustrated in Figure 6.1 as the "vertical scales" and the part which is within the reference cluster area.

3: Normalization of results from the actual to the virtual reference surface

When evaluating the results, normalize the noise levels measured on the chosen surface to a noise level that would correspond to that which would have been measured in case the virtual reference surface had been used. The corrections needed for this are specified below. It should be noted that the corrections are fairly small since the surfaces within the cluster are similar and not too different.

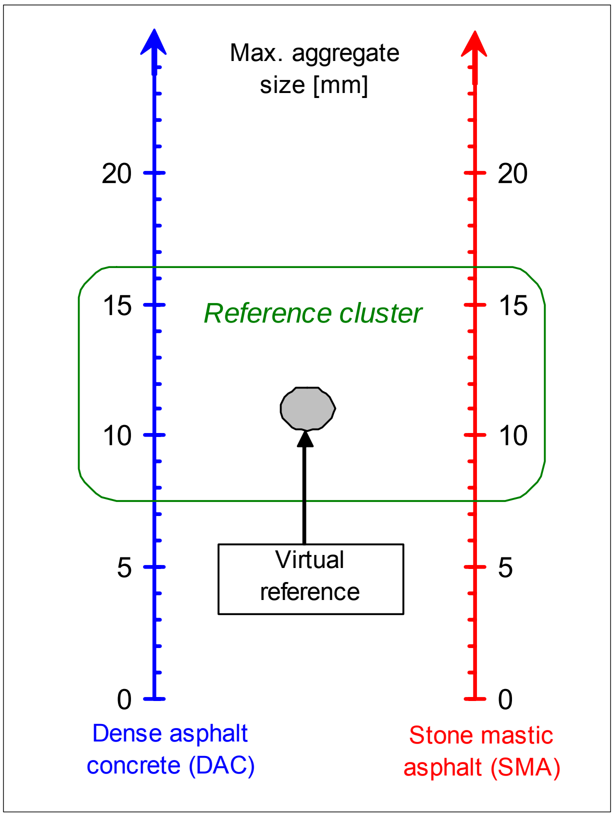


Fig. 6.1. Illustration of the "virtual reference surface" concept. The "reference cluster" shows the limits in type and maximum aggregate size within which a surface for reference use in experimental work should be selected. In USA, DAC would correspond to HMA (see text).

The variation of traffic noise in overall A-weighted noise level on the pavements contained within the reference surface cluster is illustrated very roughly in Figure 6.2 (the noise scale is undefined by purpose). This means that a user of the procedure who selects an SMA 0/16 as the reference for measurements will get a rather different result than the user selecting a DAC 0/8, as stated above. The solution to this problem is to introduce a correction to noise level for the deviation of the actual reference from the virtual reference, which will normalize the noise level to a result that would be measured on the virtual reference.

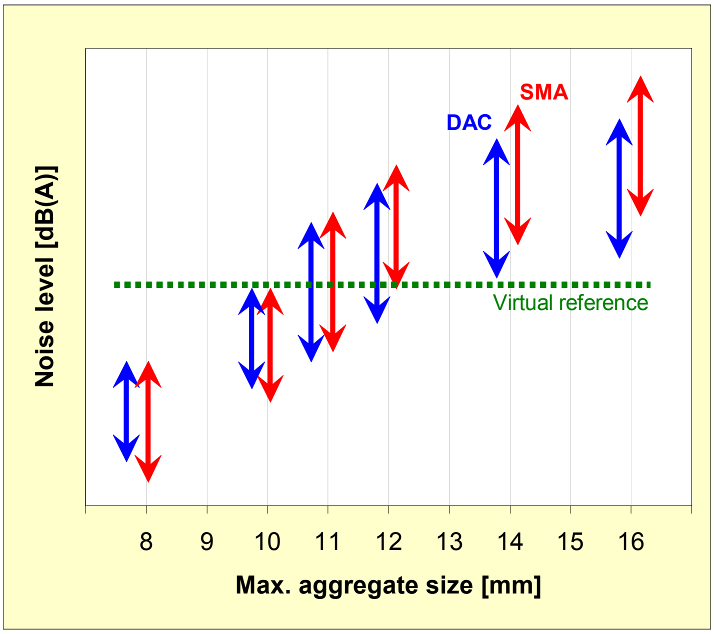
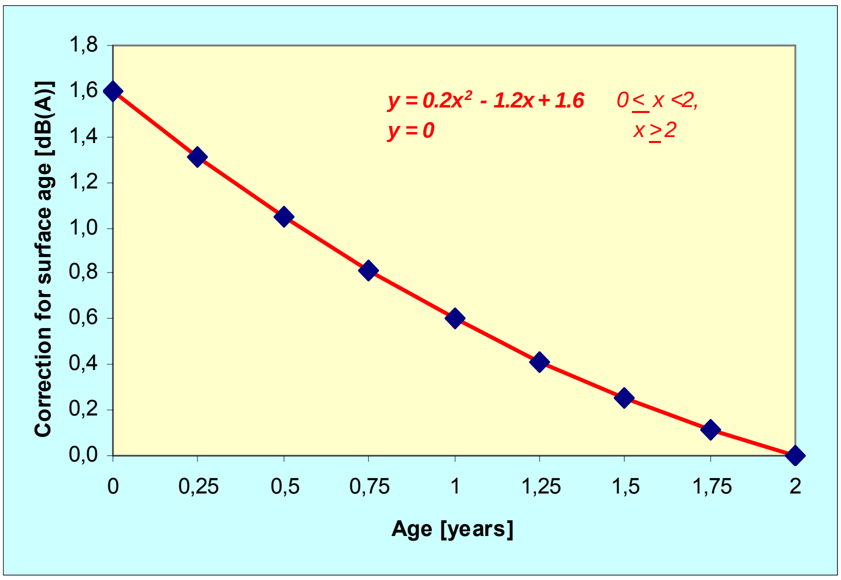


Fig. 6.2. Very rough illustration of how traffic noise level (for free-flowing traffic at medium or high speeds) changes with maximum aggregate size and type (DAC versus SMA).

The corrections that are finally selected are specified in Table 1. The reason for not using any correction for heavy vehicles is that surface influence for heavy vehicles is relatively small within such a limited range of surfaces as in the reference cluster. The values imply that the corrections within the cluster range from +1.05 dB (+2.05 if including age influence) to -1.55 dB.

Table 6.1. Corrections to be made to the measured levels to normalize from the actually used pavement within the reference cluster to the virtual reference one, according to [Sandberg, 2006].

Type of influence	**Corrections for light vehicles**	**Corrections for heavy vehicles**
Age influence **y** for an age of **m** months	See Fig. 6.3	None
Pavement type influence	Subtract 0.3 dB for SMA (HMA) surfaces and add 0.3 dB for DAC surfaces	None
Max. aggregate size influence	Subtract 0.25 dB per mm (of max chipping size) that exceeds 11 mm; add 0.25 dB per mm below 11 mm	None



.Fig. 6.3. Correction for pavement age, according to this author; but only useful within the reference cluster of pavements. Note that the correction for pavements less than 2 years of age should be added to the measured value in order to normalize it to a pavement age of 2 years or older. Age is expressed in decimals of year.

In a review of this type, where results from many countries are evaluated, it is important to have a common reference. Therefore, it is an ambition in the rest of the report to specify how comparisons between road surfaces can be recalculated to compare with the virtual reference surface described in this section.

6.2 SIRUUS

6.2.1 State-of-the art report on low noise road surfaces

One of the main deliveries in SIRUUS was a state-of-the-art report about the influence of road surfaces on traffic noise [Descornet et al, 2000]. A lot of things have happened in this subject since it was written, but apart from that the report is a valuable and comprehensive document. Therefore, it is worth including the Conclusions of that report here (the box on the next page).

6.2.2 Expanded clay surfaces

It is worth noting that in the mentioned report, no less than 5 pages (plus some figures) are devoted to the features of expanded clay surfaces, which is a special type of lightweight aggregate surfaces. See further 5.3.4 (Lightweight aggregate) and 5.3.6 (Italy). Since such surfaces have some promising noise features and since the treatment of this type of surfaces is absolutely unique, the main advantages and problems identified in the report are copied below.

6.2.3 Innovative surfaces: Ecotechnic and Euphonic surfaces

SIRUUS also attempted to develop some new low-noise surfaces; mainly led by the Italian motorway company Autostrade. Several new full-scale solutions underwent trials on short road sections and subsequently validated on long sections (with motorway and urban traffic) in France and in Italy [Camomilla & Luminari, 2004]. In accordance with the aims of the project, a reduction in road traffic noise levels of more than 3 dB(A) in comparison with "conventional" porous asphalt surfaces, and more than 5 dB(A) in comparison with dense asphalt surfaces, was obtained by these innovative full-scale solutions.

The most spectacular one was a so-called "**Euphonic composite pavement**", which consisted of a double-layer porous asphalt on top of a cement concrete structure in which cavities designed to provide so-called Helmholtz resonators were moulded. In some variants, the resonators were built into blocks made of expanded clay. This innovative surface was designed for high-speed roads; primarily for motorways. Fig. 6.4 illustrates the concept and Fig. 6.5 shows when such a surface is being built. A motorway site where the Euphonic composite pavement was actually laid as a trial in SIRUUS is shown in Fig. 6.6. The photo was taken by the author in 2005 when the surface was approximately four years old. Note the cracks which are due to the cement concrete under the porous asphalt; however, they do not significantly affect the functioning of the surface. There was also some slight ravelling in the surface; in the parking area on the far right side, where vehicles had stopped and accelerated, there was some serious ravelling and stripping as well. Fig. 6.7 shows the double-layer porous asphalt on the same test section.

Copy of Conclusions in [Descornet et al, 2000]:

The quietest road surfaces today are either porous or fine-textured. Both solutions yield similar traffic noise reduction potential i.e. roughly 3 dB(A) with respect to an ordinary dense bituminous concrete which in turn lies roughly 10 dB(A) lower than the noisiest rough-textured surfaces like paving blocks, surface dressings and old-fashioned cement concrete.

Should we stay content with the present situation or couldn't we contemplate still quieter solutions, particularly with consideration to the urban area where protection against traffic noise is almost impossible (noise screens are impractical) or extremely expensive (façade insulation)? Based on the facts collected in this report, our answer is definitely positive according to the following rationale.

Dense surfaces have achieved their best possible noise performance. The resin-bound, fine-grained surface dressing seems indeed to be difficult to outperform since megatexture is already at a minimum and finer chippings would be technically difficult to implement because it would need a thinner resinous tack coat with the risk of losing the benefit of its initial liquid state, namely to even out any megatexture of the underlying surface.

When suitably designed according to the present state-of-the-art, porous surfaces reduce noise by four ways:

- Impeding the high frequency component of tyre noise to build up thanks to permeability,
- Attenuating tyre noise in its propagation, mostly close to the tyre by impeding the horn effect through sound absorption,
- Attenuating other vehicle noise sources in their propagation, below and around the vehicle, and
- Being free of any significant megatexture which minimises tyre vibrations.

The first effect appears as a roughly constant attenuation of the higher half of tyre noise spectrum i.e. practically above 500-1000 Hz. Now, the second effect does not often show up as a marked dip in tyre noise spectrum corresponding to the frequency of maximum sound absorption of the layer, as one would expect. It is most often just blended into the first effect and, moreover, often apart from the frequency of the dominant spectral component, where sound absorption would be the most effective. Similarly, the third effect would also be more effective against engine noise, which also peaks close to that frequency region, namely 200-500 Hz, if the road were sound absorbing at lower frequencies than those achieved today. This would be all the more useful in urban conditions as low frequencies are relatively more important than along high-speed extra-urban roads and motorways. To draw full benefit of the fourth effect, small-size aggregates are preferred, which, in turn, makes it difficult to achieve a low frequency sound absorption.

So, it appears that still quieter solutions can be sought for by providing the road pavement with strong sound absorption in the low frequency region, namely 200-500 Hz while still keeping the requirement for some sound absorption in the high frequency region of 500-2000 Hz and, of course, low megatexture.

It seems quite difficult to meet these requirements with a single porous layer, which does not provide enough degrees of freedom to the designer. Then, some special structure must be considered not only to be able to optimise the acoustic performances but also the other requirements regarding skid resistance, water drainage, prevention of clogging, etc.

Double layer pavement structures have already been proposed and experimented though to a limited extent so far. Two superposed porous asphalt layers with different gradings have been tried. They allow indeed bringing the frequency of maximum absorption to lower frequencies than with a single layer. A development of this concept could be contemplated, namely by inserting a resonant structure between the upper course (still made up of two porous layers) and the base course.

A special structure has been proposed and briefly described in this report, namely the euphonic pavement. That solution also aims at providing significant extra sound absorption in the low frequencies through a two-layer system where the underlying one includes Helmholtz resonators designed to absorb low frequencies and embedded in the base layer. Here, models have to be further developed to predict the acoustic properties of the whole structure. This is one more research objective to achieve before launching full-scale experiments.

Now, the inclusion in the top layer of lightweight porous aggregates such as expanded clay has been shown to further enhance the advantages of porous layers regarding friction, glare, durability, economy and possibly sound absorption, although the reported results regarding the latter have to be further confirmed and understood before being taken on board prediction models.

These approaches would have advantages in several other respects:

- All the benefits to safety thanks to permeability are preserved, like less aquaplaning risk due to water ponding, less splash and spray behind vehicles by rainy weather, less glare due to opposite vehicles headlights by rainy night-time.
- Because the top layer would be rather thin and the lower layer(s) would offer rather easy drainage, it is anticipated that clogging will be a lesser problem than on single layers and even if it still is, cleaning would be easier since it would only address the thin top layer.

Copy of advantages and problems with expanded clay surfaces [Descornet et al, 2000]:

Advantages:

- High friction - public safety: the pavement maintains its high initial friction (wet or dry) throughout its service life (PSV > 70 and high skid resistance).
- Damage to vehicles (windscreens, headlamps, sharp-pointed loose stones): the lower density of the aggregate and the higher wind resistance due to the rough surface texture lowers the speed at impact. The resulting striking force is much smaller than with normal weight aggregates, which reduces potential damage.
- Adhesion of binder to aggregate: the rough microtexture of expanded clay aggregate provides unique superior bonding capabilities with bitumen, thus extending pavement service life.
- Pavement surface texture and aggregate top size.
- Glare: expanded clay aggregate surfaces produce little or no glare by reflected sunlight.
- Tyre noise: expanded clay has a rough microtexture that absorbs sound.
- Aggregate durability: resistance to freezing, thawing, sulphate and salt action.
- Economy: it is possible to reduce the consumption of first-class aggregates (e.g. basalt) in asphalt mixes by using expanded clay with lower-class materials (such as limestone).

Problems:

- As expanded clay can be used in various types of surfacing, there may be problems specific to these surfaces. Example: open-graded wearing course with 10 % by weight of expanded clay 7/15 and 15-25 % of voids; this type of course may give rise to the same problems as porous asphalt.
- As far as mechanical tests (namely: Los Angeles) are concerned, there are for the time being no adaptations to, or reference values for, lightweight aggregates.
- It is not advisable to use normal expanded clay aggregate in road pavements carrying high volumes of heavy vehicle traffic, as there may be problems with low compressive strength. «High-strength» or «structural» expanded clay aggregate however can be used without any problems in motorway pavements, because of their high compressive strength.

Fig. 6.4. The concept of the "Euphonic composite pavement" tried in SIRUUS. The structure of the different pavement layers, with resonators in the concrete slabs. Picture processed by this author from presentation obtained from [Luminari, 2006].

Fig. 6.5. A "Euphonic composite pavement" being built. The picture shows the different phases during construction of the cement concrete structure with resonators provided by pipes. The lower right picture shows the openings of the pipes on top of the concrete, over which the double-layer porous asphalt (see Fig.6.6) was then laid. Picture from presentation obtained from [Luminari, 2006].

A second innovative type which was tested in SIRUUS was a so-called "**Ecotechnic composite pavement**", which consisted of a double-layer porous asphalt on top of a third layer of porous material ("disconnection collaborating layer with localised pipes cavities and diffused resonant system by microporous light weight cement concrete 0-6 mm"). Under the porous asphalt layers there was a base-course of either cement concrete or cold recycled asphalt. The third porous layer is interesting since it was provided with channels that would serve both as escape channels for water and as acoustical resonators. The Ecotechnic composite pavement was originally designed to be used mainly in urban areas with low-speed traffic; although the trial took place on a high-speed motorway.

Mr Luminari told this author in February 2008 that the wearing course of the trial section in Fig. 6.6 was replaced in 2007, which means that it served its purpose for about 7 years (the author is not sure about the exact time when the pavement was laid but it must have been in 1999-2001).

Fig. 6.6. "Euphonic composite pavement" test site on motorway A1 at Anagni near Rome, Italy. Mr M. Luminari from Autostrade points at where the section starts. Photo by the author.

Fig. 6.7. The double-layer porous asphalt on the "Euphonic pavement". Top layer 20 mm thick, 6mm max aggregate, bottom layer 40 mm thick, 16mm aggregate. Photo by the author.

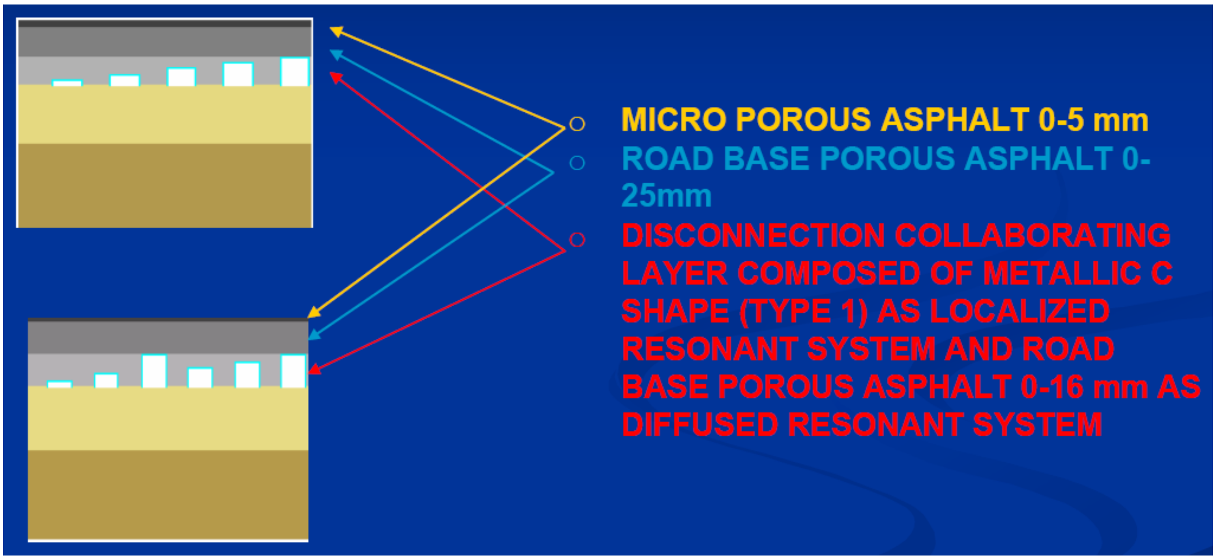


Fig. 6.8. The principle of an "Ecotechnic composite pavement". The structure of the different pavement layers, with resonators in the third porous layer, on top of the concrete slabs. Picture processed by this author from presentation obtained from [Luminari, 2006].

Fig. 6.9. An "Ecotechnic composite pavement" being built. The picture shows the different phases during construction of the third porous asphalt layer with resonators provided by (porous) steel-lined channels. The lower right picture shows the double-layer porous asphalt (see Fig.6.6). Picture from presentation obtained from [Luminari, 2006].

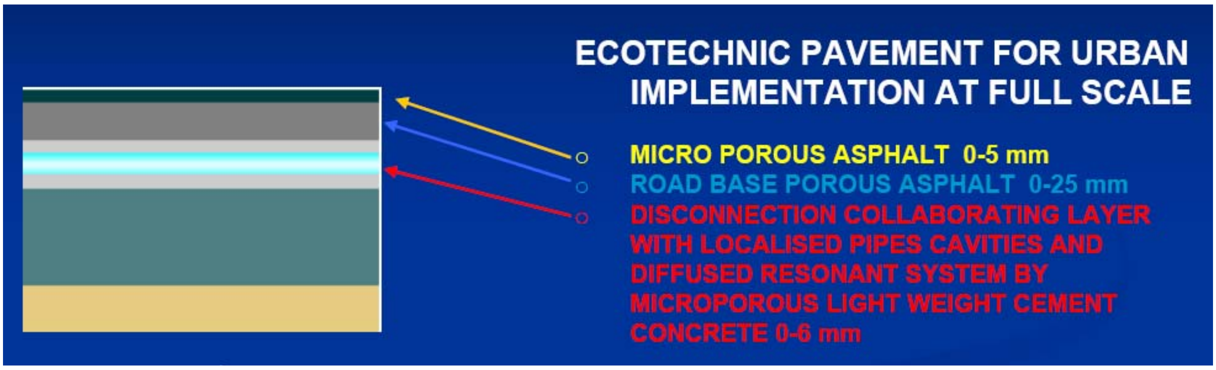


Fig. 6.10. The principle of another "Ecotechnic composite pavement". The structure of the different pavement layers, with resonators in the third porous layer (light grey), on top of a cold recycling asphalt layer (green). Picture processed by this author from presentation obtained from [Luminari, 2006].

Fig. 6.11. An "Ecotechnic composite pavement" of the type in Fig. 6.9 being built. The picture shows the different phases during construction of the third porous layer with resonators provided by (porous) pipes. The lower right picture shows the third porous layer (light grey in Fig.6.10) finished. Picture from presentation obtained from [Luminari, 2006].

The results of these experiments are poorly reported, with difficulty to identify with certainty the reference surface and the measuring method. However, it seems to this author that the most relevant results were a noise reduction of 3-7 dB in SPB levels (but it is not clearly written what the reference was). In conclusion, it seems to this author that the noise reductions of the best surfaces were approximately what one may achieve with a well designed double-layer porous asphalt; indicating just a negligible extra (acoustical) effect of the underlying resonators. Based on this experience, it is thus not worth the extra cost to use the resonators from a pure acoustical point of view.

The interesting thing is, however, the water drainage capacity of such a composite surface construction. In the report about evaluation of the Hong Kong low-noise road surfaces [Sandberg, 2008-1] it was noted that a serious problem was the poor drainage of the surfaces in rainy weather which soon saturated the porous surfaces and provided unfortunate provisions for clogging. The extra drainage provided by the channels in the concrete substructure may be an advantage in a street situation with low-speed traffic where the water and dirt needs to be transported away fairly quickly in order to prevent dirt from getting stuck in the porosities and thus to prevent clogging. A construction such as the Euphonic and Ecotechnic ones shown above would possibly solve this problem. If properly tuned acoustically, they might also provide some extra sound absorption, but this must be better determined by experiments.

For this reason it may be worth testing the Euphonic or Ecotechnic pavement in a low-speed street situation and monitoring its performance in relation to double-layer porous asphalt over the full lifetime.

The author is grateful to Mr Marcello Luminari at Autostrade per l'Italia S.p.A.[24] for sharing his pictures.

6.3 SILVIA

6.3.1 Classification of noise characteristics of road surfaces

The acoustic performance of road surfaces is presently assessed differently in the individual Member States of the EU. This makes it difficult to compare the acoustic performance of different surfaces and therefore end users may not be fully aware of the options and relative benefits available. The absence of a common approach to the assessment of performance also makes it difficult for suppliers to operate in markets outside of their own country. The provision of a harmonised classification system for road surfaces would help to overcome these problems.

In SILVIA, a classification system was proposed that is tailored to the demands required by various end-users. A complete description of the classification system is included in Appendix C of the Guidance Manual [SILVIA, 2006]. A more recent summary was presented in [Padmos et al, 2006].

The classification system assumes that one shall **LABEL** the surface with respect to its noise characteristics and, therefore, specifies measurement procedures and data processing necessary for the labelling. There are two possible labelling procedures; both based on SPB measurements but where one assumes the availability of a CPX measurement system, while the other one assumes no such availability. Due to the limitations of the SPB method in assessing only a small section of the test surface, both procedures include additional measurements to assess the acoustic performance over the full length of the trial section. The procedures are as follows[25]:

[24] From May 2007, Autostrade S.p.A. has changed name to Atlantia S.p.A.
[25] Some parts of this text are taken from [Padmos, Abbott and Morgan, 2006].

- LABEL1 (the preferred method): Assessment based on SPB measurements and a direct assessment of noise over the entire length of the trial surface using Close-Proximity (CPX) measurements. Instrumentation requirements for CPX measurements have been formulated within the SILVIA project (see the next section).

- LABEL2: Assessment based on SPB measurements and indirect assessment of noise based on measurements of the intrinsic properties of the road surface which can be related to the generation and propagation of noise; i.e. texture and sound absorption.

Table 6.2 lists the recommended methods of assessment for acoustic labelling, which is the first step, and Table 6.3 lists the Conformity of Production (COP) methods, which is step 2[26]. A flow chart illustrating Step 1 is shown in Fig. 6.12 and the COP procedure (step 2) is illustrated in Fig. 6.13.

Table 6.2. Recommended labelling system for assessing the acoustic performance of different types of road surfaces. Step 1: Determining the noise label. Note that "rigid" surfaces are defined here as both normal asphalt (dense- and open-graded) and cement concrete.

Label Identification	**Method of assessment for different road surfaces**		
	Dense-graded	**Open-graded**	
	Rigid[1]	**Rigid**	**Elastic**
LABEL1 (Preferred)	SPB	SPB	SPB
	CPX	CPX	CPX
LABEL2	SPB	SPB	SPB
	Texture	Texture	Texture
		Absorption	Absorption
			Mechanical impedance

Table 6.3. Recommended labelling system for assessing the acoustic performance of different types of road surfaces. Step 2: Assessing Conformity of Production (COP).

Label Identification	**Method of assessment for different road surfaces**		
	Dense Graded	**Open Graded**	
	Rigid[1]	**Rigid**	**Elastic**
LABEL1 (Preferred)	CPX	CPX	CPX
LABEL2	Texture	Texture	Texture
		Absorption	Absorption
			Mechanical impedance

[26] The tables are processed by the author from [SILVIA, 2006].

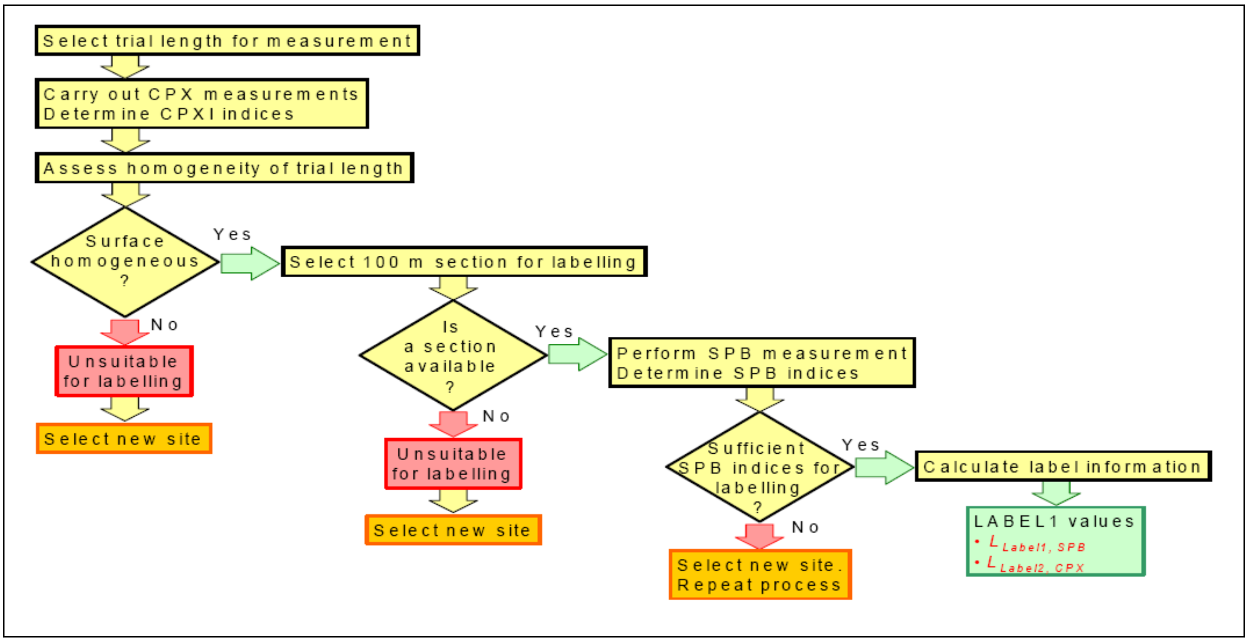


Fig. 6.12. Flow chart illustrating the labelling procedure *LABEL1*. From [Padmos et al, 2006].

The SPB, CPX, texture and absorption measuring methods are specified in ISO standards. There is no ISO standard for measuring mechanical impedance although a temporary method has been developed within the SILVIA project [SILVIA, 2006].

Acceptance of a specific surface for labelling is based on the homogeneity of a selected 100 m section being within the accepted tolerances for *LABEL2* as given in [SILVIA, 2006]. Homogeneity indicators have been specially derived for the intrinsic properties texture and absorption to estimate the variation in pass-by noise level for each data sample with the corresponding tolerances. The procedures for determining these indicators are described in the guidance manual [SILVIA, 2006].

Conformity of Production (COP) is a quality control measure to ensure that the acoustic performance, and where relevant, the intrinsic properties of a given road length, conform to the corresponding label values of a classified road surface type. Each label has a defined range or tolerance which the corresponding values measured for the road length under consideration are required not to exceed, in order to be accepted as conforming to the relevant specification [Padmos et al, 2006].

LABEL1 surfaces must be assessed with the *LABEL1* COP procedure, which means that those surfaces should be checked with CPX measurements. Similarly, a surface labelled according to *LABEL2* must be COP assessed according to the *LABEL2* procedure; i.e. the relevant combination of texture, absorption and mechanical impedance measurements. The procedures are not interchangeable between labelling and COP.

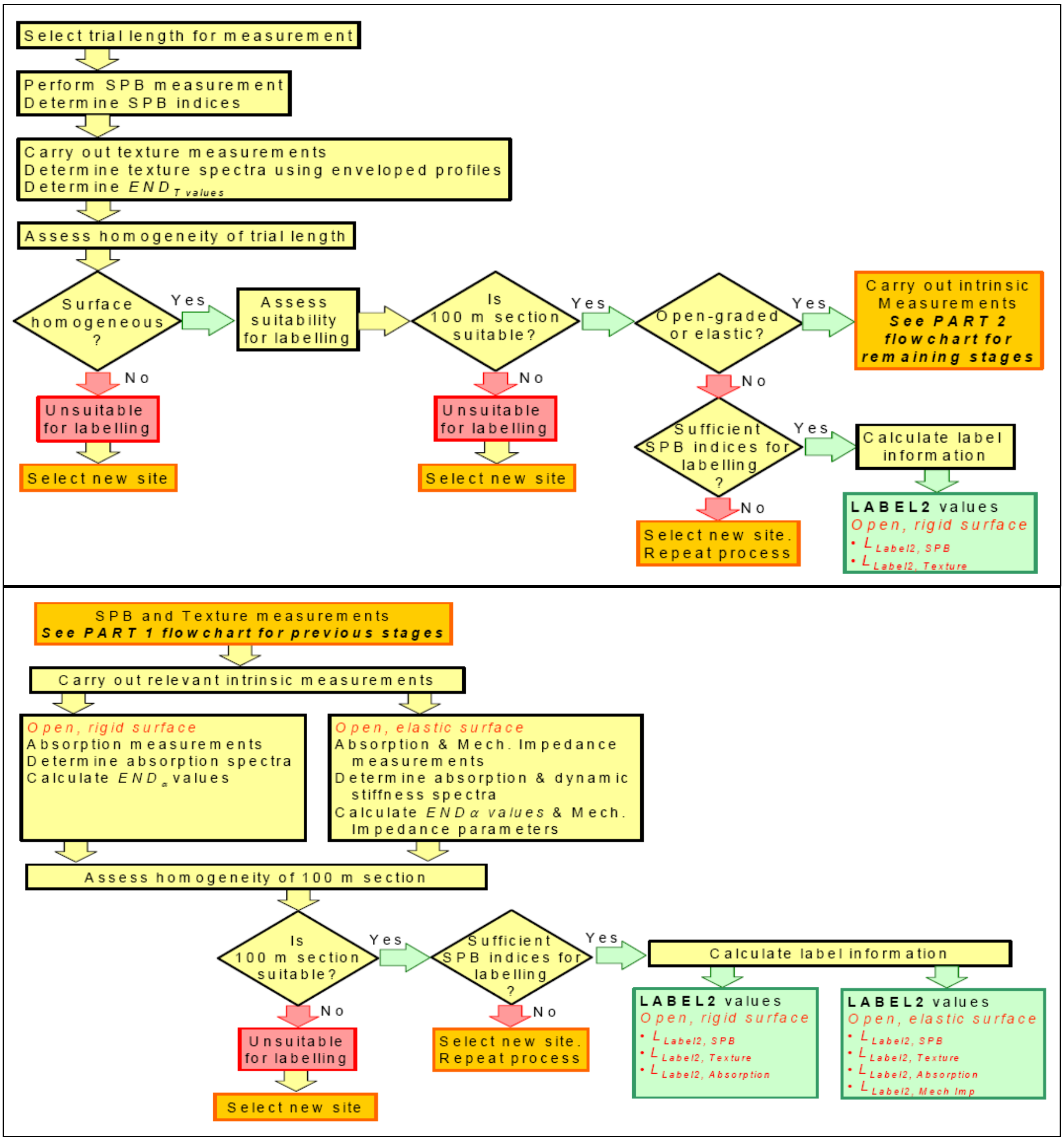


Fig. 6.13. Flow chart illustrating the labelling procedure *LABEL2*. From [Padmos et al, 2006].

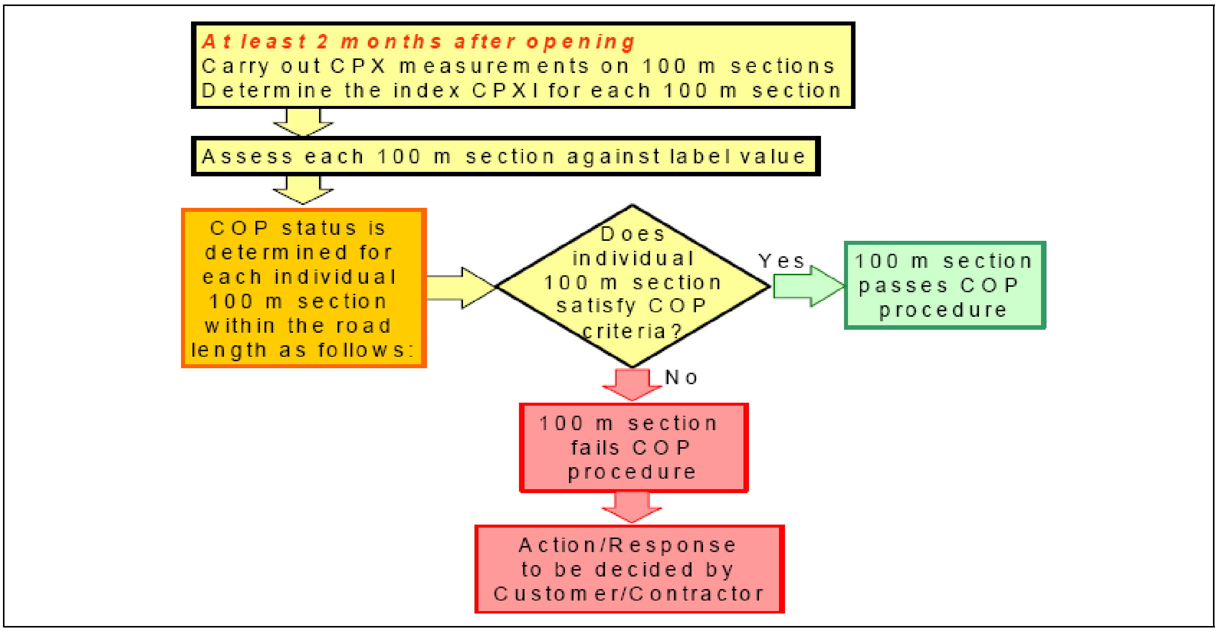


Fig. 6.14. Flow chart illustrating the COP procedure *LABEL1*. From [Padmos et al, 2006].

The COP procedures are illustrated in Figs. 6.14 and 6.15. As can be seen for both the labelling and the COP procedures, things are much easier if one can use CPX equipment (*LABEL1*). However, the alternative procedure *LABEL2* is available for those who do not have access to CPX equipment but who are willing to spend more manhours on the apparently more complicated texture and absorption procedures.

For monitoring purposes during the lifetime of a road surface, the same method could be used as for COP. In the case of the *LABEL1* method, the CPX measurements could be performed with one or two tyres instead of four as required for CPX in ISO 11819-2. In the case of the *LABEL2* method, fewer measurements are required to give sufficient information. The authorities in the different countries should define the indicator for "end of life time" [Padmos et al, 2006].

According to this author, a problem with the SILVIA classification procedure is that it stops with the labelling and COP testing of surfaces in essentially new condition. As reported elsewhere in this report, especially porous low-noise surfaces may develop very differently over a few years. Therefore, it is important to go a step further and monitor the performance of the surfaces over a few years; ideally until they have reached the end of their lifetime. But this is extremely complicated since the change in condition of a surface depends on a number of factors, such as volume of traffic, dust in the air, percentage of heavy vehicles, climate, etc, which are difficult to control or specify. This will call for standardization work; i.e. a standard procedure for testing surface change with time.

The latter issue may be addressed in a possible future European standardisation work; see further Sub-Chapter 16.8.

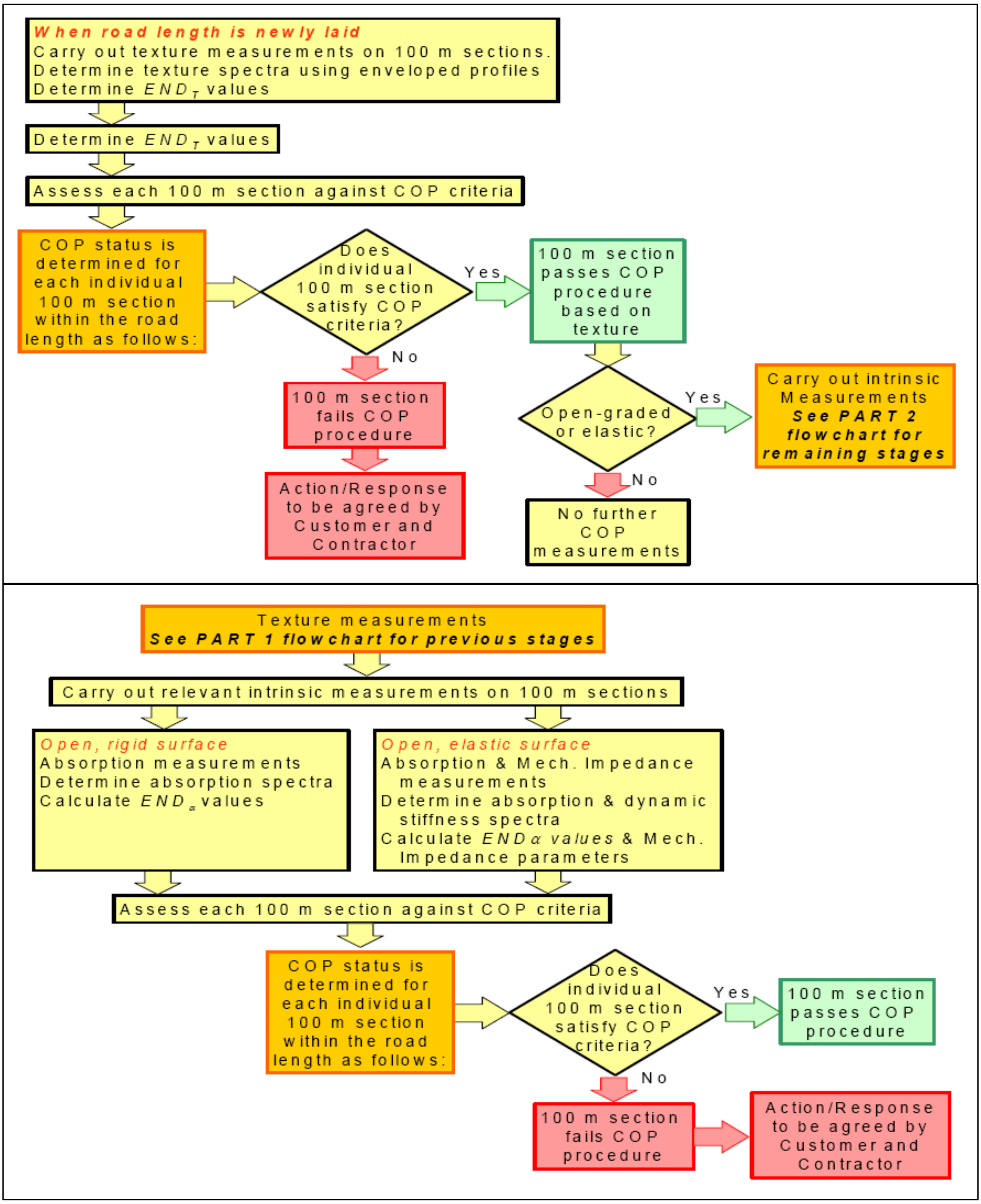


Fig. 6.15. Flow chart illustrating the COP procedure *LABEL2*. From [Padmos et al, 2006].

6.3.2 Certification of noise measurement equipment

The SILVIA project included a part which worked-out certification procedures for measurement equipment to be used for the Classification Procedure. This work is reported in [Ejsmont et al, 2004]. For example, this report specifies a number of methods to check CPX vehicles.

6.3.3 Safety effects of low-noise road surfaces

Porous asphalt[27] has been used on roads since the mid 1980's. It is currently regularly used in the Netherlands, Belgium, France, Austria, Italy, Japan, Hong Kong and New Zealand. Although the rapid drainage effects would indicate that there are potential safety benefits that can be attributed to porous asphalt, the actual safety performance is not clearly understood. To provide some insight in this problem, a systematic review of relevant studies was commissioned as part of the SILVIA project.

In Table 6.4, an attempt has been made to summarise the findings; i.e. the current evidence on the effects of porous asphalt on various risk factors.

Table 6.4. The effects of porous asphalt on various risk factors [SILVIA, 2006].

Risk factors affected	Effect of porous asphalt
Splash and spray - visibility in wet weather	Favourable
Risk of aquaplaning	Favourable
Rutting – evenness	Favourable
Light reflection	Favourable
Friction – stopping distance	No effect
Speed	**Adverse***
Performance in wintertime	**Adverse**
Need for more frequent resurfacing	**Adverse**

The net effect of these various impacts on risk factors is difficult to assess. It depends on the relative strengths of the various effects. If, for example, there is a modest effect on driving speed, the favourable effects on other risk factors may lead to a net gain in road safety. If, on the other hand, there are large increases in speed, and the first winter is long and severe, the net effect may be adverse.

The fact that the effects of porous asphalt on risk factors are so mixed and complex makes it impossible to predict any corresponding change in accident rate. This confirms the evidence from studies that have evaluated the effects on accidents directly, since these studies show highly varying effects, that on the average appear to be fairly close to zero (i.e. no change in road safety).

[27] This sub-chapter is essentially a summary of Chapter 10.1 in [SILVIA, 2006], which is based on [Elvik & Greibe, 2005].

6.3.4 Impact on water pollution of low-noise road surfaces

The use of porous asphalt[28] can affect flooding by reducing spray and drainage by producing a filtration effect. Also, compared to conventional dense asphalt, porous asphalt has an adsorption property allowing a more gradual runoff of water (limited peak flows and slower discharge) and a filtering effect [Berbee et al, 1999] [Pagotto et al, 2000].

The potentially most important negative effect on water pollution from a change from dense to porous asphalt is related to winter maintenance. According to [James, 2003], the thermal properties of porous asphalt demands more extensive use of de-icing by salt. This may have an adverse effect on runoff partly because of the increased concentrations of de-icing chemicals but also because of the increased secretion of heavy metals. However, the reported necessary increase in use of de-icer, relative to ordinary dense asphalt, varies considerably. The percentage increase in the frequency in applying de-icer varied from 30 % to 100 % and the quantity of de-icer from 30 % to 450 %.

Table 6.5 presents mean estimates from the three references mentioned above, giving average values of the three with minimum and maximum (of point estimates). The estimates of effects relate to short-term effects (approximately one year) on motorways.

Table 6.5. Relative reductions of pollutants in runoff water from porous road surfaces [SILVIA, 2006].

Pollutant	Minimum	Average	Maximum
Total suspended solids	81%	**87%**	91%
Total Kjeldahl nitrogen	0%	**42%**	84%
Total nitrogen content		80%	
Total phosphorous content		68%	
Total organic carbon		82%	
Total hydrocarbons / oil	92%	**96%**	98%
Polynuclear aromatic hydrocarbons	95%	**95%**	95%
Lead	74%	**82%**	92%
Copper	35%	**47%**	67%
Cadmium	17%	**58%**	88%
Zinc	66%	**79%**	90%
Chromium	80%	**84%**	88%
Nickel		80%	
Nitrates	0%	**23%**	69%
Ammonia	0%	**37%**	74%
Chemical oxygen demand	0%	**59%**	88%
Biochemical oxygen demand	82%	**82%**	83%

[28] This section is abridged from Chapter 10.2 in [SILVIA, 2006], which is based on [Veisten & Saelensminde, 2004].

Thus, in the short-term, there may be positive effects on runoff (absorption and filtration) and negative effects from de-icing. The run-off effect may be considered more important in areas that combine exposed watersheds and high populations / high traffic volumes. The de-icing effect may be considered more significant in the cooler areas; especially the Nordic countries and the mountainous areas of continental Europe.

6.3.5 Cost/benefit analysis of low-noise road surfaces

A method for assessing the costs and benefits of low noise road surfaces was developed as part of the SILVIA project. It was designed to assess primarily the costs of construction and maintenance of low noise pavements and benefits, expressed in monetary terms, related to the reduction in noise levels achieved with different surfaces.

The method is designed to be sufficiently flexible to handle different noise-control measures, including an ability to account for changes in the acoustic performance over time. This is, of course, important when considering the benefits provided by road surfaces. It has been noted that the effects of traffic and weathering can affect the noise reducing characteristics over time. It is also possible to analyse cases where speed is affected and how this might affect safety, fuel consumption and air pollution.

This sub-chapter is abridged from Chapter 11 in [SILVIA, 2006]. A much more detailed description can be found in the appendix “Conversion of costs and benefits to monetary terms” in [SILVIA, 2006], which is based on [Saelensminde & Veisten, 2005a].

Attached to [SILVIA, 2006] is a CD containing an Excel spreadsheet that can be applied for noise-control options but primarily an assessment of the economic effect of changing to a road surface with different noise characteristics [Saelensminde & Veisten, 2005b]. A brief outline of the approach to calculation and the use of inputs is given in the following.

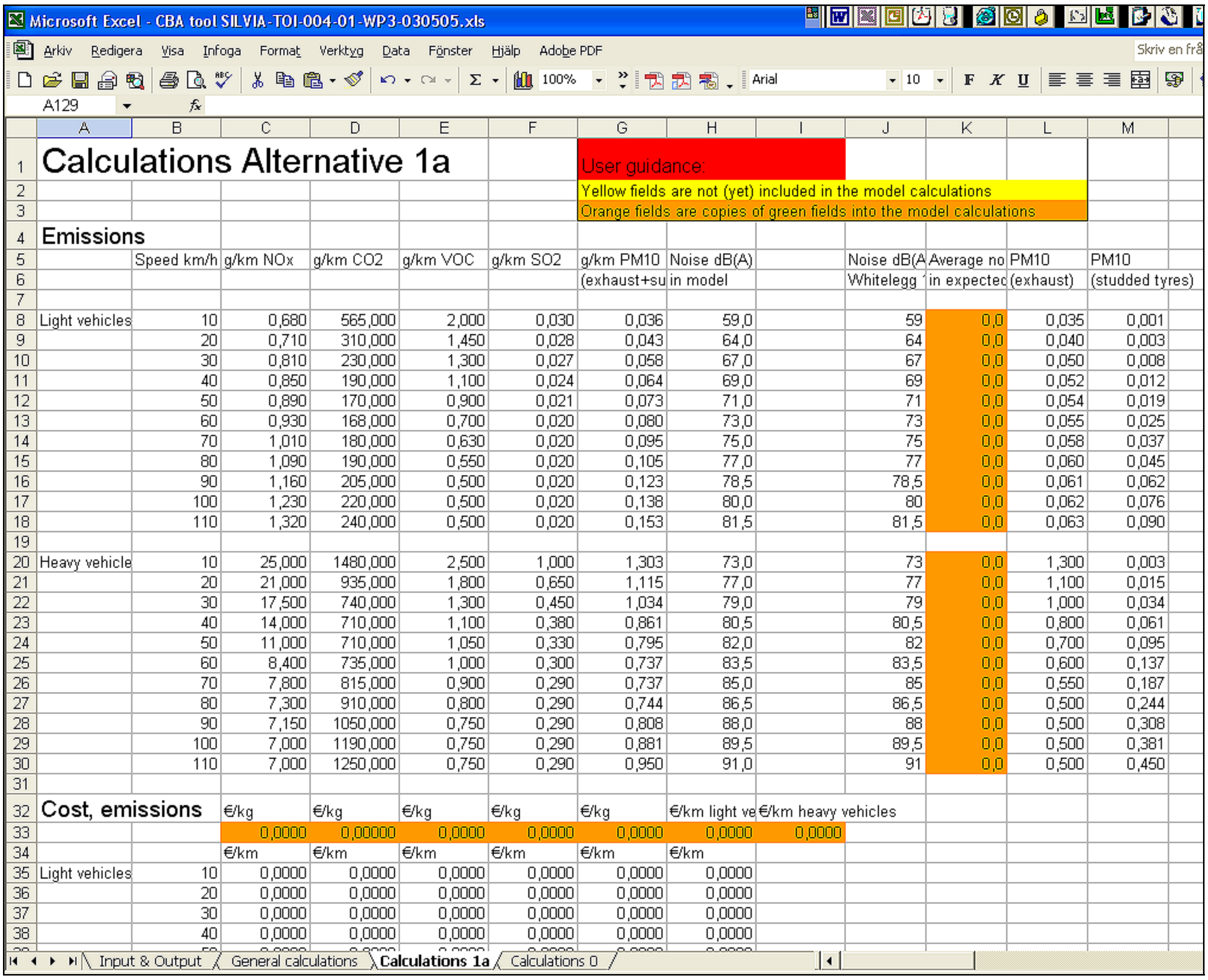
In general terms the spreadsheet consists of an "input & output" sheet and two sheets with (underlying) calculations for two road surface alternatives plus some general calculations.

The two road surface alternatives are given in the following forms:

- ‘Alternative 0’ represents the current situation without any change (i.e. “business as usual” / “do nothing”), e.g. a standard dense asphalt that is not optimised with respect to its noise characteristics;

- ‘Alternative 1’ is the improved situation with reduced noise levels, i.e. laying a surface that yields lower noise levels compared to ‘Alternative 0’.

Of course, two pavements having favourable noise characteristics can also be compared by setting the best surface of the two as Alternative 1. Unfortunately, it takes too much space here to describe or give an example of the calculations, but Fig. 6.16 gives an illustration of just a small part of the spreadsheet. See also Fig. 6.17.



Microsoft Excel - CBA tool SILVIA-TOI-004-01-WP3-030505.xls

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Calculations Alternative 1a						User guidance:						
2							Yellow fields are not (yet) included in the model calculations						
3							Orange fields are copies of green fields into the model calculations						
4	Emissions												
5		Speed km/h	g/km NOx	g/km CO2	g/km VOC	g/km SO2	g/km PM10	Noise dB(A)		Noise dB(A	Average no	PM10	PM10
6							(exhaust+su	in model		Whitelegg '	in expected	(exhaust)	(studded tyres)
7													
8	Light vehicles	10	0,680	565,000	2,000	0,030	0,036	59,0		59	0,0	0,035	0,001
9		20	0,710	310,000	1,450	0,028	0,043	64,0		64	0,0	0,040	0,003
10		30	0,810	230,000	1,300	0,027	0,058	67,0		67	0,0	0,050	0,008
11		40	0,850	190,000	1,100	0,024	0,064	69,0		69	0,0	0,052	0,012
12		50	0,890	170,000	0,900	0,021	0,073	71,0		71	0,0	0,054	0,019
13		60	0,930	168,000	0,700	0,020	0,080	73,0		73	0,0	0,055	0,025
14		70	1,010	180,000	0,630	0,020	0,095	75,0		75	0,0	0,058	0,037
15		80	1,090	190,000	0,550	0,020	0,105	77,0		77	0,0	0,060	0,045
16		90	1,160	205,000	0,500	0,020	0,123	78,5		78,5	0,0	0,061	0,062
17		100	1,230	220,000	0,500	0,020	0,138	80,0		80	0,0	0,062	0,076
18		110	1,320	240,000	0,500	0,020	0,153	81,5		81,5	0,0	0,063	0,090
19													
20	Heavy vehicle	10	25,000	1480,000	2,500	1,000	1,303	73,0		73	0,0	1,300	0,003
21		20	21,000	935,000	1,800	0,650	1,115	77,0		77	0,0	1,100	0,015
22		30	17,500	740,000	1,300	0,450	1,034	79,0		79	0,0	1,000	0,034
23		40	14,000	710,000	1,100	0,380	0,861	80,5		80,5	0,0	0,800	0,061
24		50	11,000	710,000	1,050	0,330	0,795	82,0		82	0,0	0,700	0,095
25		60	8,400	735,000	1,000	0,300	0,737	83,5		83,5	0,0	0,600	0,137
26		70	7,800	815,000	0,900	0,290	0,737	85,0		85	0,0	0,550	0,187
27		80	7,300	910,000	0,800	0,290	0,744	86,5		86,5	0,0	0,500	0,244
28		90	7,150	1050,000	0,750	0,290	0,808	88,0		88	0,0	0,500	0,308
29		100	7,000	1190,000	0,750	0,290	0,881	89,5		89,5	0,0	0,500	0,381
30		110	7,000	1250,000	0,750	0,290	0,950	91,0		91	0,0	0,500	0,450
31													
32	Cost, emissions		€/kg	€/kg	€/kg	€/kg	€/kg	€/km light ve	€/km heavy vehicles				
33			0,0000	0,00000	0,0000	0,0000	0,0000	0,0000	0,0000				
34			€/km	€/km	€/km	€/km	€/km	€/km					
35	Light vehicles	10	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000					
36		20	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000					
37		30	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000					
38		40	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000					

Input & Output / General calculations / Calculations 1a / Calculations 0

Fig. 6.16. Example of part of sheet "Calculations 1a" in the SILVIA Excel spreadsheet for CBA. From [Saelensminde & Veisten, 2005a]. See further Fig. 6.17.

The noise benefits resulting from a change from Alternative 0 to Alternative 1 are calculated in two different ways. These are summarised in (a) and (b) below:

(a) This method is based on marginal values per vehicle kilometre, involving both noise effects and any other indirect effects; e.g. on air pollution, safety, etc. In this case, the estimated noise benefits will depend on the "average marginal values", i.e. some average noise cost per vehicle kilometre in urban and/or sub-urban areas. Hence, in this case there is no specific reference to affected dwellings in the calculations. However, weighting factors can be applied to reflect differences in dwelling density. Principally, one could also include a factor for different use of the area, e.g., areas with shops/schools/workplaces and more residential areas where people are more likely to be affected by noise outside their homes.

(b) This method is based on direct calculation of noise benefits from the reduced noise in dB(A) outside dwellings multiplied by the number of homes alongside the road section on both sides (affected dwellings) and further multiplied by the valuation per dB(A) noise reduction per dwelling (per year). The dB(A) valuation is weighted according to the reference point; i.e. the reductions from higher noise levels are valued higher. The valuation function is adapted from the official Swedish monetary valuation [Navrud, 2002] and can be adjusted and approximated to the monetary valuation of noise reduction in other countries.

In addition, alternatives involving noise control options other than road surfaces are included in the input-result page of the spreadsheet. 'Alternative 2' provide estimates for the use of noise barriers while 'Alternative 3' provides estimates for noise-reducing windows (i.e. window sound insulation). However, noise barriers (Alternative 2) and especially noise insulation (Alternative 3) do not provide as wide an effect as noise reduction at the source (Alternative 1). Noise-reducing surfaces typically provide benefits over a wider area than noise barriers. Furthermore, the use of noise-reducing surfaces will avoid any negative effects associated with noise barriers such as reduced view and increased shade. In the case of noise-reducing windows the reduced noise is only experienced indoors with closed windows. Therefore, the monetary valuation is scaled down to 80 % for noise barriers and 60 % for noise reducing windows compared to low-noise road surfaces. This is an approximation to procedures presented by [Larsen and Bendtsen, 2002].

A few examples of benefit/cost calculations are presented in [SILVIA, 2006]; see Table 6.6, although it is pointed out explicitly that "It should be stressed that these estimates are based only on example data and should not be considered as anything other an illustration of the how the CBA tool can be applied". Anyway, the examples were calculated with the best estimates available for the four cases, and it appears from Alternative 1b that the low-noise surface case comes out favourable.

Table 6.6. Benefit/cost ratios (EUR/project)[29] for different road types in two different countries [SILVIA, 2006].

Noise reduction measure	Norway Ring-road 70 km/h	Denmark Ring-road 70 km/h	Denmark City street 50 km/h	Denmark Freeway 110 km/h
Alternative 1a: Low-noise asphalt (Benefits - all effects, excl noise)	0.65	2.00	0.69	4.82
Alternative 1b: Low-noise asphalt (Benefits – noise)	2.90	3.16	4.91	4.90
Alternative 2: Barrier + ev. insulation (Benefits – noise)	2.04	1.16	N/A	3.31
Alternative 3: Window sound insulation (Benefits – noise)	3.04	1.81	1.45	2.52

An example of the results as presented in the Excel spreadsheet appears in Fig. 6.17, which illustrates the results of the calculations in Table 6.6 for the case "Denmark City street 50 km/h".

[29] The unit must be checked-up, it seems wrong / The author

Project costs - road surfaces - € for given road length and road width (present value)

Alternative	Investment (layer)	Investment (Drainage)	Maintenance (Winter)	Maintenance (Cleaning)	Maintenance (Clean pipes)
Alternative 0	44,800	0	26,107	0	0
Alternative 1	150,039	53,600	39,161	9,081	21,729

Noise/environmental/accident/insecurity/time/veh.operation costs to society - marginal costs per vehicle km - € - Alternatives **0**, **1a**. (From calculation sheets 0 and 1a.)

Alternative	Noise	Local air pollution	Global air pollution	Accidents	Insecurity	Time	Vehicle operation	Sum total	Speed km/h
Alternative 0	**0.016**	0.044	0.009	0.042	0.007	0.281	0.102	0.500	50
Alternative 1a	**0.011**	0.044	0.009	0.042	0.007	0.281	0.102	0.496	50

Noise benefits to society (reduced noise costs) - calculated € value for estimated dB(A) change per household per year - Alternatives **1b**, **2**, **3**

Alternative	Average noise reduction in expected life time - dB(A)	Noise benefits per dwelling per year
Alternative 1a	2.5	
Alternative 1b		€ 222
Alternative 2	n.a.	n.a.
Alternative 3	9.0	€ 864

CBA results - relative to Alternative 0 (that is, additional benefits and costs compared to baseline alternative)

	Alternative 1a low-noise asphalt (benefits all effects)		Alternative 1b low-noise asphalt (benefits noise)		Alternative 2 barrier (plus ev. ins.) (benefits noise)		Alternative 3 insulation (benefits noise)	
	€/year	**€/project**	**€/year**	**€/project**	**€/year**	**€/project**	**€/year**	**€/project**
Benefits	20,647	167,401	147,385	1,194,974	n.a.	n.a.	574,803	4,660,399
Costs, investments	19,591	158,839	19,591	158,839	n.a.	n.a.	330,539	2,679,950
Costs, operations/maintenance	5,410	43,863	5,410	43,863	n.a.	n.a.	0	0
Tax-cost factor	5,000	40,541	5,000	40,541	n.a.	n.a.	66,108	535,990
Benefits - Costs (net benefit)		**-75,842**		**951,731**		**n.a.**		**1,444,459**
Benefit-cost ratio		**0.69**		**4.91**		**n.a.**		**1.45**
Net benefit-cost ratio		-0.31		3.91		n.a.		0.45
Total project cost per dwelling			45	366	n.a.	n.a.	596	4,836
Project costs per dB(A) reduction per dwelling			18	146	n.a.	n.a.	66	537

Fig. 6.17. Example of the result part of the sheet "Input & Output" in the SILVIA Excel spreadsheet for CBA. From [SILVIA, 2006].

6.3.6 Low-noise road surfaces

The most extensive part of the SILVIA project, at least in terms of budget, was the low-noise road surface part. This would justify a comprehensive summary in this report. However, almost all experimental work with low-noise road surfaces was made with national contributions and related to a specific partner country. Therefore, the major results are not presented in this section, but under each country later in this report.

However, here a summary of results from various countries taking part in SILVIA is shown in Figs. 6.18-6.20 below, which summarise the results for all surfaces in terms of SPB levels on low, medium and high speed roads [SILVIA, 2006]. Two "reference" surfaces are shown in the Figures for illustrative purposes:

- Surface "Ref #1" (medium-speed roads only) is based on the virtual reference surface reported in Annex D of ISO 11819-1, i.e. the average of SPB data for asphalt concrete (2-10 years old, 11-14 mm chippings) and stone mastic asphalt (3-7 years old, 12-16 mm chippings);

- Surface "Ref #2" is a virtual reference surface based on the average of SPB data for all of the DAC and SMA surfaces with 11-16 mm chippings reported in the SILVIA report "Acoustic performance of low-noise road pavements" (SILVIA-DTF-DRI-010-01-WP4-290605).

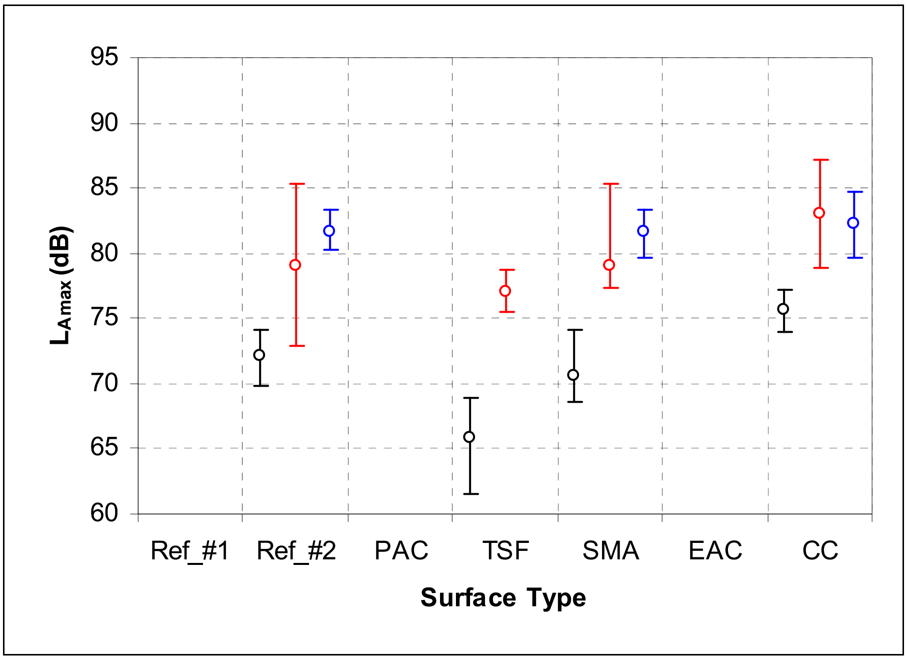


Fig. 6.18. Comparison of average SPB noise levels for different surfaces on low-speed roads; error bars show maximum and minimum noise levels for each pavement type. ○ Cars, 50 km/h; ○ Dual-axle heavies, 50 km/h; ○ Multi-axles heavies, 50 km/h.
Surface Types: Ref_#1: Virtual reference surface; Ref_#2: Virtual reference surface; PAC: Porous asphalt concrete; TSF: Thin surfacings; SMA: Stone mastic asphalt; EAC: Exposed aggregate cement concrete; CC: Cement concrete

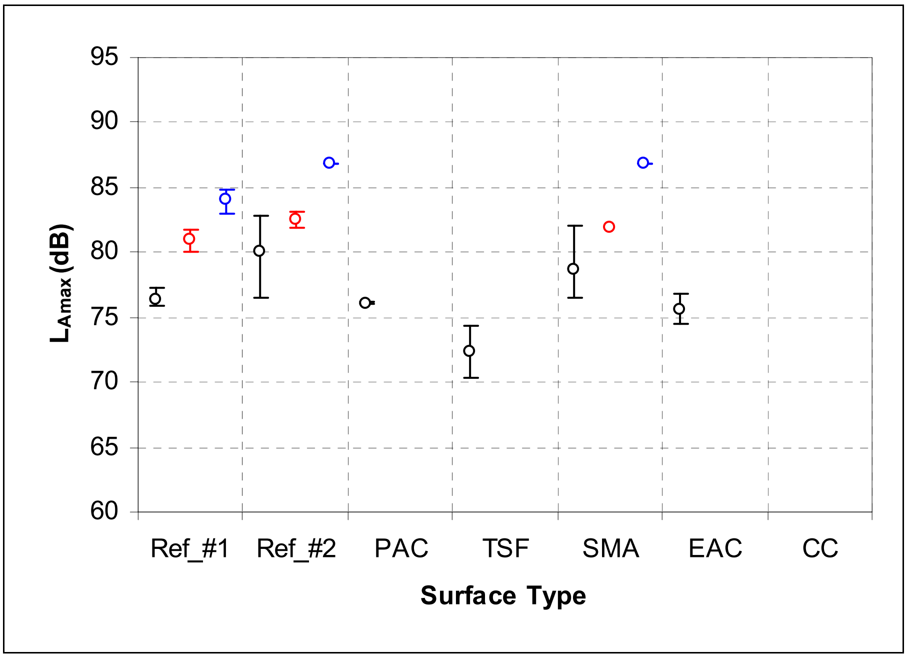


Fig. 6.19. Comparison of average SPB noise levels for different surfaces on medium-speed roads; error bars show maximum and minimum noise levels for each pavement type. ○ Cars, 80 km/h; ○ Dual-axle heavies, 70 km/h; ○ Multi-axles heavies, 70 km/h.
Surface Types: See Fig. 6.18.

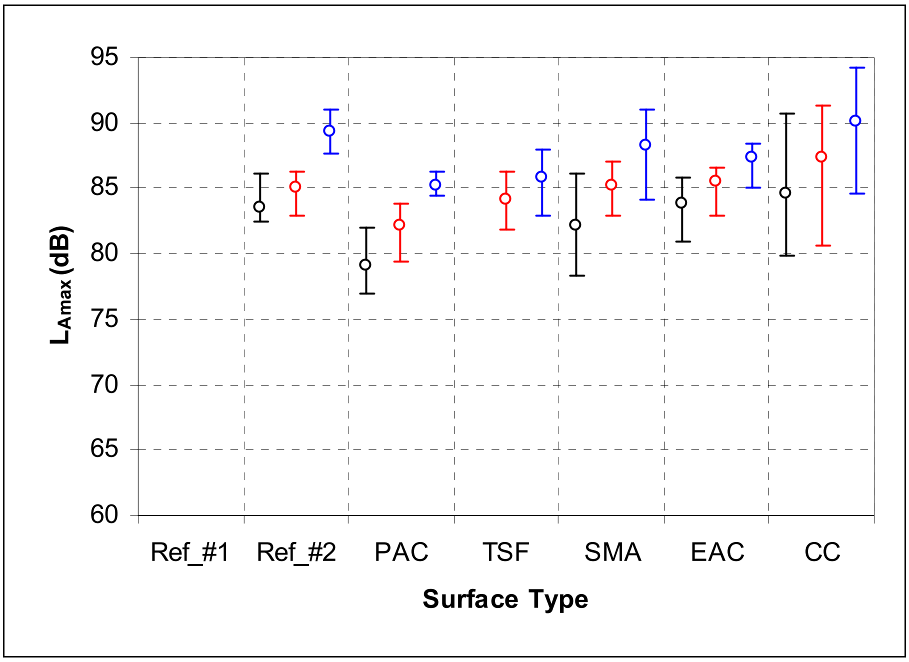


Fig. 6.20. Comparison of average SPB noise levels for different surfaces on high-speed roads; error bars show maximum and minimum noise levels for each pavement type. ○ Cars, 110 km/h; ○ Dual-axle heavies, 85 km/h; ○ Multi-axles heavies, 85 km/h.
Surface Types: Ref_#1: Virtual reference surface; Ref_#2: Virtual reference surface; PAC: Porous asphalt concrete; TSF: Thin surfacings; SMA: Stone mastic asphalt; EAC: Exposed aggregate cement concrete; CC: Cement concrete

The author estimates that the surfaces called Ref_#1 and Ref_#2 are approx. 0.5 dB "noisier" for light traffic than the HARMONOISE virtual reference, due to the higher maximum aggregate size. For heavy traffic they should be equivalent to the HARMONOISE virtual reference.

It is important to note when comparing the noise levels shown in these figures that they are average values derived from surfaces having a wide age range; i.e. not all of the surfaces were tested at the same age.

The results illustrate that there can be large variations in the maximum pass-by noise level across similar surfaces for a particular vehicle category; e.g. about 10 dB for cement concrete surfaces on high speed roads. It is likely that this variation is dependent on the age and volume of traffic with the general trend that noise levels increase as the surface ages.

The figures have been included to illustrate the range in noise levels encountered from different types of vehicles travelling on different road surfaces over different speed ranges. As the road type changes from low to high-speed roads the variation in the maximum pass-by noise level across different vehicle categories is reduced due to the wider speed variation between cars and heavy vehicles. For low speed roads where all the traffic is travelling at similar speed; i.e. on average about 50 km/h, variation in noise from different vehicle types across the surfaces studied was shown to be about 25 dB compared with less than 20 dB for high-speed roads.

6.3.7 Low-noise road surfaces in combination with other noise abatement measures

There are a number of issues that are interesting to explore when they are combined with the use of a low-noise road surface, such as:

- Low noise road surface and propagation over soft ground
- Low noise road surface and propagation over snow
- Low noise road surface and propagation over barrier
- Low noise road surface and sound transmission through facade
- Low noise road surface and multiple reflections in street canyon
- Low noise road surface and multiple reflections in tunnel

The four first ones mean that the noise spectrum is or may be largely affected, which means that the sound reaching the receiver may have a different character than near the source and the effect of the low noise road surface may be lessened since it may work in a frequency range which was a dominating one near the source but may not be so at the receiver position.

The effect of noise barriers is most significant at frequencies which are essentially the same as where a low noise road surface may be effective. When one of these measures has already been applied, for example, a low-noise road surface, there is not so much energy left that can be reduced by a noise barrier, at the frequencies where noise barriers are effective - it has already been "taken away" by the road surface.

Multiple reflections, such as in a tunnel or a street canyon, may have an opposite effect; namely that the road surface will be more effective when this effect occurs. Each time a sound wave is reflected and propagates over the street surface, there is some sound absorption taking place. The more times the sound travels over the surface the more of the sound is absorbed.

These issues were all considered in SILVIA, although the two last ones were finished after the SILVIA report was finished, and the following gives a review of the most interesting results.

The combination of low-noise road surface and noise barriers is very common. Table 6.7 presents results of an experimental study reported in [Peyrard, 2001].

Table 6.7. Effect of combining low-noise surface with a noise barrier

Case No.	Noise abatement measure applied	L_{Amax} [dB]	Difference compared to case A [dB]
A	Ref case = Dense asphalt (no abatement measure)	76.9	--
B	Low noise asphalt	74.3	2.6 *Reduction B-A = 2.6 dB*
C	Dense asphalt + 2 m high barrier	66.0	10.9 *Reduction C-A = 10.9 dB*
D	Low noise asphalt + 2 m high barrier	64.5	12.4 *Reduction D-A = 12.4 dB*

It appears that the effect of each separate measure is not added into the sum of them when both are applied. If one already has a barrier giving a noise reduction of 10.9 dB as in this case, the low-noise road surface will only add another 1.5 dB of noise reduction, while it as a single measure gave 2.6 dB in noise reduction. Only a little more than 50 % of the original noise reduction was added by the road surface when it was applied where there already was a (quite efficient) noise barrier.

With regard to the effect of low-noise surfaces in reverberant sound fields such as between facades and in tunnels; see Chapter 17.4.

As written in the beginning of this section, sound may be "coloured" by the transmission through facades or propagation over ground due to the attenuation depending on frequency. The most obvious example is what happens when sound is transmitted through a façade; in practice the window(s) will determine the effect: high and medium frequencies are substantially attenuated while low frequencies are poorly attenuated. See Fig. 6.21 for an illustration. This effect means that tyre/road noise often is better attenuated than other vehicle noise dominated by low frequencies, and thus the importance of reducing it is lower indoors than outdoors.

The effect very much depends on the climate, since different climate regions mostly have different heat and sound insulations. In the Scandinavian countries, triple-glazing is standard which means that sound insulation is very high, but with a focus on medium and high frequencies. In countries in hot climates, the case should be similar, since energy conservation would call for similar heat insulation (but in the opposite direction), but in practice heat and sound insulation is still poor in most countries with a hot climate.

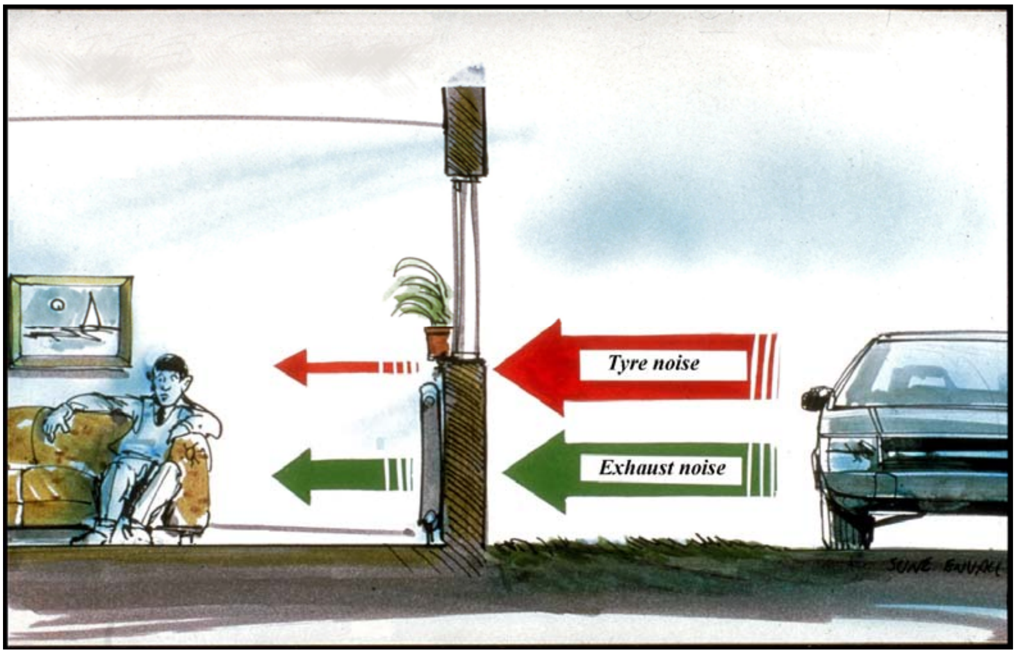


Fig. 6.21 Illustration of the "colouring" of the sound that occurs when it is transmitted through a façade. Sound which is dominated by medium and high frequencies, such as tyre/-road noise, will be rather effectively attenuated, whereas sound dominated by low frequencies, such as exhaust noise, will be poorly attenuated. From [Sandberg & Ejsmont, 2002].

The study in SILVIA lacked sufficient information, but some calculations were conducted to shed some light on the situation. Two source frequency spectra, typical of traffic on a dense and on a porous asphalt, were selected. Then a spectrum typical of the sound reduction of a façade was selected and combined with the source spectra. The result appears in Fig. 6.22 [Anfosso-Ledée, 2005].

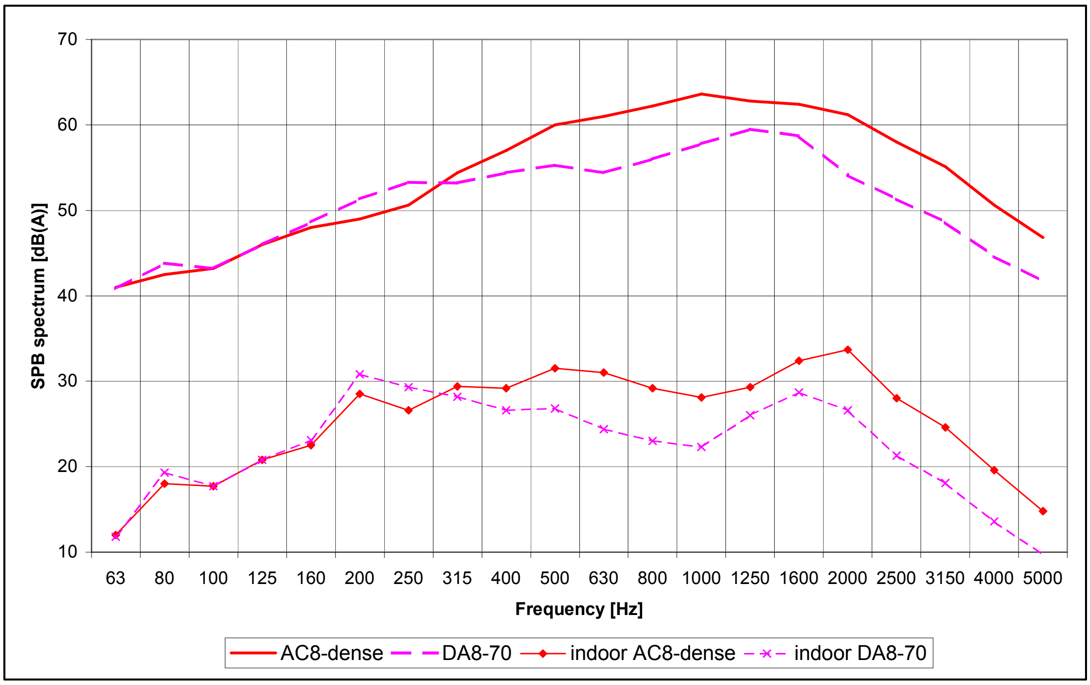


Fig. 6.22 Resulting spectra when sound is transmitted through a façade for both a dense (solid lines) and porous asphalt DA8-70 (broken lines). From [Anfosso-Ledée, 2005].

The calculated A-weighted results outdoor are 72.0 dB for the dense asphalt (AC8) and 67.5 dB for the double-layer porous asphalt (DA8-70), which gives an outdoor sound reduction effect of the porous road surface of **4.5 dB**. In the indoor case, the calculated A-weighted results are 42.0 dB for the dense asphalt and 38.9 dB for the double-layer porous asphalt, which gives an indoor sound reduction effect for the porous road surface of **3.1 dB** [Anfosso-Ledée, 2005]. Thus, the physical benefit of the porous pavement is lower indoor than outdoor. This is for a façade insulation representative of single-glazing windows. For double- or triple-glazing windows, the difference in effect outdoor-indoor is greater.

6.3.8 Guidance manual

The main output of SILVIA was a "Guidance Manual for the Implementation of Low-Noise Road Surfaces" [SILVIA, 2006]. As should have appeared already in the earlier sub-sections due to the many references made to this manual, this is a comprehensive manual for road administrators and people who work with noise aspects of roads and streets, which contains a summary of all results from SILVIA and suggestions regarding the implementation of these.

The individual chapters are summarised as follows [SILVIA, 2006]:

Summary of the Guidance Manual (from [SILVIA, 2006])

PART 1: Background information

- Chapter 2, *"The evaluation of noise"*, provides an overview of the salient issues relating the physical measures used to describe noise with perception and annoyance;
- Chapter 3, *"Overview of vehicle and tyre/road noise"* provides the background information which describes the various noise sources associated with vehicle noise emission and the important surface parameters that are important for the characterisation of a road surface (in terms of both acoustic and non-acoustic performance).

PART 2: Overview of existing low-noise surfaces

- Chapter 4, *"Review of existing low-noise pavement solutions"*, provides a broad overview of existing low-noise surfaces that are currently used across Europe, including details of material specifications and typical acoustic performance;
- Chapter 5, "*Review of existing construction and maintenance techniques*" provides a broad overview of construction and maintenance methods, including cleaning and winter maintenance;
- Chapter 6, *"Prospects for further developments of low-noise surfaces"* considers how the acoustic performance of surfaces might be optimised by changes to material properties and production techniques, how structural durability might be optimised and reviews some new/recent developments and concepts for low-noise surfaces that are not yet widely accepted for general use.

PART 3: Specifying the performance of low-noise surfaces

- Chapter 7, *"Overview of measurement methods for acoustic labelling and COP purposes"*, provides a summary of the recognised methods that are used within the project for obtaining measurement data and which form an integral part of the SILVIA surface classification system;
- Chapter 8, *"Overview of additional methods used in the SILVIA project"* provides a summary of methods developed within the project that are not yet recognised as standard methods;
- Chapter 9, *"Proposals for a noise classification procedure"*, introduces the need for and outlines the basic measurements required by the SILVIA project classification system for acoustic labelling, COP (Conformity of Production) assessment and routine monitoring.

PART 4: Quantifying the benefits of low-noise surfaces

- Chapter 10, *"Safety and sustainability benefits of low-noise road surfaces"*, summarises current knowledge on the safety aspects of low-noise road surfaces, and the effects of using these surfaces on effects such as water pollution, material use, recycling and fuel consumption. Particular emphasis is placed on porous asphalt surfaces;
- Chapter 11, *"Cost-benefit analysis"*, describes the application spreadsheet cost-benefit tool developed within the project, including worked examples.

PART 5: The performance of low-noise surfaces

- Chapter 12, *"Factors affecting the performance of low-noise surfaces"*, addresses the influence of local conditions such as roadside developments, fleet composition, repairs, studded tyres and weather effects on the performance of low-noise surfaces;

- Chapter 13, *"The integration of low-noise surfaces with other mitigation measures"*, describes the influence of other types of noise mitigation measures on the performance of low-noise surfaces.

PART 6: Advice on low-noise surfaces

- Chapter 14, *"Advice on the selection of low-noise surfaces"* summarises the conclusions from previous chapters and advises on other considerations such as changes in performance over the surface lifetime;

- Chapter 15, *"Advice on the assessment of surfaces"*, provides a summary of the procedures developed in the project for COP (Conformity of production) assessment and routine monitoring.

APPENDICES

- Appendix A, *"Measurement methods"*, provides more details on all of the measurement methods considered or applied within the SILVIA project, both for general measurements and as part of the SILVIA classification system. For the more important methods, the issues of repeatability and reproducibility are also addressed, and equations proposed for converting measurement results to appropriate single number ratings;

- Appendix B, *"Procedures for the certification of measurement apparatus"*, describes recommended procedures for certifying and approving test apparatus used to carry out the methods described in Appendix A;

- Appendix C, *"SILVIA proposals for a classification scheme"*, sets out in detail the procedures and associated tolerances for the acoustic labelling of surfaces, COP assessment and routine monitoring;

- Appendix D, *"Application of the SILVIA classification system"*, describes how the information generated during acoustic labelling might be used to define product specifications for politicians, planners and contracting parties. The derivation of road surface corrections for national noise prediction methods and the associated selection of appropriate reference surfaces are also addressed.

- Appendix E, *"SILVIA documents included on the CD-ROM",* lists all of the deliverables and other SILVIA-related documents referred to in the Manual that are stored on the accompanying CD-ROM.

6.4 SILENCE

The EU project SILENCE (see Fig. 5.4) had a Sub-Project SP F which dealt with road surfaces; see Table 6.8. Some snapshots from the SILENCE SP F work follow below.

Table 6.8. The work packages of SILENCE Sub-Project F "Road surfaces".

Work package No.	Work package title
F1	New production technologies for surfaces on urban streets
F2	New production technologies for surfaces on urban main roads
F3	Improved systems for maintenance of quieter surfaces
F4	Noise classification methods for urban road surfaces
F5	Testing of novel new road surfacing materials

One part of WP F1 was to study and reduce noise from the historical type of stone setts which are frequently used in old towns and cities in Europe. The results so far indicate that a kind of granite blocks that look similar to the ordinary stone setts reduce vehicle noise at 30-40 km/h by approximately 4 dB(A) and in fact are no noisier than an ordinary dense asphalt surface. See further [Sandberg & Bendtsen, 2007].

Another part of F1 has looked at crossings between railways and streets [Bendtsen, Ögren Sandberg, 2007]. From this study the following findings can be reported:

- It was found that there are possibilities to reduce road vehicle noise emission at a road-rail crossing by placing a suitably soft material, such as rubber tried in experiments in the project, between and beside the rails.
- The potential noise reduction by using the rubber material is approximately 2-5 dB. See Fig. 6.23 for an illustration.
- However, it must be observed that the workmanship is extremely important when mounting the rubber material, as it will lose its entire advantage if the joints with the surrounding road material are not good or in good condition.
- It has also been demonstrated in these experiments that arranging the road-rail crossing in such a way as to get an angle of 45^o between road and rail instead of the common 90^o, reduces noise by approximately 4 dB(A).
- Combinations of these two measures might give up to 8 dB of noise reduction.

A third part of WP F1 has tried thin layers. Interim results from tests (CPX method) in Malmö in southern Sweden indicated an initial tyre/road noise reduction of 3 dB for a special thin layer asphalt surface (essentially dense) constructed by Skanska (Fig. 6.24) in relation to an SMA 0/11 in new condition. This is a low-speed street with 50 km/h posted speed. However, when measurements were repeated a year later the noise reduction was essentially gone.

VTI has found two dense asphalt surfaces with 8 mm aggregate size used on wide road shoulders in Sweden which give the same noise reduction, 5 dB compared to an SMA 0/16, as a double-layer porous asphalt surface gives after one year of traffic exposure. However, it is not yet known how its characteristics change with wear.

Fig. 6.23. Rubber material called STRAIL tried in road-railway crossing in Sweden [Bendtsen, Ögren Sandberg, 2007]. Noise reduction was found to be 2-5 dB compared to conventional cement concrete material.

Fig. 6.24. Thin layer asphalt surface tried in Malmö in Sweden [Schmidt, 2007]. Noise reduction was found to be 3 dB(A) compared to an SMA 0/11 surface of same age. 50 km/h street.

In Work Package F2, promising new surface types useful for high-speed roads have been identified. For example, these include the asphalt rubber surfaces frequently used in Arizona. Also improved variants of thin layers have been identified for testing. VTI has manufactured slabs for testing (Figs. 6.25 and 6.27) in the German machine shown in Fig. 6.26, composed of two dense asphalt surfaces similar to SMA and two similar surfaces but with a substantial proportion of rubber granules added. The intention is to test the "pure" effect of the rubber. The tests should have been made in the early autumn of 2007 but have been delayed due to problems in Germany.

Work Package F3 has focused on identifying spots with poor maintenance and in need of repair, and the effects these have on noise emission. For example, reports have been produced on:

- Overview of technologies and systems to detect pavement discontinuities including assessment of importance to noise reduction
- Report on noise-related parameters of existing pavement monitoring systems and possibilities of integrating acoustic parameters

Fig. 6.25. Road surface slabs containing a substantial proportion of rubber granules produced by VTI for testing in the German laboratory test machine shown in the next figure.

Work Package F4 included the following major activities:

- Update and improvement of classification procedures for low noise road surfaces and adaptation of them to urban conditions.
- This includes producing a new method for measuring Leq before and after laying of a low-noise road surface in an urban area and compensating for changes in traffic and speed
- Measurements of noise characteristics of road surfaces
- Measurement of noise from discontinuities on road surfaces (manholes, bumps, etc)
- Collection and compilation of data about the noise characteristics of road surfaces into a database. This is the responsibility of VTI; see [Ögren & Sandberg, 2007].

Work Package F5 intended to test a number of candidate low noise road surfaces in a laboratory drum machine. See Figs. 6.26-6.27. This machine allows measurements at the conventional "near-field CPX positions", as well as in the hall at approx. 7 m from the test tyre.

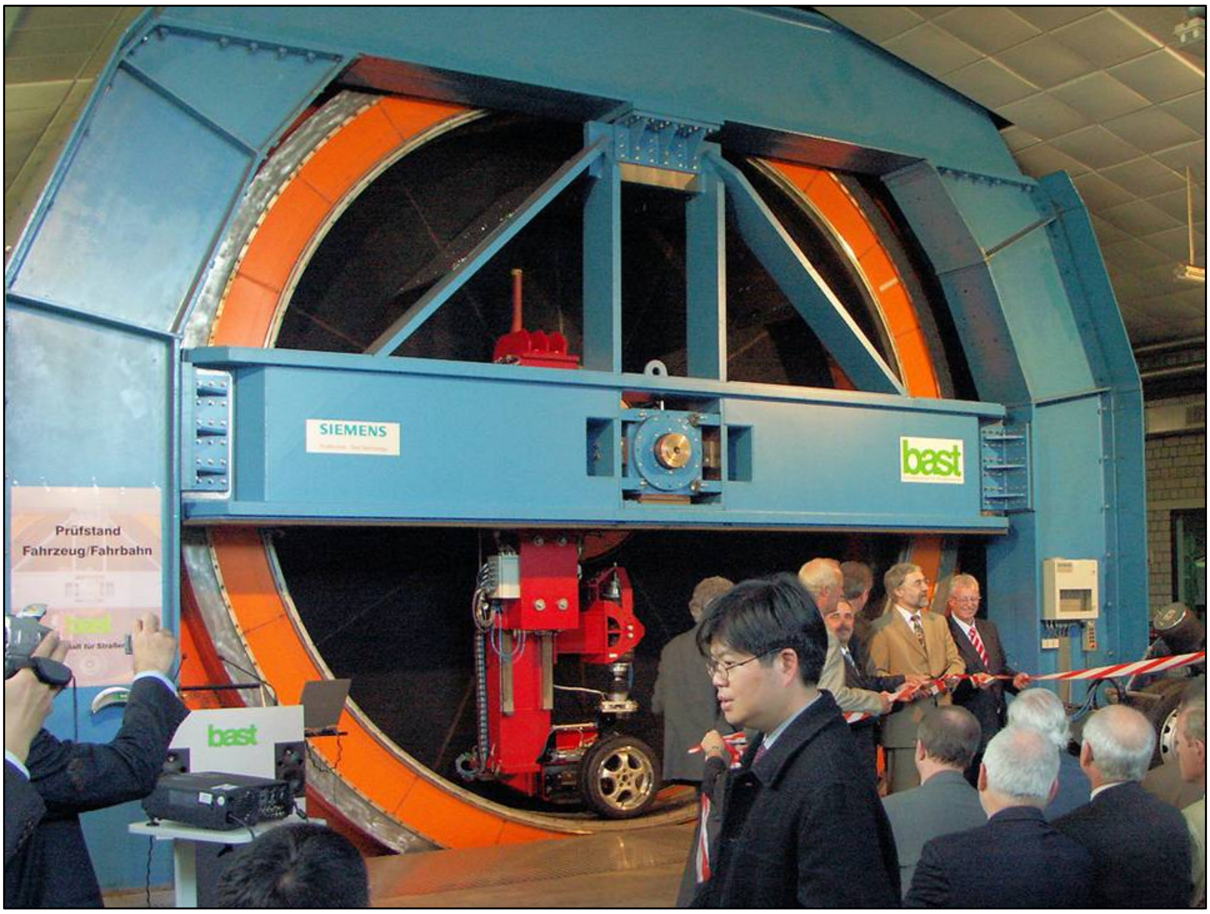


Fig. 6.26. The German laboratory test machine, using a 6.5 m inner diameter drum on which road surface slabs are mounted. Note the car tyre at the bottom. Photo from the inauguration of the improved facility in April 2007.

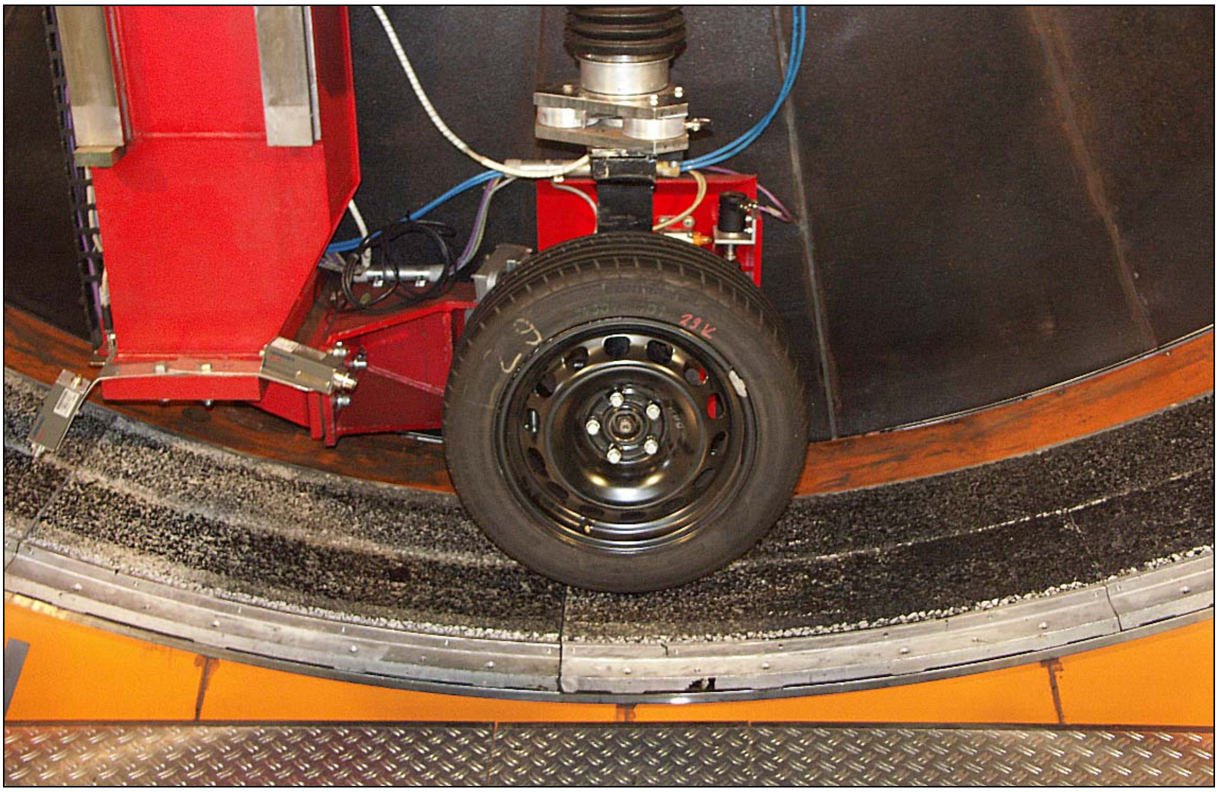


Fig. 6.27. Samples of gap-graded asphalt rubber and SMA from VTI in Sweden under test (same as shown in Fig. 6.25) with the German laboratory test machine PFF in February 2008. The white material in the lower parts of the texture are remnants of a material used by BASt to increase optical reflectivity of the surface to enable texture measurements.

6.5 QCITY

In QCity, two major activities have been conducted so far of interest to this report:

A major medium-speed road (70 km/h) has been repaved with a double-layer porous asphalt surface. At this location there is a slight longitudinal grade and also a moderate curve. The maximum aggregate size in the top layer is 11 mm (named “VIACODRÄN 11”), with 16 mm in the bottom layer [Ulmgren, 2007]. Air voids were 15 % (the target was 20 %) and the total thickness was 90 mm [Ulmgren, 2008]. The noise reduction was measured at 5.5 dB in relation to the old SMA surface [Brandberg, 2006]. Fig. 9 in the Evaluation Report [Sandberg, 2008-1] would predict 5.0 dB. See Fig. 6.28 for an illustration of the road under trial. The curve is behind the observer in the photo. After one year there was some clogging in the wheel tracks but no damages were observed; neither in the uphill nor in the curve sections. In April 2008 when the surface was almost two years old it was still in good condition. In the autumn of 2008, at the age of 2 years, only 1-2 dB of the noise reduction remained, as measured by VTI and TUG with the CPX method using the SRTT and AVON reference tyres. The reason why the noise reduction deteriorated so quickly is probably that the initial voids content was low (15 %).

Work with development of what QCITY calls "poroelastic road surface" has continued. This author thinks that the term is misleading, since the surfaces they deal with are not substantially elastic and are not always very porous either. A more appropriate term would be "asphalt rubber". In fact, except for a much higher rubber content (8 % compared to 2 %), the QCITY surface is rather similar to the open-graded type of asphalt rubber used in Arizona and tried in Sweden (see the SILENCE project in 6.4 and also 7.3). Another difference is that the rubber is added in the so-called dry process (i.e. as a supplementary aggregate[30]), instead of the wet process (i.e. rubber is added to the binder and mixed with it).

In the autumn of 2006 a trial section of this type of high-rubber-content surface was laid on a 50 km/h street in Gothenburg, Sweden [Ulmgren, 2007]. Rubber was added as granules 1-2 mm, giving a rubber content of 5-10 % by weight of the total mix (8 % according to [Malker et al, 2007]), the binder was polymer-modified bitumen (about 8 %), and max aggregate size in the asphalt mix was 8 mm. The air voids content was 15 % [Malker et al, 2007]. Noise reduction was first reported to be 6-8 dB(A) compared to a new SMA 0/11 [Ulmgren, 2007]. In a later presentation, a noise reduction of 6 dB(A) was reported in relation to a DAC 0/11 [Nilsson, 2008].

When studying the original measurement report it turns out that the noise reduction measured at cruise-by for a passenger car was from 3.5 dB (A-weighted) at 30 km/h to 5.6 dB at 70 km/h compared to a new SMA 0/11; see Fig. 6.31. When using a measurement method where microphones were placed in front of and behind a test tyre on a car[31], noise reductions of approx. 5.8 dB over the 30-70 km/h range were measured in comparison to the SMA 0/11 and approx. 7.4 dB in comparison to an SMA 0/16. The higher elasticity of the asphalt rubber surface was found to be the main reason for the noise reduction, rather than sound absorption [Malker et al, 2007]. What this author thinks is somewhat inconsistent with that conclusion is the difference in sound spectra on the two surfaces; see Fig. 6.32, which shows a noise reduction as a function of frequency which is similar to that obtained for a surface which reduces air pumping noise. But the typical dip in the spectrum for a porous surface, due to sound absorption is missing.

Unfortunately, a month after the measurements the surface was replaced with a conventional one. The durability appeared to be too low, which was due to the use of a binder which appeared to be inappropriate for this type of surface [Ulmgren, 2008].

Instead, in September 2007 a new surface of essentially the same type was laid on Eklanda-gatan in central Gothenburg, which is a 2-lane 50 km/h street carrying an AADT of 13 000, including 4 % of heavy vehicles, mainly buses; see Figs. 6.29-6.30. This street has a moderate longitudinal grade. Another thing increasing the stress on the surface is the parking along the street which requires the frequent turning of wheels at standstill or at very low speeds. Noise reductions of approx. 5.5 dB were measured in new condition as a before-after L_{A24heq} (A-weighted equivalent level over 24 hours) from the regular traffic on this street [Brandberg, 2007]. The reduction appeared to be essentially similar over the frequency range from 160 Hz to 5000 Hz, which would suggest that both the vibration impact and the air pumping mechanisms are affected and thus both the elasticity and the air drainage would contribute to the noise reduction. The author thinks that this is an excellent result bearing in mind that this was for the total traffic at approx. 50 km/h, including power unit noise and heavy vehicles, and measured on the side of the street where vehicles drove uphill. On the other side (closest to the downhill traffic), approx. 0.7 dB higher noise reductions were measured.

[30] Although the rubber granules are first "wetted" with some fluid.

[31] This is somewhat similar to the CPX method of ISO/DIS 1819-2 but microphones were located at positions which will favour sound absorbing road surfaces, normally overestimating the noise reduction of such surfaces.

Fig. 6.28. Double-layer porous asphalt laid in 2006 on Högsboleden in Gothenburg, Sweden, with noise-exposed residential buildings close-by.

Fig. 6.29. So-called "poroelastic road surface" laid on a 50 km/h street in Gothenburg, Sweden, in the uphill lane. A more appropriate term would be "asphalt rubber", according to this author. In the downhill lane the surface has been replaced with a single-layer porous asphalt. Photo by the author in May 2008 when the surface (uphill) was 8 months old.

Fig. 6.30. Close-up view of the surface on the test section in the previous figure, after about 8 months of operation. The coin is 22 mm in diameter. Note the black parts which contain a very high proportion of rubber.

To avoid the durability problems of the first trial, the binder in the second experiment was substantially improved. After 6 months, the surface was still in good condition in the uphill lane, but in the downhill lane, the wearing course had separated from the basecourse at some spots; probably due to the braking of heavy vehicles when driving downhill. The surface in the downhill lane was then replaced with single-layer porous asphalt "VIACODRÄN 11". The same thing happened in the uphill lane in December 2008, when the surface was 15 months old and replaced with a VIACODRÄN 11. Thus, it was the adhesion between wearing course and base course which was the problem and not ravelling or rutting. It is expected that this adhesion problem may be corrected now that the reason for it is known; probably by an advanced tack coat as a glue between the top and the base layers.

Before the last section was removed, VTI and TUG made noise measurements with the CPX method. The results showed a noise reduction of 3 dB as an average for CPX tyres SRTT and AVON at 50 km/h, compared to an old SMA 0/11. This must be considered as quite good in view of the difficult traffic conditions.

The cost of this type of surface is estimated to be approx. double that of the conventional SMA, mainly as a result of the complex and expensive binder and the rubber processing [Ulmgren, 2008].

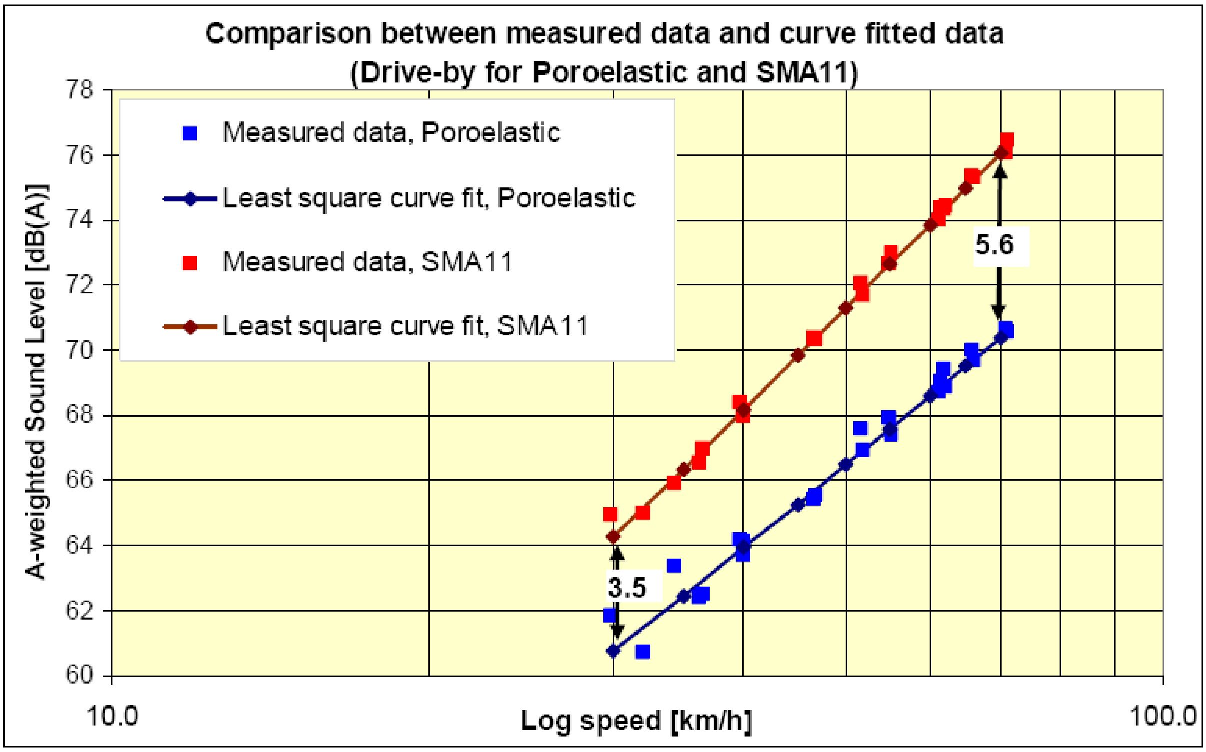


Fig. 6.31. Measured noise levels on the so-called poroelastic road surface in relation to an SMA 0/11 surface, in the QCITY project. Diagram from [Malker et al, 2007].

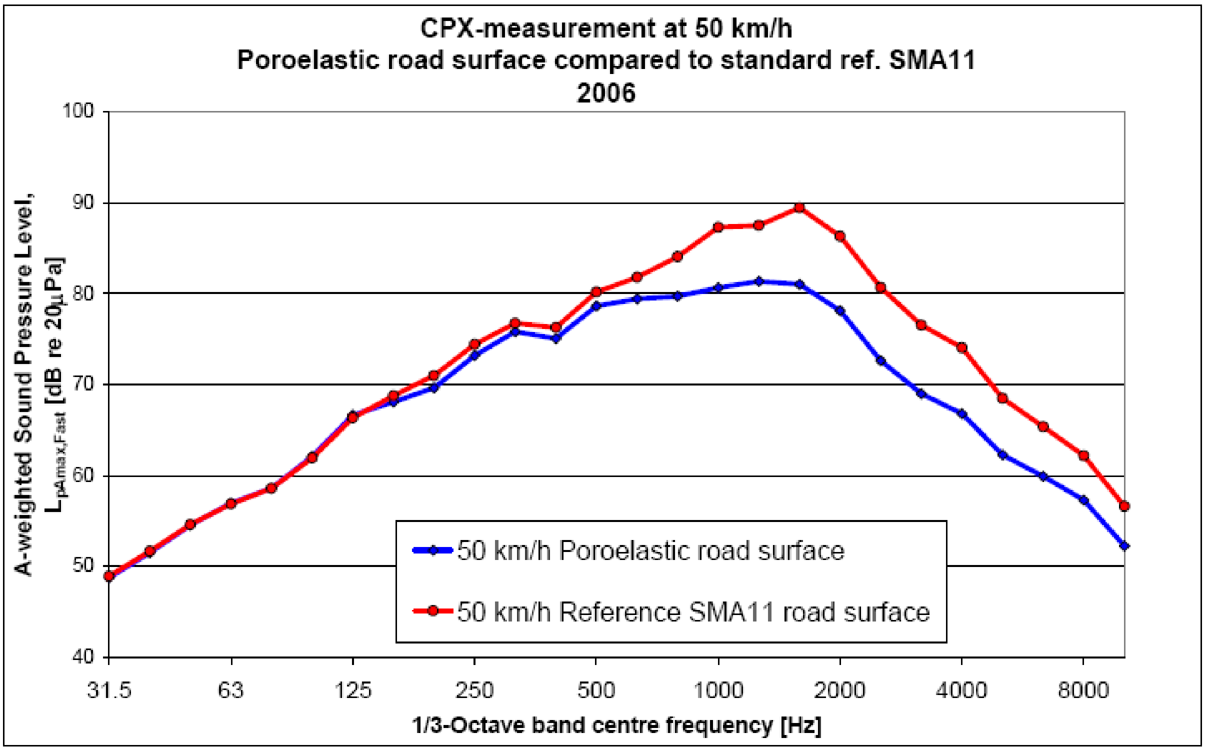


Fig. 6.32. Measured sound frequency spectrum on the so-called poroelastic road surface in relation to an SMA 0/11 surface, in the QCITY project. Measurements made with microphones immediately in front of and behind a test tyre. Diagram from [Malker et al, 2007].

A third trial with the high-volume rubber asphalt surface was made in 2008. On a 50 km/h local street in Gothenburg, NCC laid in 2008 a surface called VIACOGRIP 8. It is the same concept as for the other two trials, but the voids content is "only" 8-10 % and the rubber content is a little lower: 6 % by weight. Maximum aggregate size is 8 mm and thickness is 40 mm. Noise reductions were measured at 50 km/h with a variant of the CPX method used in the QCITY project (tyre unknown) as follows:

Noise reduction compared to DAC 0/11 was 2.5 dB
Noise reduction compared to SMA 0/16 was 5.1 dB

There is no information as to the age or condition of the conventional DAC surfaces, but at least the VIACOGRIP surface was new. Fig. 6.33 presents the results in third-octave band spectra. Since the voids content is 8-10 % sound absorption should not be responsible for the noise reduction. It is probable that it is the lower stiffness of the surface which is the reason, although one cannot exclude adhesion effects (i.e. the stick-snap or stick-slip mechanisms).

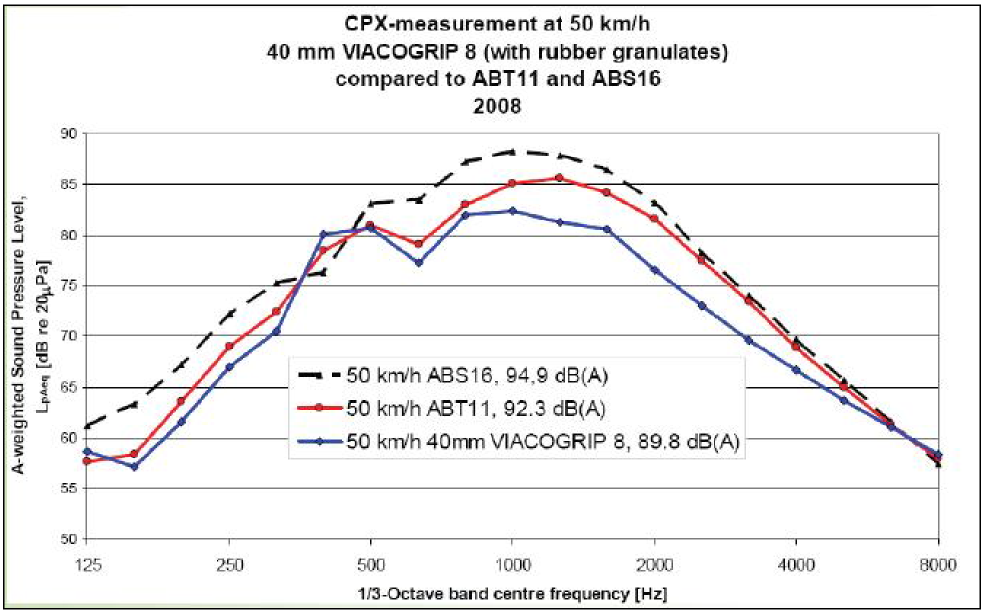


Fig. 6.33. Measured sound frequency spectrum on the so-called VIACOGRIP 8 road surface in relation to a DAC 0/11 ("ABT11") and an SMA 0/16 ("ABS16") surface, in the QCITY project. Measurements made with the special "CPX method" used in the QCITY project. Diagram from [Nilsson, 2009].

This and the measured results suggest that this type of so-called poroelastic surface is an equally effective concept as conventional porous surfaces in new condition, but maybe more easily adapted to urban low-speed conditions. Apart from (possibly) a better strength against turning or accelerating vehicles than conventional porous asphalt, it could be that a surface for which the noise reduction is based on higher elasticity could, potentially, have better long-term efficiency than a surface based on porosity, the latter of which will become clogged in a low-speed situation. On the other hand, it is not yet known how the structural durability of a surface like the one discussed here will turn out to be. It seems to be important to investigate the durability further.

See further a discussion in Section 7.5.

7. EXPERIENCE IN SWEDEN

7.1 Special concerns in road surfacing policy

Sweden is a large country, approx 2000 km from the south to the north, with an area of 450 000 m^2 and a population of 9 million. A large part lies north of the artic polar circle and the southern part is close to northern Germany. The climate is mild in summertime (daytime high 15-30 ^oC in the entire country, but chilly or cold in wintertime (daytime high -10 ^oC to +10 ^oC in southern Sweden and -20 - 0 ^oC in northern Sweden). In wintertime it is mandatory to use M+S tyres and most vehicles use steel studs in their winter tyres to increase traction and friction on ice or packed snow surfaces. Studded tyres increase the wear of the tyres on the road surfaces dramatically; calling for extremely durable aggregates with large maximum sizes. Salt is used extensively for deicing; most of the winter-time in middle and southern Sweden the roads are partly wet due to a combination of condensation, deicing by salt, and due to the low angle of the sun and short days; which rarely give the surfaces a chance to dry up. The life-cycles of road surfaces are therefore generally short, on high-volume roads it may be as short as 4-8 years; despite the use of extremely wear-resistant aggregates. Due to the high surface wear (mainly due to studded tyres) and the wet roads in the winter season, the road environment is generally extremely dirty; some of this dirt may be a major contributor to clogging of porous surfaces.

7.2 Noise characteristics of Swedish road surfaces

This author has recently produced a compilation of noise characteristics of Swedish road surfaces for the Swedish Road Administration [Sandberg, 2007]. It includes a comprehensive table of noise correction factors in dB to be added to the basic value of noise predicted on a reference type of surface. The Swedish reference surface is currently an SMA 0/16[32], which means that all correction values are the differences in noise level for traffic running on a particular surface compared to the same traffic running on an SMA 0/16. The correction factors depend on speed, proportion of heavy vehicles in the traffic and surface age. Table 7.1 shows the latest compilation of correction factors.

The values in the table are valid only for free-flowing traffic. At intersections or other places where vehicles are braking and accelerating, the correction factors approach 0 dB. The values in the table are based on an "expert evaluation" based on a very large number of studies, both in Sweden and abroad.

It is believed that the table is valid also for countries in the European Union, except those which rather recently became members, for which the current vehicle noise limits have been in force for 10 years or more. In countries where the vehicle noise limits are not as stringent as in Europe, the difference between the surfaces will be less at low speeds and for high proportions of heavy vehicles. This is because tyre/road noise will be less important in relation to power unit noise of vehicles. Another effect may be that tyres in Europe may be perhaps 1 or 2 dB noisier than in (for example) Japan and USA, since European tyres generally are produced for higher speeds than in Japan and USA, due to the free speed on short sections of German motorways.

[32] Stone Mastic Asphalt with a maximum aggregate size of 16 mm

Table 7.1 Correction factors for traffic noise emission on Swedish road surfaces compared to an SMA with max 13-16 mm aggregate size, which is considered to be the reference surface. For free-flowing traffic only. Legend: * single layer, ** double layer.

Road surface			Correction terms in dB(A), for a speed interval and a certain proportion (%) of heavy vehicles							
No.	Type (and max. aggregate size in mm)	Age [year]	40-60 km/h 0-5 %	40-60 km/h 6-19	40-60 km/h 20-100	61-80 km/h 0-5 %	61-80 km/h 6-19	61-80 km/h 20-100	81-130 km/h 0-5%	81-130 km/h 6-100
1a.	**SMA (max 13-16 mm)**	**1-20**	**ref**	**ref**	**ref**	**ref**	**ref**	**ref**	**ref**	**ref**
1b.	Same, newly laid	<1	-1	-1	-1	-1	-1	-1	-1	-1
2a.	SMA (max 10-12 mm)	1-20	-1	-1	-1	-1	-1	-1	-1	-1
2b.	Same, newly laid	<1	-2	-1	-1	-2	-1	-1	-2	-1
3a.	SMA (max 7-9 mm)*	1-20	-2	-1	-1	-2	-1	-1	-2	-1
3b.	Same, newly laid*	<1	-3	-2	-2	-3	-2	-2	-3	-2
4a.	SMA (max 4-6 mm)	1-20	-3	-2	-1	-3	-2	-1	-3	-1
4b.	Same, newly laid	<1	-4	-3	-2	-4	-3	-2	-4	-2
5a.	Asphalt concrete, dense (max 11-16 mm)	1-20	-1	-1	0	-1	-1	0	-1	0
5b.	Same, newly laid	<1	-2	-1	-1	-3	-2	-1	-3	-2
6a.	Asphalt concrete, dense (max 7-10 mm)	1-20	-3	-1	0	-3	-2	-1	-3	-1
6b	Same, newly laid	<1	-4	-2	-1	-4	-3	-2	-4	-2
7.	Slurry Seal and other extr. thin surfaces	0-5	-3	-2	-1	-3	-2	-1	-3	-1
8.	Thin surfacing type Novachip max 11mm	0-10	-1	0	0	-1	-1	-1	-1	-1
9.	Hot rolled asphalt (HRA)	0-20	0	0	0	+1	+1	0	+1	+1
10a.	Surface dressing, single, max 16-20mm	1-20	0	0	0	+1	+1	0	+1	+1
10b.	Same, newly laid	<1	+2	+1	0	+2	+1	-1	+1	0
11a.	Surface dressing, single, max 10-12mm	1-20	-1	0	0	-1	0	0	-1	0
11b.	Same, newly laid	<1	-1	0	0	-1	-1	-1	-1	-1
12a.	Surface dressing, single, max 6-9 mm	1-20	-1	0	0	-2	-1	0	-2	0
12b.	Same, newly laid	<1	-2	0	0	-2	-1	-1	-2	-1
13a.	Surface dressing, double, max 16-20mm	1-20	-1	0	0	-1	0	-1	-1	0
13b.	Same, newly laid	<1	0	-1	-1	0	-1	-2	0	-1
14a.	Surface dressing, double, max 10-12mm	1-20	-1	0	0	-1	-1	-1	-1	-1
14b.	Same, newly laid	<1	-1	-1	-1	-1	-1	-2	-1	-1
15a.	Asphalt concrete, porous, HABD*, 14-16mm	<1	-3	-2	-2	-3	-3	-3	-3	-3
15b.	Same, 1-2 years	1-2	-2	-1	-1	-2	-2	-2	-2	-2
15c.	Same, 3-7 years	3-7	-1	0	0	-2	-1	-1	-2	-1
16a.	Asphalt concrete, porous, HABD*, 10-12 mm	<1	-4	-3	-3	-5	-5	-5	-6	-5
16b.	Same, 1-2 years	1-2	-2	-1	-1	-3	-3	-2	-4	-3
16c.	Same, 3-7 years	3-7	-1	0	0	-2	-1	-1	-3	-2
17a.	Asph. concr., porous, Skanska*, 14-16mm	0	-3	-2	-2	-3	-3	-3	-3	-3
17b.	Same, 1-3 years	1-3	-3	-3	-2	-4	-4	-4	-4	-4
17c.	Same, 4-5 years	4-5	-3	-2	-2	-4	-4	-3	-4	-4
17d.	Same, 6-7 years	6-7	-2	-1	-1	-3	-3	-2	-3	-3
18a.	Asph. concr., porous, Skanska**, 11+16 mm	<1	-6	-5	-4	-7	-7	-7	-8	-7
18b.	Same, 1-2 years	1-2	-5	-4	-3	-6	-6	-6	-7	-6
18c.	Same, 3-4 years	3-4	-3	-2	-2	-4	-3	-3	-4	-3
18d.	Same, 5-6 years	5-6	-1	0	0	-2	-1	-1	-2	-1
19a.	Asph. concr., porous, DK type**, 8+16mm	<1	-7	-7	-6	-7	-7	-6	-7	-6
19b.	Same, 1 years	1	-6	-6	-5	-6	-6	-5	-6	-5
19c.	Same, 2-4 years	2-4	-5	-5	-4	-5	-5	-4	-5	-4
19d	Same, 5-6 years	5-6	-3	-2	-2	-3	-2	-2	-2	-1
20a.	Asph. concr., porous, DK type**, 8+16mm	<1	-7	-7	-6	-7	-7	-6	-7	-6
20b.	Same, 1 years	1	-4	-4	-3	-5	-5	-4	-5	-4
20c.	Same, 2-4 years	2-4	-2	-2	-1	-3	-3	-2	-2	-2
20d	Same, 5-6 years	5-6	-1	-1	0	0	0	0	0	0

Table continued from the previous page

21.	Cement concrete, dense smooth, 20-80 mm	0-40	+1	+1	+1	+1	+2	+2	+1	+2
22.	Cement concrete, dense smooth, 12-18 mm	0-40	0	+1	+1	+1	+2	+2	+1	+2
23a.	Cement concrete, EACC, max 22 mm	2-10	0	+1	+1	+1	+1	+1	+1	+1
23b.	Same, newly laid	<2	-1	-1	0	-1	-1	-1	-1	-1
24a.	Cement concrete, EACC, max 11-16mm	2-10	0	0	0	0	0	0	0	0
24b.	Same, newly laid	<2	-1	-1	-1	-1	-1	-1	-1	-1
25a.	Cement concrete, EACC, max 7-9 mm	2-10	-2	-1	0	-2	-1	0	-2	-1
25b.	Same, newly laid	<2	-3	-2	-2	-3	-2	-2	-3	-2
26.	Cement concrete, diamond ground (unworn)	0-5	-3	-2	-2	-3	-2	-2	-2	-1
27.	Cobblestones, very old-fashioned type	0-90	+6	+5	+4	+6	+6	+5	+6	+6
28.	Paving setts, traditional blocks, 10x10 cm	0-90	+3	+3	+2	+4	+4	+3	+4	+4
29.	Paving setts, improved blocks (DK type)	0-90	+1	+1	+1	+2	+2	+2	+2	+2
30.	Interlocking blocks, normal type	0-10	+2	+2	+2	+3	+3	+3	+3	+3
31.	Interlocking blocks, best type	0-10	-1	0	0	-1	0	0	-1	0
Reference surface according to ISO 10844 (used for vehicle noise tests, etc) corresponds approx. to No. 3 above										

Some features may be worth commenting:

- If a reference to the HARMONOISE virtual reference[33] is made (see sub-chapter 6.1), 1.6 dB shall be added to all correction factors; i.e. negative values will be 1.6 dB less negative.

- The range between the best and the worst cases is 14 dB (+6/-8) at the highest speeds and 13 dB at the lowest speeds, for traffic where the heavy vehicles can be neglected.

- The range between the best and the worst cases is 13 dB (+6/-7) at the highest speeds and 10 dB at the lowest speeds, for traffic where the heavy vehicles dominate.

- If one excludes paving setts (since they are not common on roads with intensive traffic) and porous asphalt concrete (since they are expensive), the range between the best and the worst cases is 6 dB (+2/-4) for light vehicle traffic and 4 dB (+2/-2) for traffic where the heavy vehicles dominate.

A corresponding presentation of the most important surfaces with focus on future application in Sweden follows in Table 7.2 below [Sandberg, 2007b]. The table was produced in order to highlight the most promising road surfaces for future use in a new Swedish road surfacing policy which takes into account noise properties. Therefore, the table considers not only noise reduction (both new and as a lifetime average), but also the costs and lifetime of the surfaces.

Note that the asphalt rubber surfaces are just recently tested in Sweden. The thin surfacings with 6 mm max chipping size and the surface dressing bound with epoxy have never been tested in Sweden. Mostly, thin surfacings in Sweden have had maximum 11 mm chippings. The surface dressing would have high durability despite its small chippings due to the very strong binder. But in Sweden it is "politically incorrect" to use epoxy.

The expected lifetime in the table refers to a heavy trafficked highway or street and with a level road without sharp curves. This would be rather typical of a serious traffic noise exposed

[33] The reference is then an average of dense asphalt concrete and stone mastic asphalt, both with max 11 mm aggregate, see [Sandberg, 2006].

case. Cost level refers to the initial laying cost, whereas the total lifecycle cost also must consider the lifetime.

Table 7.2 The author's estimation of the noise reduction of the most promising existing road surfaces in Swedish conditions (for an area covering the part of Sweden including cities such as Göteborg - Stockholm - Sundsvall). The table is intended to illustrate the compromise between noise reduction, lifetime and cost.

Surface	Projected lifetime	Noise reduction when new	Average noise reduction over a lifecycle	Cost level	Notes
SMA 0/16	8 years	Ref	Ref	Ref	Most common Swedish surface
SMA 0/11	6 years	1 dB	1 dB	Same as ref	
SMA 0/8	4 years	2 dB	2 dB	Same as ref	
DAC 0/11	5 years	1.5 dB	1.5 dB	Same as ref	
DAC 0/8	3 years	2.5 dB	2.5 dB	Same as ref	For urban use
Thin surfacings 0/6	4 years	4 dB	3 dB	Low	For urban use
Surface dressing 4/6 Epoxy binder	5 years	5 dB	4 dB	High	For urban use
Asphalt rubber 0/11 dense	8 years	2 dB	2 dB	Medium	
Asphalt rubber 0/11 porous (20 %)	6 years	6 dB	4 dB	High	
Porous asphalt 16mm 25 %, single layer	5 years	5 dB	3 dB	High	
Porous asphalt 11mm 25 %, single layer	4 years	6 dB	4 dB	High	
Porous asphalt 8mm 25 %, single layer	3 years	7 dB	5 dB	High	For urban use
Porous asphalt 11mm 25 %, double layer	4 years	7 dB	5 dB	Very high	
Porous asphalt 8mm 25 %, double layer	3 years	8 dB	6 dB	Very high	For urban use

It may be concluded that substantial noise reductions are indeed possible, but it will require much higher costs than today. It may well mean 4 times as high annual costs for the most advanced cases compared to the reference. These costs shall be compared to the economic evaluation of the noise reductions.

The author thinks that the table shows that thin surfacings hold a high benefit/cost potential.

7.3 Revival of porous asphalt in Sweden

Since 2003, a double-layer porous asphalt, as well as a single-layer porous asphalt have been tested within the SILVIA project on motorway E18 west of Stockholm, having a posted speed of 110 km/h and carrying a moderate traffic. The contractor was Skanska AB. The maximum aggregate size in the top of the double-layer asphalt was 11 mm, while the single-layer surface had a 16 mm maximum aggregate size. This experiment has been quite successful and shown that even in the Swedish climate with a high proportion of studded winter tyres it is possible to get a 5 dB or more of noise reduction over several years. Especially, the double-layer porous surface was efficient during the first years, and Skanska was awarded the 2006 price for environmentally friendly road by the Swedish Road Administration, as well as the "Great Building Price" for 2007 from a private organization, although the justifications contain substantial exaggerations. After four years of operation, it is no longer the price-awarded double-layer surface which is the most effective one, but the single-layer surface has kept its noise-reducing capacity rather constant while the double-layer surface has deteriorated from the initial 6-7 dB of noise reduction to about 1 dB after four years of operation, compared to the conventional SMA 0/16.

Following the rather successful trial mentioned above, there has been a revival in the use of porous asphalt surface in Sweden. For example, this was followed up in 2005 with a similar double-layer porous asphalt surface (max 11 mm aggregate in the top layer) being laid on a 1300 m long section of motorway E4 through the Stockholm suburb of Botkyrka. This section carries a very intensive traffic (for Swedish conditions) at a posted speed of 90 km/h and was repaved in 2005 under unfavourable (cold) conditions with this low-noise surface because of frequent complaints by the residents and noise levels exceeding the standards. Already the cold repaving conditions (around 10 ^{o}C and only night-time work allowed) should have ruined this project, since a double-layer surface should be laid under warmer conditions in order not to get poor adhesion between the two layers, according to [Luminari, 2006].

After more than two years of operation, at the end of 2007, this section still worked well; albeit with increasing noise levels. Initial noise reductions relative to the conventional SMA 0/16 were 6 dB the first year and were down at 3 dB after two years. After more than two years of operation most of the surface was still looking dry in rainy weather which suggests that it could not be totally clogged; see Fig. 7.1. Although most of the surface appears to be in good condition, in one lane in one of the directions, over a short distance, the top layer has separated spotwise from the lower layer. Otherwise, some ravelling is visible but not serious. The author believes that the separation between the two layers is an effect of the laying process being made in too cold weather. The lanes being in the worst condition were repaved in the summer of 2008, after three years of operation. Then, only the top layer was exchanged, after first milling away the old top layer and using a cleaning machine from the Netherlands to clean the bottom layer before the new top layer was applied, and using a minimum of intermediate binder. The author believes that had the original paving operations been made in warm rather than in cold weather, the lifetime of the surface under the prevailing conditions would probably be 4-5 years. A normal SMA 0/16 would have a lifetime of 4-6 years there. The contractor (Skanska) promised a lifetime of at least 6 years with 6 dB of noise reduction maintained (including a new top layer), but this author considered this promise as totally unrealistic. The promise was broken already after two years, as the noise reduction was halved after two years. Nevertheless, the project must still be considered a success according to this author; especially since the original paving was made under the worst climate conditions, which should never had been accepted.

Fig. 7.1 Double-layer porous asphalt on motorway E4 southwest of Stockholm when driving in rainy weather at the surface age of two years. Note the essentially dry porous asphalt surface close to the camera compared to the wet SMA surface beginning approx. 70 m ahead.

7.4 Testing asphalt rubber in Sweden

The Swedish Road Administration (SRA) has been interested in the Arizona application of asphalt rubber friction courses for some time[34]. After some study visits to Phoenix, it was decided to lay some test surfaces in the late summer of 2007. The following surfaces were laid, of which the first one is a conventional SMA surface:

AR 0: Reference surface for comparison purposes - SMA 0/16.
Rural highway, posted speed 90 km/h

AR 1: Asphalt rubber - gap-graded, essentially an SMA 0/16 with 20 % of the binder replaced with rubber granules, approx. 10 % binder content. Voids content is approx. 3 %.
Rural highway, posted speed 90 km/h

AR 2: Asphalt rubber, essentially an SMA 0/16 with 20 % of the binder replaced with rubber granules, approx. 10 % binder content (same as the above). Voids content is approx. 3 %.
Motorway, posted speed 110 km/h

AR 3: Asphalt rubber, essentially an SMA 0/11 with 20 % of the binder replaced with rubber granules, approx. 10 % binder content (same as the above, except smaller aggregate). Voids 3 %.
Motorway, posted speed 110 km/h

AR 4: Asphalt rubber - open-graded, a semi-porous asphalt concrete with max 11 mm chippings, with 20 % of the binder replaced with rubber granules, approx. 10 % binder content. Voids content is approx. 15 %; thickness 40 mm. Local highway, posted speed 70 km/h

[34] Note that also Section 6.5 describes trials in Sweden with asphalt rubber surfaces, but within the large European project QCITY which is the subject of 6.5.

Fig. 7.2 shows a part of the AR 1 test section and surface close-up. The insert shows that the asphalt rubber surface has a binder (including rubber) which surrounds the aggregate "fatter" than in an ordinary SMA. It also shows typical binder-excessive patches in the left lane in the photo. In general, it appeared that the construction company at these first "shots" did not yet control the mixing or paving procedure since it was a rather consistent observation that the asphalt rubber test sections became relatively inhomogene; in particular this was obvious when studying the time histories of noise levels when driving over the AR 4 test section. Therefore, with more experience, there should be a significant potential for improvement.

Table 7.3 shows the preliminary test results, together with noise reductions predicted with a model used by the author, assuming that the surfaces are all having normal binder (no rubber).

Fig. 7.2 View of part of the asphalt rubber test section AR 1, with the insert showing a close-up view of the surface. Note the inhomogene binder-excessive patches in the left lane, while the right lane is fine. The patches in the median (nowadays a normal procedure in Sweden) are depressions milled to provide wake-up of drowsy drivers accidentally passing the median.

Table 7.3. The first results measured on the asphalt rubber surfaces listed in the text when they were approximately one month old; plus predicted noise reductions (see text). Cells with significant reductions are coloured in green. GG = Gap-graded (dense, voids 3 %), OG = Open-graded (voids 15 %), AR = asphalt rubber

Surface Number and type	Predicted noise reduction cars / trucks	For tyres representing cars		For tyres representing trucks	
		Measured noise reduction at 50 km/h	Measured noise reduction at 80 km/h	Measured noise reduction at 50 km/h	Measured noise reduction at 80 km/h
AR 0 SMA0/16	Ref.	Ref.	Ref.	Ref.	Ref.
AR 1 AR16GG	0 / 0 dB	-0.1 dB	-0.2 dB	0.4 dB	0.3 dB
AR 2 AR16GG	0 / 0 dB	0.8 dB	0.9 dB	-0.3 dB	-0.4 dB
AR 3 AR11GG	1.3 / 0.0 dB	1.8 dB	2.1 dB	0.1 dB	-0.3 dB
AR 4 AR11OG	2.2 / 0.9 dB	3.7 dB	4.6 dB	2.5 dB	2.7 dB

The values in the table are measured noise reductions compared to the reference surface, which was an SMA 0/16 of equal age (i.e. new). The measurements were made with the CPX method, performed by the Technical University of Gdansk in Poland, using four tyres:

- CPXA: The old CPX tyre A according to the draft version of ISO 11819-2 from 2000
- CPXD: The old CPX tyre D according to the draft version of ISO 11819-2 from 2000
- ASTM: The SRTT tyre, standardized by ASTM, version 2006
- GRMT: Goodrich MudTerrain

The ASTM SRTT has been selected as a new ISO reference tyre. The MT tyre was previously a candidate for the new second ISO reference tyre, but was in 2008 replaced with the Avon AV4 tyre. The CPXA and ASTM tyres are intended to represent the road surface influence measured when using a fleet of car tyres, while the CPXD and GRMT tyres are intended to represent the road surface influence measured when using a fleet of truck tyres.

When comparing the "Predicted" noise reductions with the actually measured ones, it appears that the actually measured ones are somewhat higher. This may be explained either by a systematic error in the author's model, or by an effect caused by the rubber. The author believes that the model is not so inaccurate that it could explain all the differences and, therefore, believes that the deviations are indeed caused by the rubber inclusion. In that case, the experiment suggests that the advantage of adding rubber (and modifying the mix accordingly) is as follows:

For the gap-graded mixes: Advantage of rubber 0.5 dB
For the open-graded mix: Advantage of rubber 2.0 dB

Note that these are preliminary findings. At the moment there is no explanation as to why the rubber may be more effective for the open-graded mix than for the gap-graded one.

Had the reference surface been an SMA of an age one year or older, then the noise reductions would have been about 1 dB higher.

Measurements in 2008, at a surface age of one year, indicated that the noise reductions remained the same as when the AR surfaces were new. This is good news for the open-graded variant as this would normally (without rubber) become a little clogged after one year.

It seems that the best AR surface gave a noise reduction of 4-5 dB. When this is achieved with only 15 % voids and with an exceptional high percent of binder (10 %), such a surface can be predicted to have a significantly longer lifetime and durability than a conventional porous asphalt; which would need to have something like 22 % voids to achieve the same noise reduction for a thickness of 40 mm. The reason would be the much higher protection against oxidation by air in the asphalt rubber surface than in the conventional porous asphalt. But only field experiments can tell if this is a right judgement.

New AR surfaces were laid in Sweden in 2008. Results are still subject of evaluations. Nevertheless, it can be mentioned that one of the surfaces, laid on a 70 km/h high-volume 2x2 lane road in Norrköping (Road E22), failed after only a couple of weeks. The surface was similar to the one in Table 7.3 named AR11OG. Laying was made in the late autumn in rather chilly and humid weather. The problem was poor adhesion to the basecourse, resulting in parts of the wearing course separating from the basecourse. The AR surface was then milled away. Before that, however, VTI and TUG measured noise reduction with the CPX method to be approx. 5 dB in comparison to the older surface there which was an SMA 0/16. The AR surface, having a voids content of approx. 17 % was partly humid from a previous rain during the measurement, and thus partly filled with water, which should have underestimated the noise reduction referring to dry conditions. It is believed that the reason for the separation of the two layers was that laying was made in unfavourable weather conditions and maybe without cleaning the basecourse sufficiently before laying. Another reason could be that surfaces with fairly high rubber contents indeed have a tendency to separate more easily from the basecourse; see further Section 6.5.

See further Chapter 6.5 about the QCITY asphalt rubber surface.

7.5 Discussion related to the asphalt rubber tests in Sweden

It seems likely that the asphalt rubber surfaces are extra interesting to apply in urban low-speed situations. Therefore, in this section an attempt is made to estimate the effect of the rubber on the noise emission, based on the following:

- The measurements in the QCITY project in 2006, reported in 6.5, on an asphalt rubber surface with 15 % air voids and approx. 8 % rubber content (by weight)
- The measurements in the QCITY project in 2008, reported in 6.5, on an asphalt rubber surface with 8-10 % air voids and approx. 6 % rubber content (by weight)
- The measurements in the Swedish project reported in 7.4, on asphalt rubber surfaces AR 4 with 15 % air voids and approx. 2 % rubber content, and AR 3 with 3 % voids
- Same as above, but on conventional surfaces without rubber

In Tables 7.4-7.5, noise reductions for the various surfaces are compared, after having been normalized to similar conditions by this author. The noise reductions are measured with the CPX method and the ASTM S.R.T.T. tyre (in the VTI-related work) or with a somewhat similar method (QCITY work, see 6.5). Reference conditions used are as follows:

- Test speed: 50 km/h
- Aggregate size, maximum: 11 mm (reference surface in new condition)

It is also assumed that air voids under 7 % are considered as similar to 0 %, from an acoustical point of view, and in such cases the layer thickness is irrelevant. The noise measurements were not made in a similar manner and with the same test tyres, but the effect of this is neglected here.

Table 7.4. Comparison of the different tested asphalt rubber surfaces and their references. Due to the differences in nominal max aggregate size, a correction is estimated to normalize all to 11 mm

Surface type	Rubber content	Air voids	Thick-ness	Binder content	Max. aggr. size	Noise reduction (raw)	Noise correc. for difference from 11 mm aggreg. size
QCITY surface	8 %	15 %	40? mm	8 %	8 mm	5.8 dB	-0,8 *
VV/VTI surface AR4	2 %	15 %	40 mm	10 %	11 mm	3.7 dB	-1.3 **
QCITY Viacogrip 8	6 %	9 %	40 mm	8? %	8 mm	2.5 dB	-0,8 *
VV/VTI surface AR3	2 %	3 %	40 mm	10 %	11 mm	1.8 dB	-1.3 **
SMA 0/11 (QCITY)	0 %	<5 % ?	40 mm	5 % ?	11 mm	0 dB (ref)	0 (ref)
SMA 0/16 (VV/VTI)	0 %	<5 % ?	40 mm	5 % ?	16 mm	0 dB (ref)	-

* Correction from 8 to 11 mm max aggregate size, according to Table 6.1 (3x0.25 dB)

** Correction from using 16 mm max aggregate size as a ref for noise measurements, to using 11 mm, according to Table 6.1 (5x0.25 dB)

Table 7.5. The same as in the previous table but after normalization to 11 mm max aggregate size (only the first of the surfaces had a different actual aggregate size - 8 mm). The resulting noise reduction is listed in the rightmost column.

Surface type	Rubber content	Air voids	Thick-ness	Binder content	Max. aggre-gate size (normalized)	Noise reduction (normalized)
QCITY surface	8 %	15 %	40? mm	8 %	11 mm	5.0 dB
VV/VTI surface AR4	2 %	15 %	40 mm	10 %	11 mm	2.4 dB
QCITY Viacogrip 8	6 %	9 %	40 mm	8? %	11 mm	1.7 dB
VV/VTI surface AR3	2 %	3 %	40 mm	10 %	11 mm	0.5 dB
SMA 0/11 (QCITY)	0 %	<5 % ?	40 mm	5 % ?	11 mm	0 dB (ref)

The results suggest the following:

- The effect of adding 2 % of rubber (by total weight of the mix) in a gap-graded (dense) mix is approximately a 0.5 dB noise reduction. This is consistent with both the SILENCE tests mentioned in 6.4, as well as the tests conducted in the Hong Kong EcoPark; see 11.4 in [Sandberg, 2008-1].
- The effect of increasing voids from 3 to approx. 15 % is approximately a 2 dB extra noise reduction, given a 2 % rubber content. This is about 1 dB more than expected from Fig. 9 in the Evaluation Report [Sandberg, 2008-1].
- The effect of increasing the rubber content from 2 to 8 % (by total weight of the mix) is approximately a 2.5 dB noise reduction, given 15 % air voids content.
- The effect of increasing the rubber content from 2 to 6 % (by total weight of the mix) is approximately a 1.5-2.0 dB noise reduction, given approx. 9 % air voids content.

The author draws the following conclusions from this:

- Adding just 2 % rubber into a dense mix has only a very marginal effect. It is believed that the effect is caused by the elasticity of the mix (softer noise impact mechanism).
- Adding 2 % rubber into a mix having approx 15 % voids gives approximately 1 dB more noise reduction than when it is made in a dense mix. The author suggests that this may be an effect of the somewhat enclosed air voids which provide "mini cushions" in the mix, making it even softer than the rubber alone (see later under USA in this report). The effect of the voids may therefore not only be sound absorption and air drainage, but also this cushion effect which contributes to the elasticity.
- Increasing the rubber content to four times that of the previously mentioned mix (from 2 to 8 %), gives an extra 2.5 dB of noise reduction. This is believed to be mostly due to the increased elasticity of the mix and the following softer surface. The main effect is the softer surface, although sound absorption and air drainage play a role too.
- As mentioned in 6.5, the author thinks that the sound spectra in Fig. 6.32 not really support conclusions downgrading the air drainage effect, and emphasizing the reduction of the vibration impact mechanism. It may be that the vibration impact mechanism is efficient at higher frequencies than we have believed earlier. Therefore, the mechanisms here should be studied more.
- To obtain a reasonable noise reduction by a gap-graded asphalt rubber surface, in relation to a normal SMA surface with similar aggregate, the rubber content must be increased to substantially above 2 %; (say) by up to at least 6 %, which may give 1.5-2.0 dB of noise reduction due to the rubber effect.
- For long-term acoustic durability the rubber addition my have the advantage over porosity that its effect probably is more durable than porosity, since the latter is subject to clogging. Furthermore, the asphalt rubber mix should provide a better protection against oxidation of the binder and thus give less ravelling. The relatively low air voids combined with the elasticity should also provide a surface less subject to ravelling caused by high lateral forces in the tyre/road interface, such as in curves and at intersections.
- It is speculated that the main deterioration effect of the asphalt rubber open-graded surface may be that the air voids are decreased with time due to compaction, reducing the "cushion effect"; also that the originally relatively small sound absorption and air drainage effect disappears due to clogging combined with the compaction.

- For this reason the author thinks that asphalt rubber surfaces of the open-graded type are potentially more interesting for use as low-noise road surfaces on urban low-speed roads than conventional porous asphalt surfaces
- Furthermore, on urban low-speed roads, a compromise between the open-graded and the gap-graded types but having rubber content of at least 6 % may be useful. This will not depend on porosity for noise reduction, but on low stiffness, and will thus not be subject of clogging.
- It may be worth trying rubber contents up to about 10 % (by weight of the total mix) in which case one might predict a 3-4 dB noise reduction. Such high rubber contents, however, put extremely high demands on the binder in order to give durable surfaces.
- Already, it is rather well documented that a rubber content of 2 % is perfectly durable (see the sections about USA later in this report), but as pointed out above, higher contents should be tried too.

7.6 Steel slag as a favourable aggregate substitute

A test section on a highway in the middle of Sweden near a steel industry was paved with a surface resembling an SMA 0/11, except that the main aggregate was replaced with steel slag of the same gradation. Steel slag has a somewhat “microporous” surface, although the pores are not interconnected, and it was speculated that perhaps this might have had an influence on noise properties.

The results indicated a noise level 1 dB lower than on the adjacent SMA surface, measured in 2008 with the CPX method and the ASTM SRTT tyre (representing light vehicle tyre/road noise), but no difference measured with the Avon AV4 tyre (representing heavy vehicle tyre/road noise). One dB of noise reduction (for light vehicles) is not very useful, but the results are interesting since the steel slag has the potential of providing a stronger bond with the binder than normal stone aggregates and is also very durable. Therefore, this author has suggested that steel slag shall be tested in the top layer of a double-layer porous asphalt to hopefully provide a more durable surface where ravelling may otherwise be a problem. The positive effect would also be present in single-layer porous asphalt. The availability and price of such material will depend on the existence of and distance to steel-producing industries. The potential of emission of particulate matter including heavy metals must be considered, however. If this material can give a 1 dB higher noise reduction and better durability than conventional aggregate, it will mean a considerable advantage.

7.7 Developer of residential area paying for the use of LNRS

In 2008 a double-layer porous asphalt surface of the type described in 7.3 was laid on a section of a highway (E18) bordering a new residential area called Järvastaden being built in a northern suburb of Stockholm. The interesting thing with this project is that the quite substantial extra cost of this surface was paid by the company that develops the residential area, despite the highway is publicly owned, and that this was made in order to improve the acoustical environment for the residents [Jarvastaden, 2009]. It means that the company considers it worth the costs to do so; i.e. that the residents assign such a high value to their acoustical environment that it is worth the extra cost of the surface. It seems to be considered a good selling argument that the traffic on the adjacent highway is quiet.

8. EXPERIENCE IN DENMARK

8.1 Early work

In the early 1990's, two Danish experiments utilizing (single-layer) porous asphalt were carried out, with the objective of developing and testing drainage asphalt on a national highway near Viskinge (posted speed of 80 km/h) and an urban road Østerbrogade in Copenhagen (posted speed of 50 km/h).

The highway experiment was followed-up for 7 years and provided information on the gradual loss of noise reduction of porous asphalt in a highway condition. Very briefly, the results indicated an initial noise reduction of PAC 0/8 and PAC 0/12 of around 4 dB compared to a DAC 0/12, reduced to 3 dB at the age of 5 years and to 1 dB at the age of 7 years. The PAC 0/8 performed the best. The urban Østerbrogade experiment went on for only three years and showed that an initial 3 dB noise reduction compared to a DAC 0/12 was reduced to 1 dB already after one year and to zero after two and three years [Bendtsen, 1998].

8.2 The Øster Søgade project – a premium low-speed road study

In the summer of 1999, a road section of 400 m length was repaved with drainage asphalt on Øster Søgade in Copenhagen. Traffic volume there is 7000 AADT and the posted speed limit is 50 km/h. Three different types of double-layer drainage asphalt were used along with one reference section which was ordinary dense asphalt; see Tables 8.1-8.2. The objective was to investigate the acoustic performance of double-layer drainage asphalt in urban areas and to investigate the general performance of this type of surface with regard to safety, winter maintenance, durability, etc. Since this project is possibly the best ever conducted for low-noise road surfaces on a low-speed road, it is covered quite extensively in this report.

Table 8.1. Overview of the four test sections on Øster Søgade in Copenhagen. From [Bendtsen & Larsen, 2002].

Test section	Description	Total thickness	Top layer		Bottom layer	
			Thickness	Chippings	Thickness	Chippings
DA8-70	Porous asphalt	70 mm	25 mm	5/8 mm	45 mm	11/16 mm
DA5-55	Porous asphalt	55 mm	20 mm	2/5 mm	35 mm	11/16 mm
DA5-90	Porous asphalt	90 mm	25 mm	2/5 mm	65 mm	16/22 mm
AC8dense (ref.)	Dense asphalt	30 mm	30 mm	0/8 mm	-	-

Table 8.2. Technical data for the pavements at the time of the construction in 1999. From [Bendtsen & Larsen, 2002].

Pavement	AC8 dense	DA5 Top layer	DA8 Top layer	DA16 Bottom layer	DA22 Bottom layer
Type of bitumen	70/100	50/100-75 (SBS)	50/100-75 (SBS)	50/100-75 (SBS)	50/100-75 (SBS)
Bitumen in %	5.8	6.3	5.4	3.9	3.5
Max. chippings in mm	8	5.6	8	16	22
Filler in %	8	6	6	5	5.5
Material < 2mm in %	44	10	8	7	7

An overview of one of the sections is shown in Fig. 8.1. When using porous pavements on urban streets with kerbstones it is necessary to install drainage pipes on both sides of the road. Therefore, the surfaces were lined with an advanced drainage system with drainage pipes running at the kerb on both sides of the street. The cost of pipes and installation was estimated to be EUR 54 per m [Bendtsen et al., 2002]. Fig. 8.2 shows one of the drains at the kerbside.

Fig. 8.1. Overview of one of the test sections on Øster Søgade in Copenhagen, in 2000. Note that there is one lane per direction (plus a bicycle path with dense surface on the right), but also parking bays on the right side.

Fig. 8.2. The drainage system running along each kerb (2000). There are pipes running underneath the drains. Note that there are also slots on the vertical side of the red “brickstone”, to make possible water from inside the porous layers to run away laterally into the pipe.

The frequency spectra of the surfaces, as measured after one year of operation, are shown in Fig. 8.3. It can be seen that noise reduction of 3-5 dB occur over the frequency range 400-8000 Hz, with maximum effect around the peak in the traffic noise spectrum [Bendtsen & Larsen, 2002]. Measurements were made with the SPB method and the spectra are valid for a mix of light and heavy vehicles on the site.

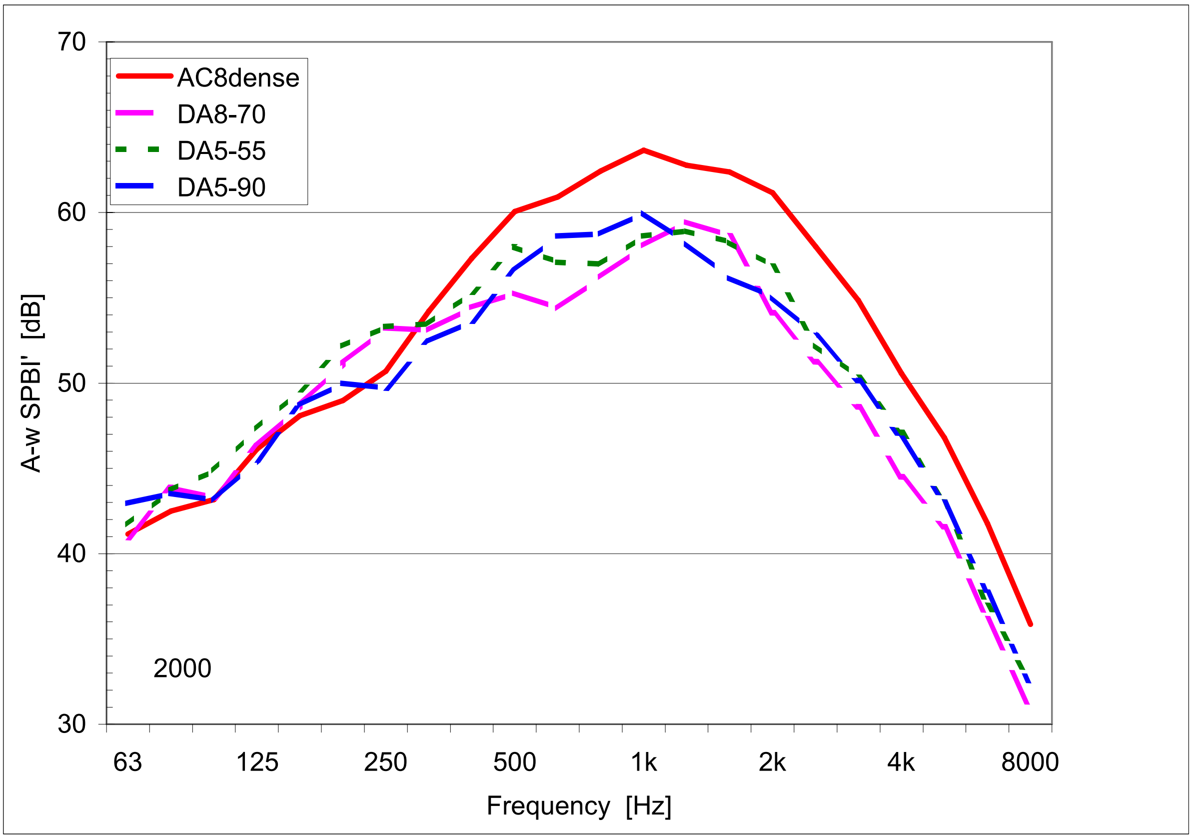


Fig. 8.3. Frequency spectra of traffic noise on the four test sections on Øster Søgade in Copenhagen. From [Bendtsen & Larsen, 2002].

Based on data and experience of these test sections the economic benefits of porous asphalt and alternative, conventional noise reduction means was studied [Larsen & Bendtsen, 2002]. The economic comparison of the various alternatives came out very favourably for the porous asphalt alternative, see Fig. 8.4. The results of a questionnaire to the people living close to the street about the annoyance they experienced from traffic noise were also studied [Larsen & Bendtsen, 2002]. The perceived noise annoyance reported as a before-after comparison is shown in Fig. 8.5. It shows that the annoyance was dramatically reduced by the porous asphalt, but also to some extent for the new dense asphalt that replaced the old and worn one.

High pressure cleaning was made twice a year, but the results were inconsistent and only occasionally showed a positive effect on noise reduction. It was noted that significant clogging occurred and progressed by time, and that dirt was pulled in from an adjacent dense asphalt pavement and increased clogging near this dense pavement. Ravelling occurred too, already visible after one year, but it was not so serious that it required repair until the end of the lifetime.

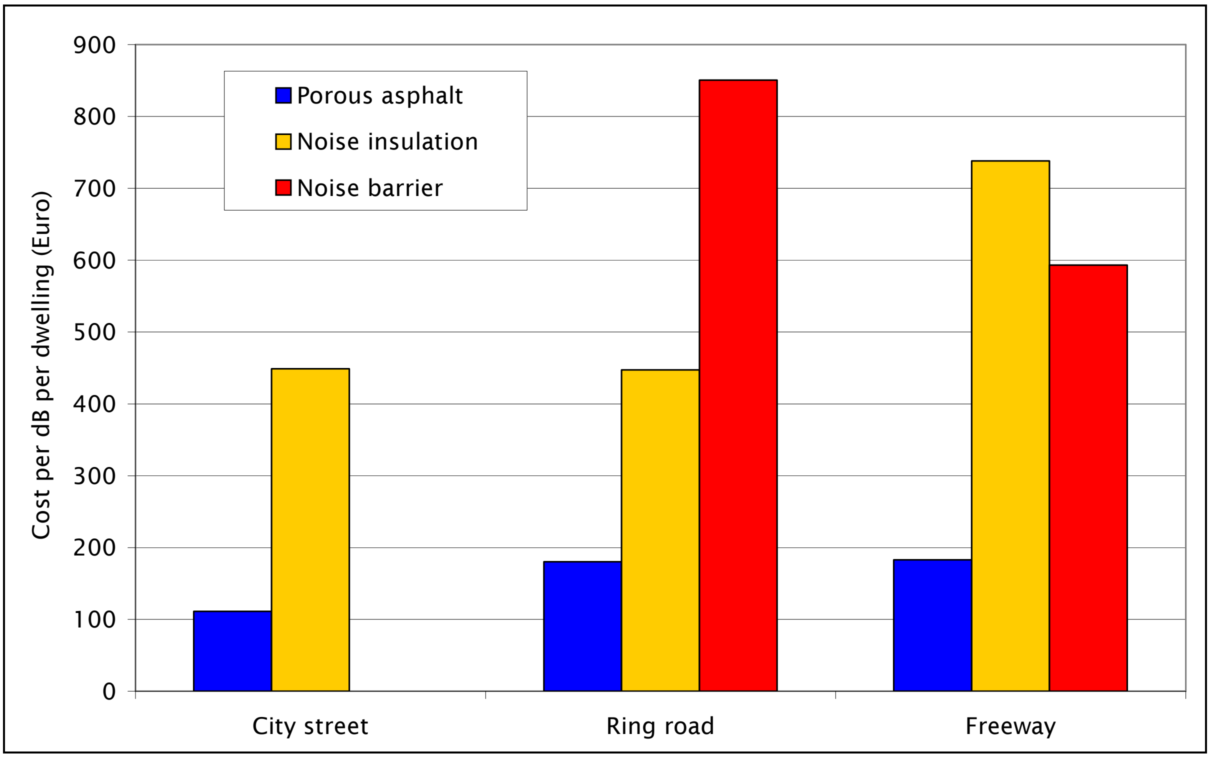


Fig. 8.4. Cost per dB noise reduction per dwelling for the three measures repaving with porous asphalt, improved noise insulation of windows and building of noise barriers for each of the three cases [Larsen & Bendtsen, 2002].

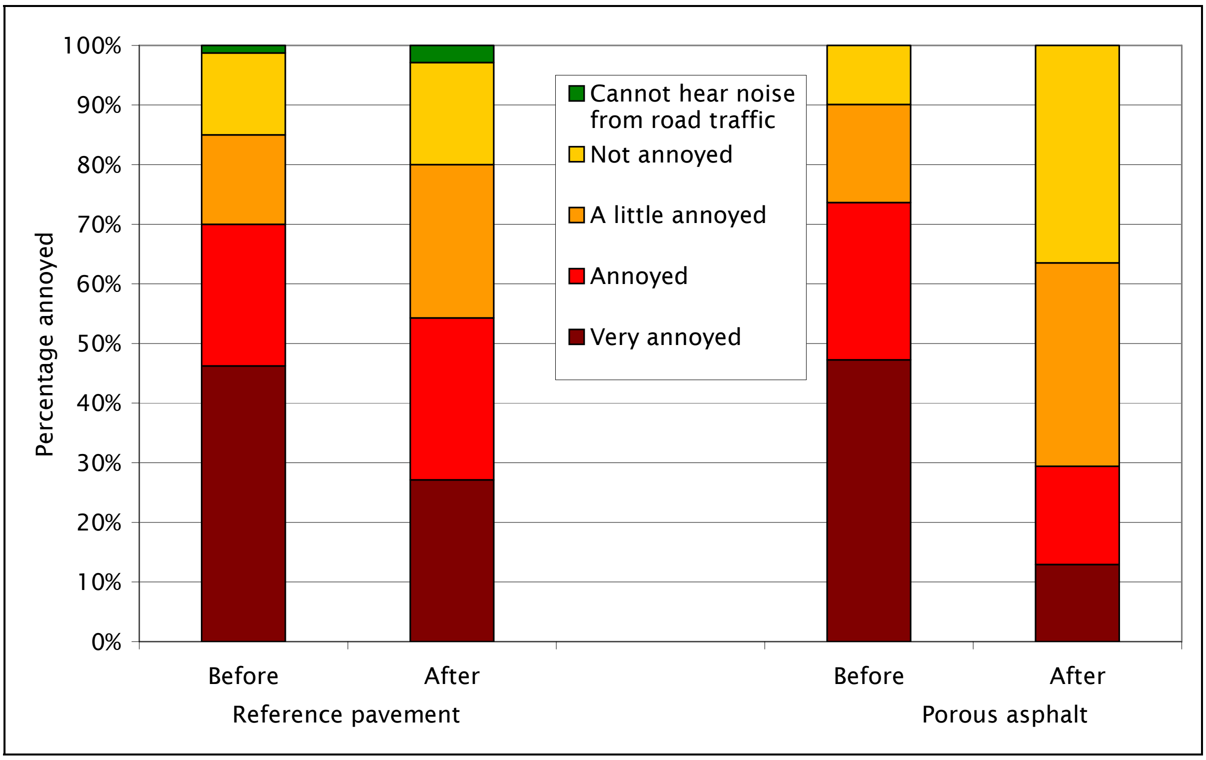


Fig. 8.5. Annoyance of noise from road traffic, indoors with open windows, before and after Øster Søgade was paved with noise-reducing porous asphalt [Larsen & Bendtsen, 2002].

The noise reduction, compared to the reference DAC 0/11, was measured with the SPB method for light and heavy vehicles each year 1999-2007. The results for the period 1999-2006 are shown in Fig. 8.6 (results for 2007 are not available to the author) [Kragh, 2007]. The three porous surfaces are shown in the same order as in Table 8.1. Note that there is an error in the figure: the surface II has a 5 mm aggregate size, not 8 mm. Note also that the surface which was the best initially turned out the be the worst over the full time period, while the reverse was true for the surface which was the "worst" initially. Thus, the most favourable of the three surfaces was the one with 8 mm aggregate size and 70 mm thickness.

The lifetime was eight years since in 2007 the surfaces needed replacement. The municipality of Copenhagen then decided to have the top layer milled away and replaced by new porous asphalt with 8 mm maximum aggregate. This type had proven to be the most durable; acoustically and structurally. Noise measurements were carried out in 2007 as part of the SILENCE project, both before and after replacing the top layer. The measurements showed that at two of the test sections most of the initial noise reduction was regained while this was not the case at the one test section that was the thinnest (a total of 55 mm while the others were 70 mm and 90 mm thick, respectively) [Kragh & Bendtsen, 2008].

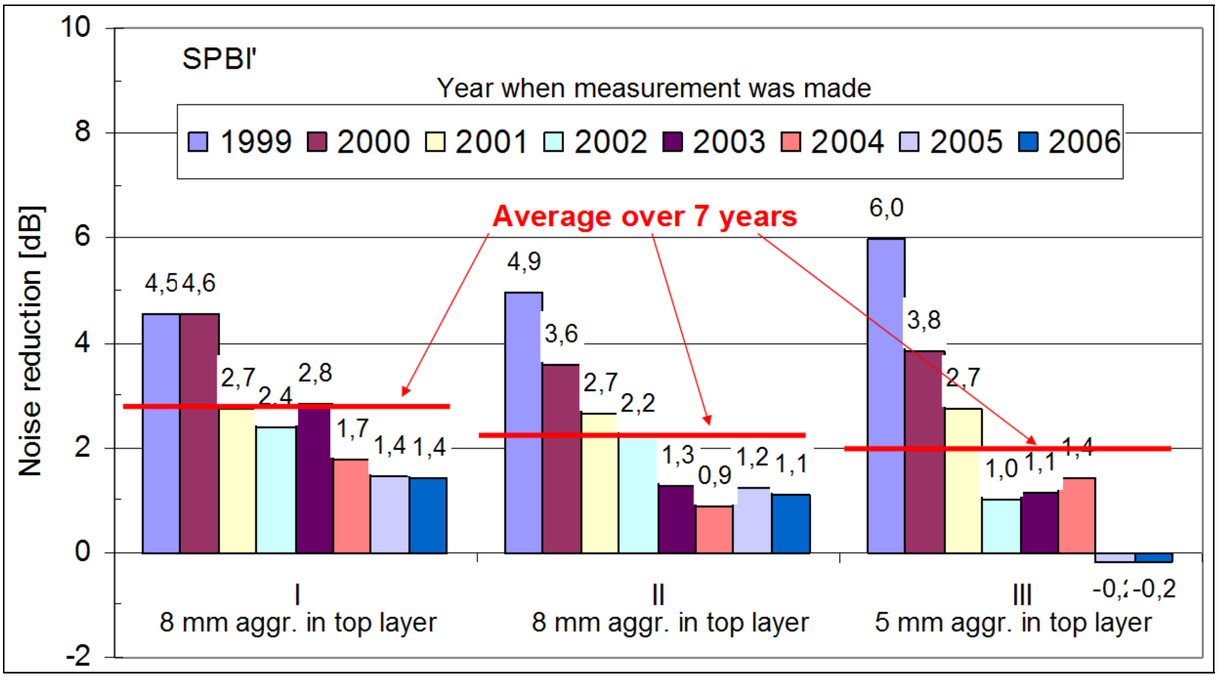


Fig. 8.6. Results of annual noise measurements on Øster Søgade, expressed as the SPB Index for a typical mix of light and heavy vehicles. Diagram from [Kragh, 2007], somewhat processed by the author. See the text for further information.

Finally, Figs. 8.7-8.8 show photos from a study visit in April 2007, just before the surfaces were repaved. Severe ravelling occurred mainly at some exits from other small streets and in the wheel paths at some places, and minor ravelling occurred practically everywhere.

Fig. 8.7. The condition of the porous surface in April 2007. Severe ravelling in the wheel paths can be seen (this is, however, at one of the worst places). Compare with Fig. 8.1.

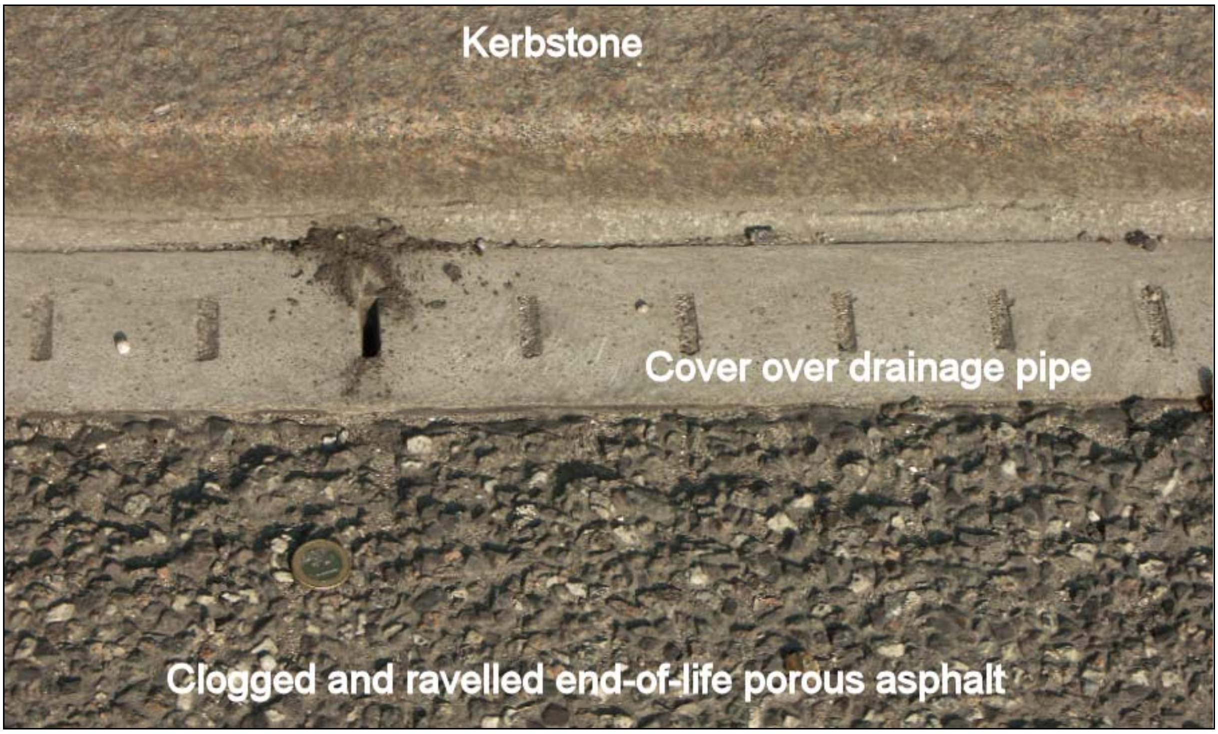


Fig. 8.8. The condition of the cover over the drainage pipes along the kerbstones in April 2007. Note that the drainage slots have become clogged and that one was cleaned for illustration purposes. The slots should be somewhat wider in order to avoid clogging.

8.3 Later tests with porous asphalt on Danish low-speed roads

After the quite successful trial on Øster Søgade, some further experiments have been conducted on low-speed streets in Copenhagen. One of them was laid in August 2005 and is shown in Fig. 8.9 two years later. This major street had a traffic volume of 60 000 AADT, a relatively high proportion of heavy vehicles, and a posted speed of 60 km/h. Traffic is accelerating from a light-controlled intersection (seen at the rear in the picture) until another intersection. The surface is a double-layer porous asphalt with max. 8 mm aggregate in the top layer and 16 mm in the bottom layer, with a total thickness of 70 mm; i.e. the same as the most successful variant at Øster Søgade. Noise reduction was measured at 4.0 dB the first year (in 2005) compared to DAC 0/8. Some clogging was observed after one year and in 2007, at an age of two years, severe clogging was visible near the kerb and probably extending over most of the area. Note that on this street there was no drainage pipe system laid along the kerbstones; something which may have caused faster clogging than "necessary". No serious ravelling had occurred yet in April 2007, but moderate ravelling was observed at the exit from a petrol station which was located at the lower left corner of the photo. It was the author's concluding observation that this section was equally successful as the Øster Søgade experiment but at a much more demanding location; with exception of a faster progressing clogging due to the lack of an effective kerbside drainage system.

Fig. 8.9. Two years old double-layer porous asphalt on Lyngbyvej in Copenhagen. Initial noise reduction was 4 dB compared to a DAC 0/8. Ravelling was visible so far only from a petrol station exit at the lower left.

The second new section was a 500 m long porous surface laid in 2005 on Vigerslevvej. The street had 60 km/h as posted speed limit and had one lane in each direction. Traffic was lower than on Lyngbyvej but contained a relatively large proportion of heavies. This location had essentially the same surface as Lyngbyvej, but the bottom layer was 70 rather than 50 mm thick, with a total of 90 mm thickness. Voids content was initially 22 %. The binder was polymer modified. See Fig. 8.10.

Noise reduction was measured at 4.2 dB (L_{Aeq}) the first year compared to DAC 0/8. Clogging was observed at the visit in April 2007, at an age of two years. It was "total" near the kerb and extending moderately over part of the lane, but in the middle of the lane and near the median the surface was still relatively "unclogged"; see Fig. 8.11 (right). Along the kerbstones one could see a lot of dirt accumulated even on top of the surface; at some places perhaps approx. 10 mm of dirt layer; see the left part of Fig. 8.11. Due to a lot of dirt everywhere on this street, it seemed as if the street had been sanded in wintertime to reduce low friction due to ice, or if gravel-carrying trucks had spilled a lot; something which of course ruins a surface like this[35].

Note that, as on Lyngbyvej, on this street there was no drainage pipe system laid along the kerbstones. Neiter Lyngybej, nor Vigerslevvej, are regularily cleaned in order to reduce the clogging.

Fig. 8.10. Part of the 500 m long porous surface laid in 2005 on Vigerslevvej, where the double-layer porous asphalt was laid also over a couple of light-controlled intersections.

[35] Unconfirned speculation by the author.

No significant ravelling was observed in April 2007 except a minor part at an exit from a parking bay. There were a couple of light-controlled intersections, at which no ravelling was observed. Even at the beginning of the section, which was at a light-controlled intersection with frequent stop-and-go traffic, and somewhat turning, no serious ravelling had occurred. The porous 500 m long section contained several bus stops paved with a dense, non-flexible material for increased strength against braking and accelerating buses, near which no damage was observed.

The author's conclusion is that this surface section was a success from the ravelling point of view (so far), as well as regarding initial noise reduction, but a total failure due to clogging near the kerbstones as a result of a combination of the lack of an effective drainage system and an exceptional amount of dirt on the carriageway. The latter must be due to some serious mistake in the maintenance. It seems to be a waste of money to lay an expensive porous surface on such a location when it is quickly contaminated with sand and gravel.

The author also concludes that the lack of an effective drainage system along the kerb has caused unnecessary quick clogging of both the Lyngbyvej and Vigerslevvej porous sections.

Fig. 8.11. Along most of the 500 m long porous surface laid in 2005 on Vigerslevvej, there was exceptional dirt accumulated near the kerbstones (left part). Yet, some metres away from the kerb, the surface had still a relatively unclogged porous structure (right part). Photos shot in 2007 when the surface was two years old.

Finally, before leaving the section related to porous asphalt, a note on the structural strength is justified. Some people tend to fear that the structural strength and durability of porous asphalt is insufficient to carry vehicle loads. The Danish experience, however, is that the structural strength of porous asphalt is approximately 80 % of the structural strength of a conventional dense asphalt. Therefore, no extra supporting layer to provide extra structural strength is needed when replacing dense with porous asphalt.

8.4 Danish participation in the Dutch IPG program

8.4.1 Topics studied

The Danish Road Institute (DRI) had an agreement with the IPG project to assist the IPG with certain tasks. This included for example:

- To study the ravelling mechanisms
- To make CT scanning of porous asphalt bore cores and study the clogging of these
- To study the efficiency of thin layers by experiments in Denmark
- To review the knowledge and experience of thin layers in France and internationally
- To organize a study trip to Japan
- To organize a number of invitational and international seminars/workshops

Some of these activities are briefly summarized in the following.

8.4.2 CT scanning analysis of ravelling

The overall aim of the ravelling study at DRI was to gain knowledge on the ravelling process from a micro level investigation of the geometrics of the bituminous mastic and to relate this to the performance of porous pavements on the roads. This section is adapted from [Nielsen, 2007-1].

Bore cores from 16 road sections in the Netherlands with single-layer porous pavements of different age, performance and traffic were investigated. Microstructure parameters were defined and measured using CT scanning and visual assessment of thin sections. The two overall hypotheses were that these parameters depend on age and performance of the pavement and the vertical position (top and bottom zone) in the pavement.

It was found that the main overall deterioration mechanism was related to the adhesion and cohesion between mastic and aggregate. The adhesion condition expresses the state of the adhesion between mastic and aggregates and is important for the climatic induced durability and aging of the porous pavement. The cohesion condition expresses the cohesion of the mastic and is important for the traffic induced durability and the fixing of the aggregate in the mix (ravelling resistance). The distinction between adhesion and cohesion is not always clear beyond the general terms of adhesion being “close to the aggregate” and cohesion “far from the aggregate”. Cohesion is not in general correlated to the age of the pavement and cohesion is in general better rated than adhesion.

It was observed that clogging correlates with adhesion. This is probably due to a deterioration mechanism visually observed on thin sections of the core; the bituminous mastic deteriorates in pavements with poor adhesion and leaves clogging in the voids. In these pavements mastic also has a rough surface, indicating deterioration of the mastic itself.

The content of small-size voids and mastic is significantly larger in the top zone for poor performing roads. See Fig. 8.12. This indicates that voids have been formed due to deterioration of the mastic which is considered an important deterioration mechanism. This is also in accordance with the observed decrease in adhesion and increase in clogging with age for poor performing roads. Further, the hypotheses that the condition of the mastic gets poorer with age and that the condition close to the surface is poorer for poor performing pavements was confirmed.

Mr Nielsen recommended focusing not only on the age of the roads, but in particular on the ageing of the mastic (binder), including fundamental studies of the influence of oxygen, water, frost, UV and chemical agents (de-icing agents and windshield washer agents). The finding that it is necessary improving the adhesion between aggregate and mastic in order to avoid ravelling was found to be valid.

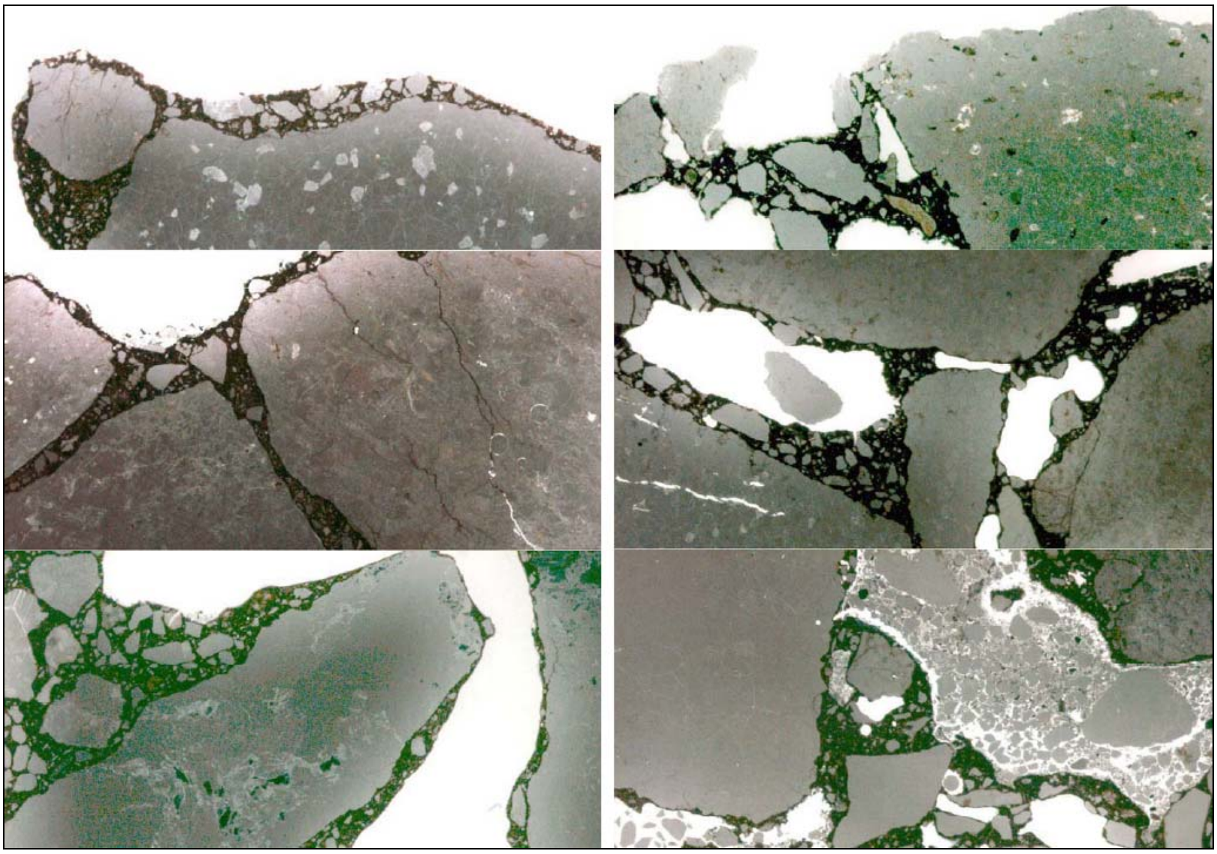


Fig. 8.12. Thin section images from road cores with good (left) and poor adhesion (right). From [Nielsen, 2007-1].
Left part: Good adhesion. From top to bottom: Section A - Emergency lane, surface and top zone. Section B - Emergency lane, bottom zone.
Right part: Poor adhesion. From top to bottom: Section E - Fast lane, surface and top zone. Section F - Slow lane, bottom zone.

8.4.3 Clogging, cleaning and CT scanning

DRI first made a review of the international literature on clogging; excluding the Dutch literature since this was already dealt with in the IPG project. The following section is adapted from the report by [Bendtsen & Raaberg, 2007].

In the international literature, many references have been found which mention clogging. Most of the references only use the word and do not go into a special description of what the materials that causes the clogging consist of or where in the porous pavement the clogging is located. There are some different opinions on where in the pavement layer the clogging begins. The general opinion in most of the literature is that clogging occurs in the top of the pavement and this is highlighted by Danish analyses of thin and plane sections of drill cores where the clogging material can be seen in the pores.

The clogging is due to solid particles and liquid originating from both traffic and the surroundings of the road. Some literature describes it as dust, sand, rubber (from tyres), oil etc. The materials that formed the clogging contain heavy metals and the water used for cleaning the pavements must be treated in a way that protects the environment from further contamination. It was found that also surfaces paved with porous asphalt on which traffic is negligible clog due to dust and sand.

To avoid the clogging, all papers agree that for higher speed of the vehicles and more traffic passing over the pavement the less clogging occurs. Also, concerning the design of the porous pavement, most of the papers agree that the higher air voids content the less clogging. This will of course have an influence on the lifetime of the pavement in an undesirable way because the bitumen is hardened due to oxidation, but the use of polymer modified bitumen can be seen as a factor to avoid this.

Danish experiences indicates, at least for urban roads with lower speeds that the maximum aggregate size must not be too small in order to avoid or reduce the tendencies for clogging. Less tendencies of clogging was in the longterm experiment on Øster Søgade seen at two-layer porous pavements with 8 mm maximum size in relation to pavements with 5 mm aggregate.

By designing the porous asphalt in the right manner, consequently, it would be possible to get a pavement which clogs less when observing these advices:

- The air void content shall be between 25 and 30 %, which has been stated in several of the papers.
- The maximum size of aggregate used must not be too small (around maybe 8 mm).
- The shape of the aggregates should be taken into account. Cubic aggregates are favourable.

According to the results of the literature study the recommendations for reducing the tendencies of clogging of porous pavements are:

- To secure a high air voids content.
- To use not too small maximum aggregate size.
- To use cubic aggregate.
- To secure that the geometric characteristics of the road are appropriate so that rain water can run to the roadside.
- To perform cleaning on urban roads with porous pavements.
- Perform cleaning after a period with rain as this might soften up the clogging material.

So far the international review. Another report addressed analysis and assessment made by DRI of bore cores from the Dutch motorway A28 at Staphorst by CT scanning before and after cleaning [Nielsen, 2007-2]. Cleaning was performed on the A28 Dutch motorway by three different contractors, using their own special equipment:

- Dura Vermeer, Steamcleaner (10 cores before and 10 cores after cleaning)
- BAM Wegen Regio West (5 cores before cleaning, no cores after cleaning)
- Heijmans Infrastructuur (7 cores before cleaning, 8 after cleaning).

From all CT scanned profiles of voids and mastic contents it was noted that, in general, cleaning had very limited or almost no effect on clogging [Nielsen, 2007-2].

Finally, within this topic, DRI made CT scanning analyses of bore cores to investigate the clogging effect. The following text is adapted from [Nielsen, 2007-3]. This study reported results of analyses and assessments of bore cores from motorways A28 and A17 in the Netherlands and an urban street (Øster Søgade) in Copenhagen. The objective was to study the clogging of pavements of different ages in both the Netherlands and Denmark to be able to assess the effect of modifying cleaning processes to improve the acoustic lifetime of the pavements.

The visual assessment showed clogging 10–30 mm from the surface and no clogging close to the surface at a three years old porous pavement on A28. Clogging was evenly distributed over the cross profile of the pavement. On an eleven years old pavement on A17, the visual assessment shows clogging 0-20 mm from the surface in the emergency lane and a little deeper in the centre between wheel tracks, but less clogging in the edge of the slow lane. CT scanning cross-profiles identified clogging as being clearly concentrated in the centre between wheel tracks and close to the surface in the emergency lane.

For the Danish Øster Søgade, the visual assessment confirmed that the surface layers, and specifically the finer mixes, had got clogged. This is in accordance with clogging identified in the CT scanning cross-profiles. Comparing the Dutch pavements with the Danish urban pavements it seems that clogging concentrates more near the surface in the urban pavement; this effect being most pronounced for the fine 2/5 mm mix.

CT scanning and thin- and plane section analyses are unique in the identification and analysis of clogging of porous pavements. CT scanning gives an overview of the microstructure and the extent and distribution of clogging. Thin sections provide very detailed visual information about the microstructural condition and clogging formations.

Both techniques seem to be able to identify the best and worst situation but are more uncertain in the middle range. It is therefore suggested to classify clogging into three classes: No clogging; uncertain classification; serious clogging. Overall, both techniques are dependent on the coring of pavements and the information obtained is limited to these cores. Therefore the two techniques should be supplemented by more general surveys and regarded as specific and detailed information in selected spots.

Fig. 8.13 shows Mr Nielsen doing analysis at DRI of a thin section from a bore core. Fig. 8.14 shows a typical result of plotting the air voids as a function of the depth from the surface down into the porous pavement (as represented by a bore core in this case). Note the severe clogging between 5 and 20 mm from the top of the surface; i.e. in the top layer of the 70 mm thick double-layer porous asphalt. Fig. 8.15 shows an example of severe clogging in voids and cracks in the aggregate of an old porous asphalt surface.

Fig. 8.13. Analysis by CT scanning of a thin section cut through a sample bore core of clogged porous asphalt, at the Danish Road Institute, made by Mr Carsten Bredahl-Nielsen.

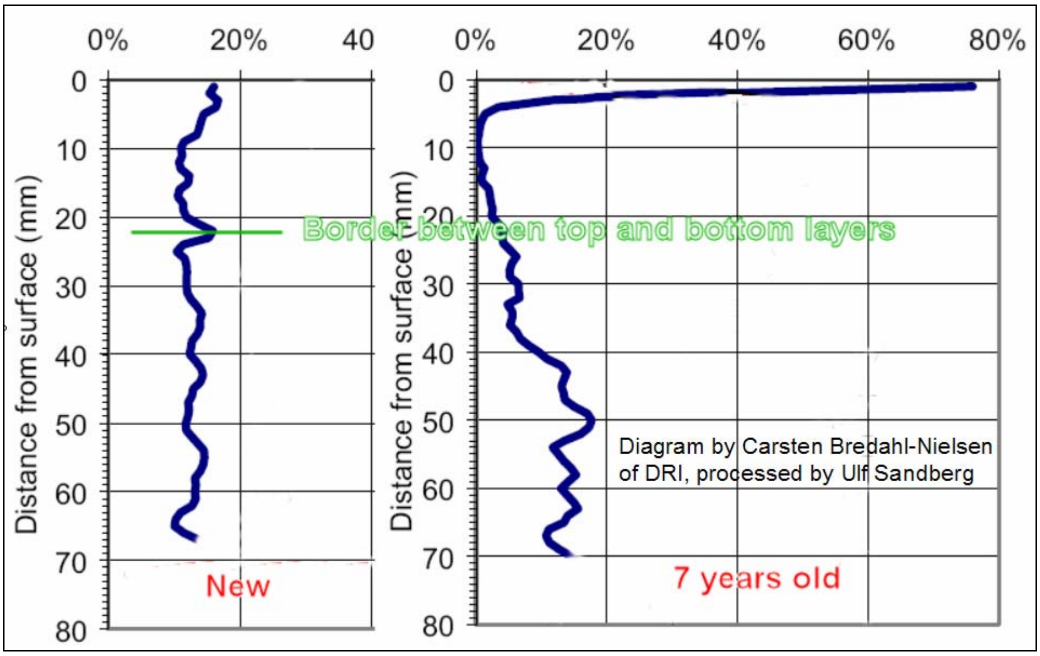


Fig. 8.14. Measured air voids content of 70 mm thick pavement sample of double-layer porous asphalt, as a function of distance from the top. Sample of new pavement (left) vs 7 years old one (right). Diagram adapted by the author from diagram obtained from Mr Nielsen.

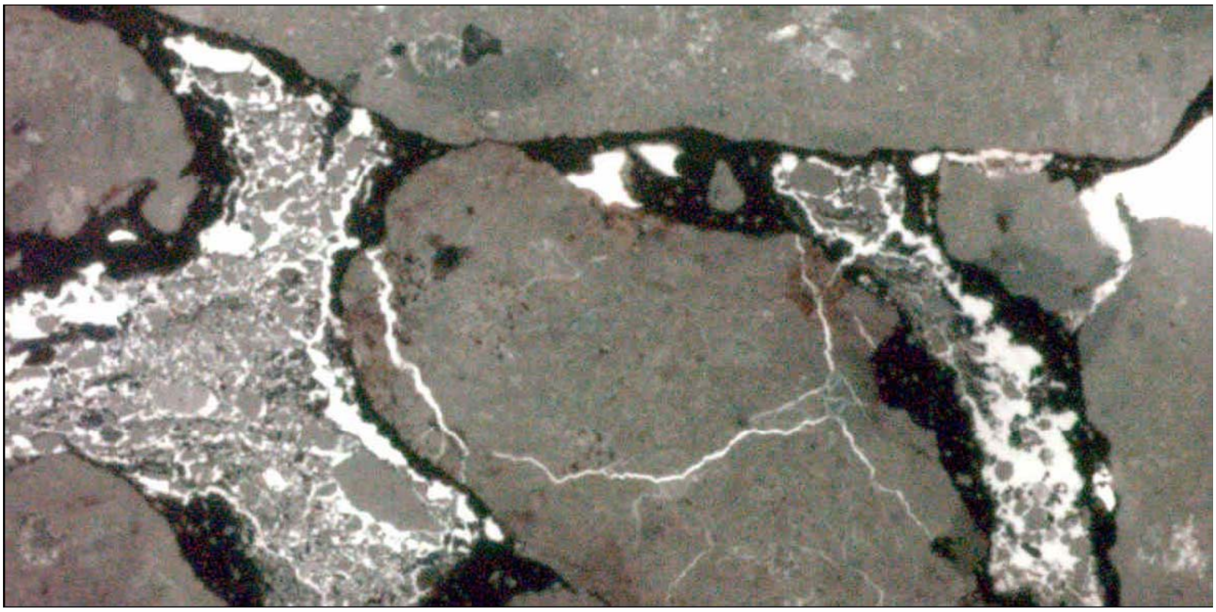


Fig. 8.15. Thin section image, at 5-10 mm from the surface, from road bore core of porous asphalt on the Dutch motorway A17, at km 20.895, centre of the slow lane. Clogging in voids and cracked aggregate are seen. Image size is 10 mm x 5 mm. From [Nielsen, 2007-3].

8.5 Thin layers

8.5.1 International review

DRI wrote a review of French experience of developing and using thin layers, since such surfaces tended first to appear in France. Even though this review was conducted by DRI, it is summarized under the sub-chapter about France.

As part of the first phase of the DRI-IPG thin layer research, a literature study on the existing international knowledge in the field of thin layers and noise reduction was conducted [Bendtsen et al, 2005]. The study included an inventory of existing suitable thin road sections for further research. In annexes the results from meetings held with American experts on asphalt rubber pavements in Arizona in March 2005 are presented. The conclusions of the literature review are copied below (with some language and minor non-technical adjustments by this author).

The literature review was carried out in order to find answers to a list of seven research questions. International literature was investigated. Generally, thin layers have only been used as noise-reducing pavements for a little more than five years and, therefore, the literature on this subject is limited, and the information retrieved normally covers measurements and evaluations when pavements are new or a few years old. Therefore, there is a need for further research in order to establish lifetime measurement series of the performance of noise-reducing thin layers. The report did not include French or Dutch material which were dealt with elsewhere.

In the following sections, the outcome of the literature study is presented in relation to the seven research questions listed by the DRI authors.

1- What are the different types of known thin layers and what is the noise reduction of those layers?

Noise-reducing thin layers have been constructed on the basis of different pavement concepts:

- Open graded asphalt concrete (AC-open).
- Stone Mastic Asphalt (SMA).
- A thin layer constructed as an UTLAC ("Ultra Thin Layer Asphalt Concrete") (*Danish designation TB k*). On the existing road surface, a thick layer of polymer modified bitumen emulsion is spread. On the top of this unbroken bitumen emulsion, a very open-graded mix is paved (like porous asphalt) with a (built-in) Marshall air void of approximately 14 %, or even more. The unbroken bitumen emulsion "boils up" in the air voids of the pavement leaving only the upper part of the structure open. This reduces the built-in air void of the pavement because the pores of the pavement are filled with bitumen.

The noise reduction depends on the reference pavement used. Relative to a dense asphalt concrete pavement with a maximum aggregate size of 11 mm (a typical Danish reference) noise reductions of 1 to 3 dB have been measured on urban roads (speed 50-60 km/h), as well as on highways with speeds around 110 km/h. If a dense asphalt concrete pavement with a maximum aggregate size of 16 mm were used as a reference, instead, noise reductions of 2 to 4 dB have been measured.

The thin layers have been designed and optimised for low noise emission by:

- the use of small maximum aggregate size (6 or 8 mm)
- creating a open surface texture
- creating a smooth surface texture

In USA, a pavement type with an open surface texture where part of the aggregate is replaced by rubber material has been developed. This also seems to have a noise-reducing potential.

2- What is known about long-term noise reduction?

Little is known so far about the long-term noise reduction. A time series of measurements in Denmark indicates that the noise reduction is unchanged after two years.

3- What is known about traffic safety (skid resistance and winter conditions)?

Generally, measurements show that thin noise-reducing layers have a good and rather high skid resistance. No special information about the performance of thin layers under winter conditions has been found.

4- What is known about splash and spray compared to dense and porous pavements?

Measurement results covering this field have not been found.

5- What is the structural lifetime of thin layers?

No results about the structural lifetime of noise reducing thin layers have been found.

6- Are there limitations or special concerns to be taken when applying thin layers in Denmark and the Netherlands?

No results have been found!

7- What is known about construction as well as maintenance costs of thin layers?

Some studies indicate that the construction cost of noise reducing thin layers is equivalent to the cost of "ordinary" pavements. No information has been found about maintenance cost.

This author's comment: Note that the literature review above was published in 2005. Information from later research may or may not confirm and supplement the findings.

8.5.2 Danish work on low-speed urban roads

A Danish project started in 2003 on development of thin noise reducing pavements on urban roads[36]. The goal was to develop and test thin layers as noise-reducing pavements under Nordic conditions. The project was a part of the European SILVIA project.

Thin open pavements are open only at the upper part of the pavement. The basic concept for noise reduction is to create a pavement structure, with as big cavities at the surface as possible in order to reduce the noise generated from the air pumping effect, and at the same time ensuring a smooth surface to reduce noise generated by the vibrations of the tyres. The different types included:

1. Open-graded asphalt concrete ("AC-open") with built-in Marshall air voids of 8-14 %.
2. Stone Mastics Asphalt (SMA) with built-in Marshall air voids of approx. 4-8 %.
3. A thin layer constructed as an UTLAC (Ultra Thin Layer Asphalt Concrete) (Danish designation TB k). See description in the previous sub-chapter.
4. Dense-graded asphalt concrete surfaces with 8 and 11 mm aggregate are included as reference pavements.

A comprehensive measurement program covering noise, structural behaviour, durability and traffic safety was conducted. Noise measurements were made with the Statistical Pass-By (SPB) Method.

In June 2003, six trial pavements were laid on Kongelundsvej in southern Copenhagen, near the international airport. This road with one lane per direction has a posted speed limit of 60 km/h and a traffic volume of 12 500 AADT of which 8.6 % are heavy vehicles. Fig. 8.16 shows this test section. The six pavements were:

- DAC 0/11 (in Danish AC11d), used as reference (there were two sections of this pavement)
- DAC 0/8 (in Danish-English AC8d), a conventional DAC but thin and with small aggregate
- DAC 0/6open (in Danish-English AC6o), a conventional DAC but with extra open texture
- SMA 0/6+ (in Danish-English SMA6+), a conventional SMA but with some oversize aggr.
- TSF 0/6, (in Danish TP6), a thin layer with max. 6 mm aggregate (see "UTLAC" above).

[36] This section is based on [Bendtsen et al, 2005] from which significant parts have been copied.

Fig. 8.16. Suburban road with 4 thin layer pavements and two DAC 0/11 references: Kongelundsvej near Copenhagen international airport (posted speed 60 km/h).

Similar pavements were laid at two other urban roads: Søren Frichs Vej in the city of Aarhus and Udbyhøjvej in the city of Randers; both had a posted speed limit of 50 km/h. Pavements were 17-25 mm thick, except the references which were thicker.

Fig. 8.17 shows the results of SPB noise measurements on all the three roads and made when the surfaces were new (Year 0) and two years later (Year 2). The first bar from the left, within each triple cluster, represents Kongelundsvej, the second (middle) bar represents Søren Frichs Vej and the third bar represents Udbyhøjvej. Similar data exist for dual-axle heavy vehicles, but these values are associated with higher uncertainties [Thomsen et al, 2006-1].

The results in Fig. 8.17 show that the initial noise reductions were 1.0-2.5 dB if compared to the new DAC 0/11 (AC11d) and approx. 1 dB higher if compared to a two year old DAC 0/11. After two years the noise levels have increased by approximately 1 dB but this is also the case for the reference surface. Therefore, if one compares surfaces of smilar age, the noise reductions are essentially unchanged after two years. The TP6 pavement appeared to be the best one.

Fig. 8.18 shows frequency spectra from the sections on Kongelundsvej for light vehicles at 60 km/h. It appears that the major noise reductions occur at high and medium frequencies; suggesting that both vibration-excitation and air pumping noise are reduced.

Note that in comparison to the Dutch thin layers at 50 km/h (see Chapter 9.3), the Danish noise reductions are approximately half as big as the Dutch. But, as argued in 9.3, the Dutch thin layers are probably much more advanced.

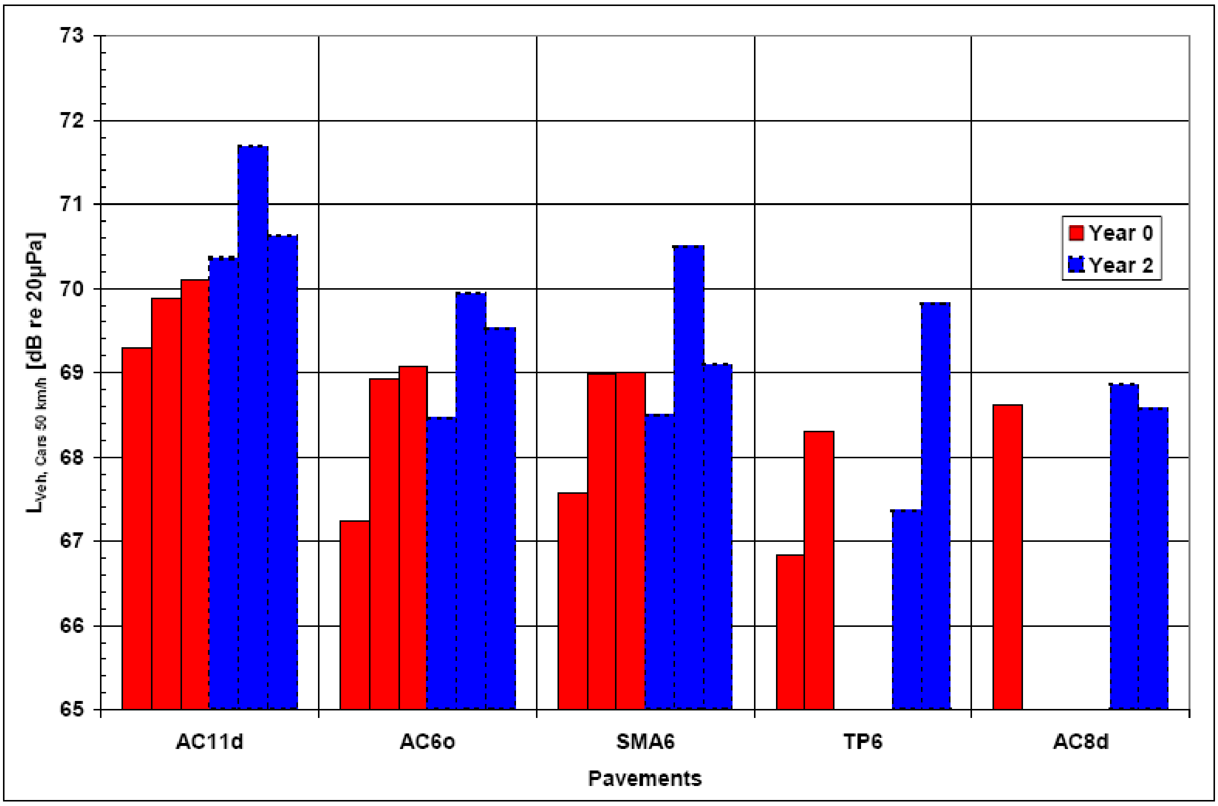


Fig. 8.17. Results of SPB noise measurements, for light vehicles normalized to 50 km/h, on all the three tested roads and made when the surfaces were new (Year 0 - red) and two years later (Year 2 - blue). See the main text for surface designations and identification. From [Thomsen et al, 2006-1].

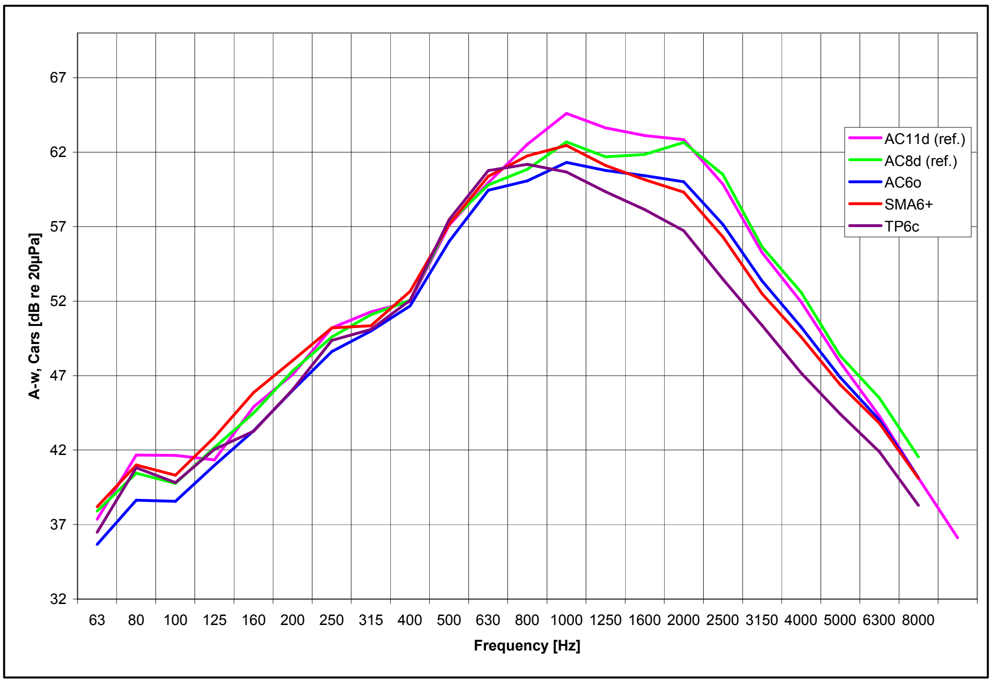


Fig. 8.18. Results of SPB frequency spectra measurements, for light vehicles normalized to 60 km/h, on all the test sections on Kongelundsvej and made when the surfaces were new. From [Thomsen et al, 2006-1].

Apart from the DRI work for the Dutch IPG project on thin layers, in the EU project SILENCE work has been carried out to optimize the noise reduction of different types of pavements for urban roads. The Danish Road Institute (DRI) participated in this work together with the Swedish National Road and Transport Research Institute (VTI) and BASt in Germany. Joint international development work has been carried out including laboratory experiments. The objective was to find pavements with promising noise reduction [Andersen et al, 2008].

DRI has in cooperation with the municipality of Copenhagen and the Colas road construction company in a full-scale experiment tested some SMA pavements and open-graded thin layer pavements optimized for noise reduction by using small aggregates of 4-6 mm and by constructing relatively high built-in air voids content [Andersen et al, 2008]. Eight different pavements were constructed in June 2007 on Kastrupvej in Copenhagen including seven thin layers and one dense reference. The posted speed there is 50 km/h and traffic volume is 7500 AADT, with 7 % heavy vehicles.

The technical properties of the tested thin layers are presented in Table 8.3. Note that a + in the pavement name indicates that there is an oversized aggregate too. The intention with adding a small proportion of oversize aggregate is to open-up the surface to reduce the air pumping, with a negligible negative effect on vibration excitation to the tyres. Fig. 8.19 shows the results of SPB measurements on cars. An initial noise reduction for passenger cars of 4.3 dB in relation to a DAC 0/11 reference pavement has been achieved. Fig. 8.20 shows the relation between the SPB levels for cars and the voids content, which suggests that porosity of these pavements has a significant effect on sound absorption and noise levels. Also CPX measurements were made but they are not shown here. However, they indicated that one some pavements there is a substantial variation in noise level along the test section, which means that homogeneity is not very good and the location of SPB measurements is critical.

Table 8.3. Technical data for the Kastrupvej pavements. From [Andersen et al, 2008].

Pavement type	Max. aggreg. mm	Binder %	Air voids % geo.
DAC 0/11 (ref.)	11	-	5.4
SMA 0/6	6	6.9	15.3
SMA 6+ 5/8	6 + 5/8	7.1	3.4
SMA 6+ 5/8 (1)	6 + 5/8	7.0	5.7
SMA 6+ 5/8 opt.	6 + 5/8	6.5	13.9
OGAC 0/6	6	-	-
SMA 0/4	4	7.0	8.8
SMA 4+ 5/8	4 + 5/8	6.7	10.2

The following conclusions were made [Andersen et al, 2008]: Statistical pass-by levels at 50 km/h for cars on seven optimized thin layer test sections showed:

- there was a range of variation (SPB) of 3 - 4 dB
- the most silent types are those with high air voids %
- there is a good relation between SPB and CPX measured results
- there is a possible problem with homogeneity
- there were disappointing noise results on SMA 0/4

It is planned to continue the measurements in the coming years in order to be able to analyse the long-term acoustical and structural performance of these test pavements.

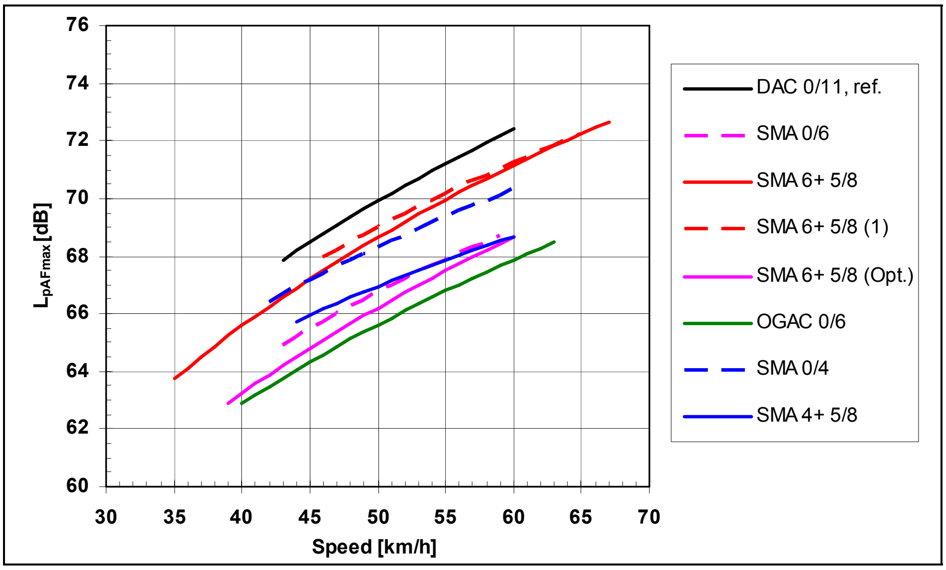


Fig. 8.19. The results of SPB measurements in 2007 for cars on the thin layers on Kastrupvej in Copenhagen. From [Andersen et al, 2008].

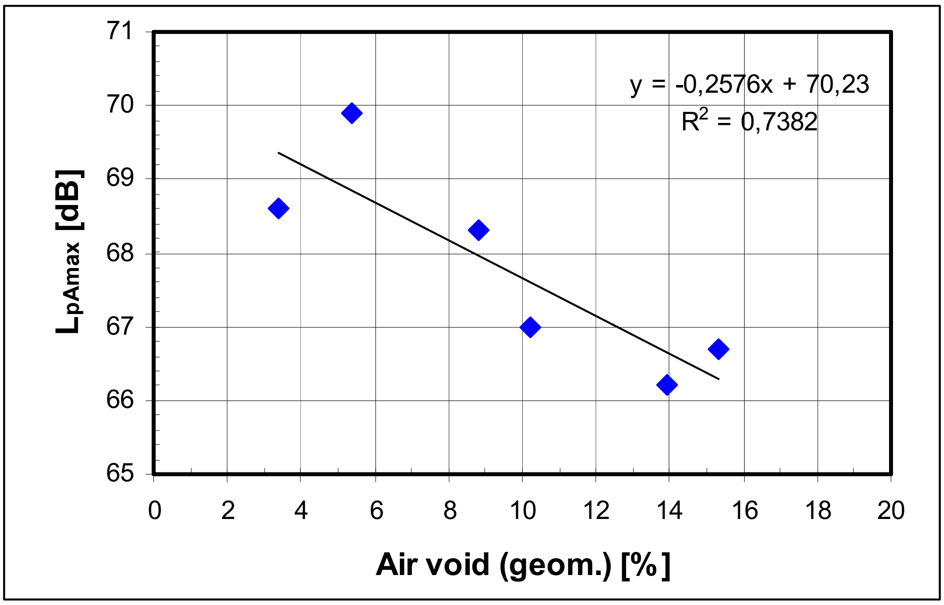


Fig. 8.20. The relation between the SPB levels for cars and voids content on the thin layers on Kastrupvej in Copenhagen. From [Andersen et al, 2008].

8.5.3 Danish work on high-speed roads

In 2004, the Danish Road Directorate started the first experiment with thin layers on a high-speed highway M10, near the town of Solrød[37]. Posted speed is 110 km/h, there are three lanes in each direction and traffic volume is 80 000 AADT. Five different types of thin layers and a reference pavement were laid on the tested highway in August 2004. A dense asphalt concrete with 11 mm maximum aggregate size was used as a reference. The major specifications are presented in Table 8.4. In the lanes with heavy traffic, a polymer-(highly)modified 50/100 bitumen was used and in the other lanes medium-modified SBS bitumen was used. The aggregate gradings of the pavements appear in Figure 8.21.

Table 8.4. Technical data for the Solrød M10 pavements. From [Thomsen et al, 2006-2]. Note that "tracks" should read "lanes".

Test section	Max. aggregate size [mm]	Bitumen	Thickness [mm]	Weight [kg/m^2]
AC11d (reference)	11	Tracks, heavy loaded 50/100-75 (SBS) Other tracks 50/70-53 (SBS)	33	80
SMA8 (SMA LN 8)	8	Tracks, heavy loaded 50/100-75 (SBS) Other tracks 50/70-53 (SBS)	29	60
AC8o (Microville)	8	Tracks, heavy loaded 50/100-75 (SBS) Other tracks 50/70-53 (SBS)	28	60
TP8c (Combifalt 8)	8	Tracks, heavy loaded 50/100-75 (SBS) Other tracks 50/70-53 (SBS)	22	45
SMA6+ (SMA 6+)	6 + 5/8	Tracks, heavy loaded 50/100-75 (SBS) Other tracks 50/70-53 (SBS)	26	60
SMA8+ (SMA LN 8+)	8 + 8/11	Tracks, heavy loaded 40/60 (SAS) Other tracks FLEX	33	60

The measured noise levels, or rather the noise reductions compared to the reference DAC 0/11 are presented in Fig. 8.22. Note that had one used DAC 0/16, as in the Dutch IPG program, the noise reductions would have been one dB higher. Yet they are about 50 % lower than the majority of measurements on Dutch thin layers have indicated.

[37] This section is based on [Bendtsen et al, 2005] from which significant parts have been copied.

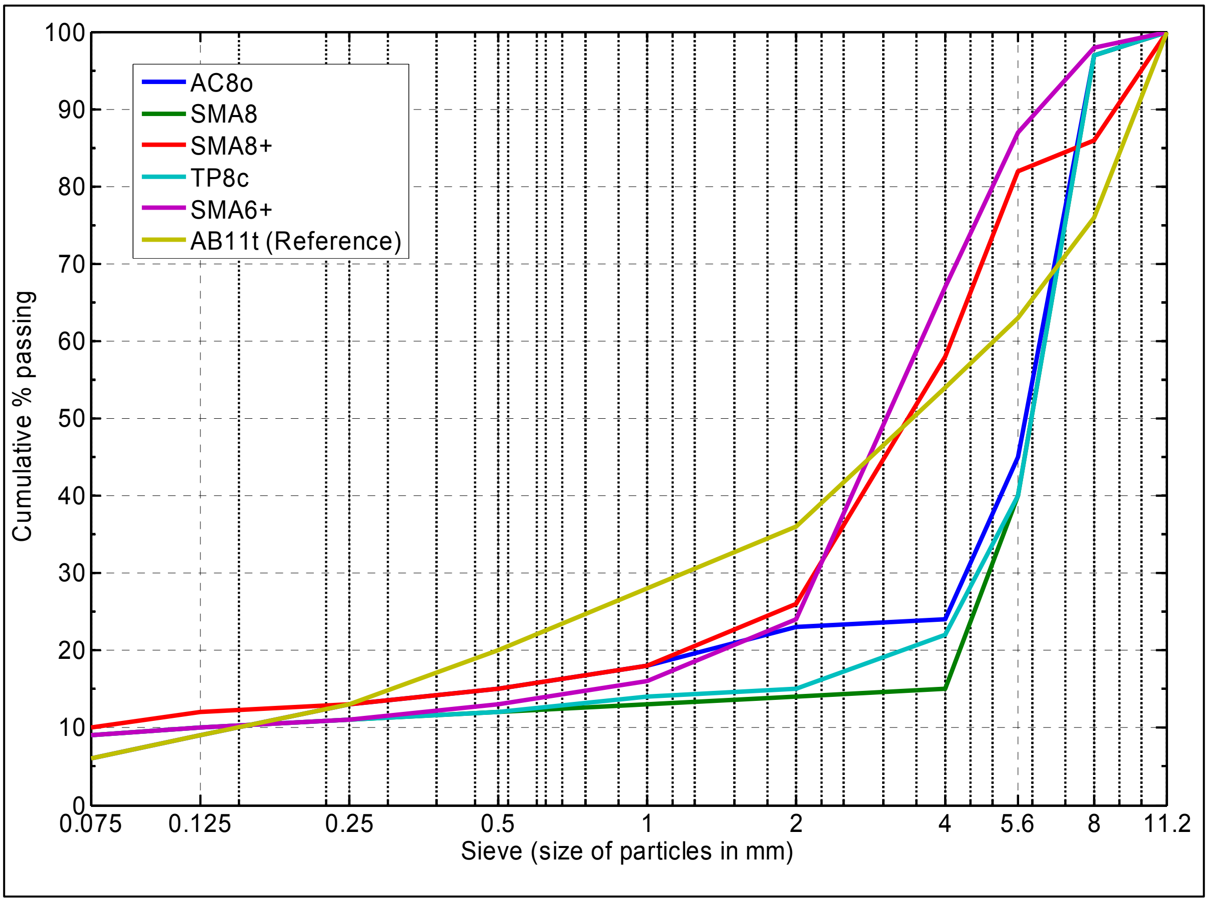


Fig. 8.21. Grading curves for the trial pavements in Solrød. From [Bendtsen, 2007].

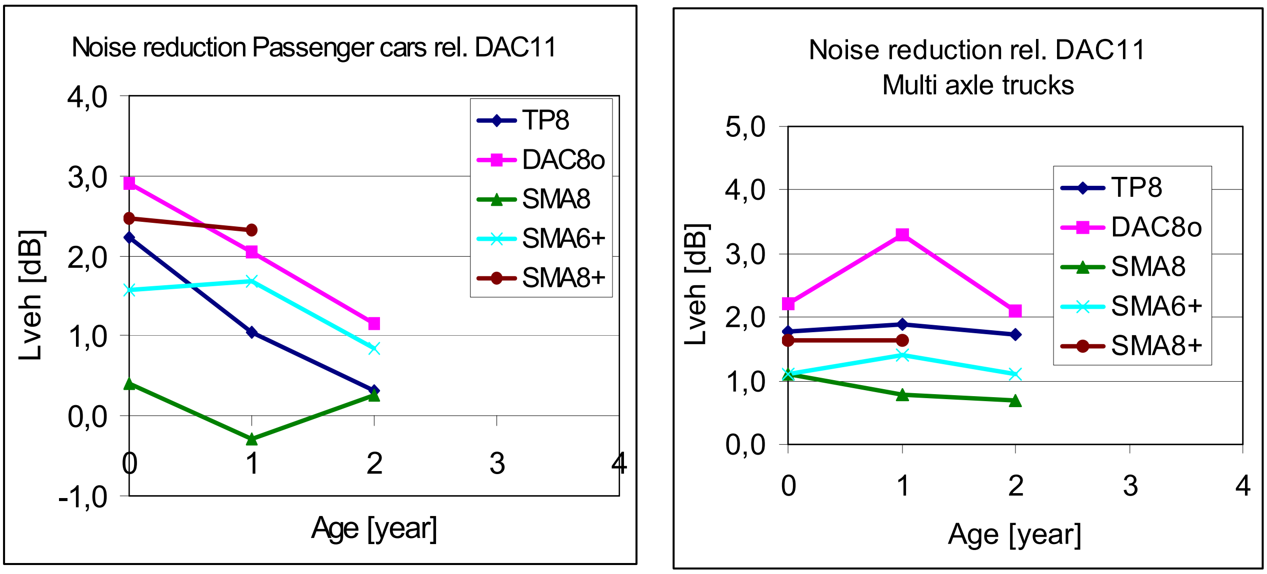


Fig. 8.22. Measured SPB noise reduction, in three consecutive years, for the trial thin layers in Solrød. The reference surface is DAC 0/11. Cars were measured at 110 km/h and multi-axle trucks at 85 km/h. From [Bendtsen, 2007].

One more experiment on a highway has been initiated. It is the so-called Herning experiment, taking place on roads near the city of Herning [Bendtsen et al, 2007-2]. This project is part of the DRI-IPG cooperation and the purpose is to optimize thin layers for the best possible performance. Ten optimized thin layers were laid on a test section on a new Danish highway near Herning in 2006. The speed limit on most of the test sections is 90 km/h - but 130 km/h on two of them. Dense asphalt concrete with 11 mm maximum aggregate size is a reference pavement with the same age as the test pavements. Both the acoustical and the structural durability of the thin layers are in focus in this project.

Table 8.5 presents the technical data for the tested thin layers. Note that the SMA6+ pavement is an SMA6 with some extra aggregate 6-8 mm with the intention to open-up the surface texture. The grading curves are shown in Fig. 8.23.

Design criteria were:

- Use cubic stone material
- Good compaction
- Use small maximum aggregate size
- High built-in air voids content
- Use modified bitumen

Table 8.5. Technical data for the optimized thin layers in Herning. From [Bendtsen et al, 2007-2].

Pavement	Filler [%]	Material under 2 mm [%]	Max. aggregate size [mm]	Bitumen [%]	Air void [%]	Layer thickness [mm]
UTLAC8	8.5	22	8	5.7	12	22
UTLAC6	8	25	5.6	6.0	13	18
PAC6 – cl. 2	7.5	20	5.6	6.5	14	24
PAC8 – cl. 1	7.5	22	8	5.6	14	25
PAC8 – cl. 2	8	15	8	6.0	16	24
SMA 6	9	18	5.6	8.0	9	18
SMA 6+	7.5	26	5.6 + 5/8	7.3	6	22
SMA8	7.5	19	8	7.1	8	24
DAC6o	-	-	6	-	-	-
DAC8o	-	-	8	-	-	-
DAC11	6.5	35	11	5.2	2.3	-

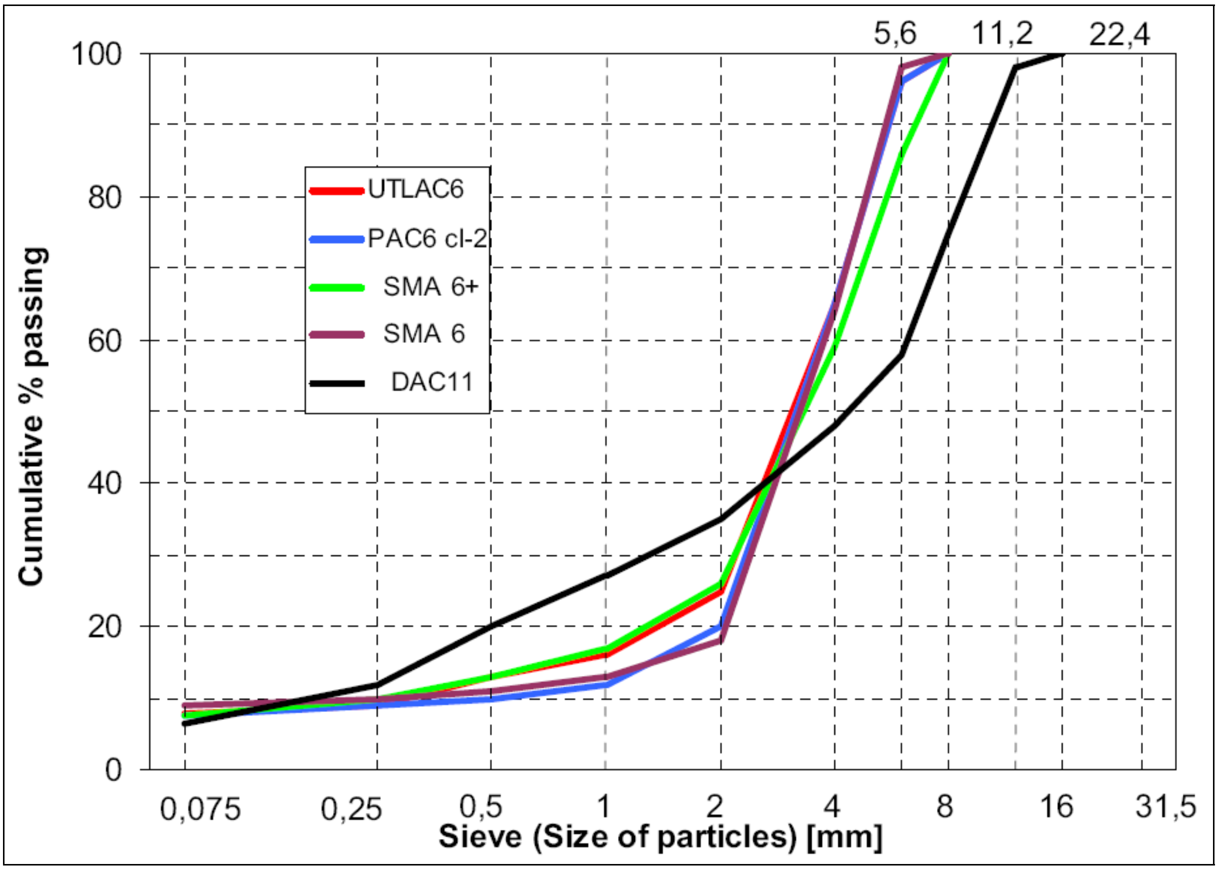


Fig. 8.23. Grading curves for the trial pavements in Herning. From [Bendtsen et al, 2007-2].

The results of SPB noise measurements for passenger cars when the surfaces were new is presented in Figure 8.24 as noise reductions compared to the same reference pavement as in the M10 Solrød experiment. There is a range of nearly 5 dB between the noisiest and the quietest of the test pavements. Similar measurements for multi-axle trucks are presented in Fig. 8.25. For two-axle trucks, the results are rather similar as for multi-axle trucks. Note that the noise reduction is almost the same for cars as for trucks. Often thin layers with their smooth texture are not so efficient for trucks, but this was not the case here. However, ranking of the pavements is highly different for trucks and cars, and this might reflect the different sensitivities to texture of car and truck tyres. DAC6o and SMA6+ seem to offer the best performance when both light and heavy vehicles are considered. The former gives a noise reduction of 4.7 dB compared to a DAC 0/11 of the same age which, for a reference of DAC 0/16 as used in the IPG program, would correspond to approximatrely 6 dB. This is just a little less than the tested Dutch thin layers at highway conditions.

It is planned to continue the measurements in the coming years in order to monitor both the acoustical and the structural development of all the test sections near Herning.

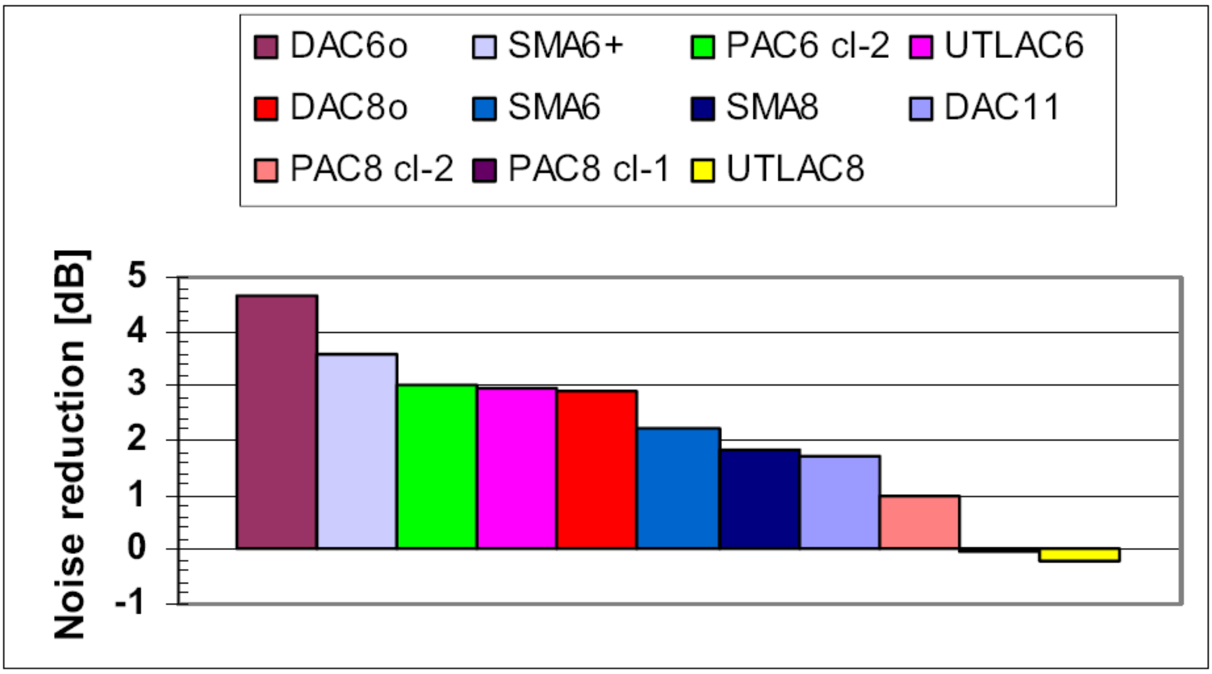


Fig. 8.24. Measured SPB noise reduction for cars at 90 km/h for the trial thin layers in Herning. The reference surface is DAC 0/11 in the M10 Solrød experiment. From [Bendtsen et al, 2007-2].

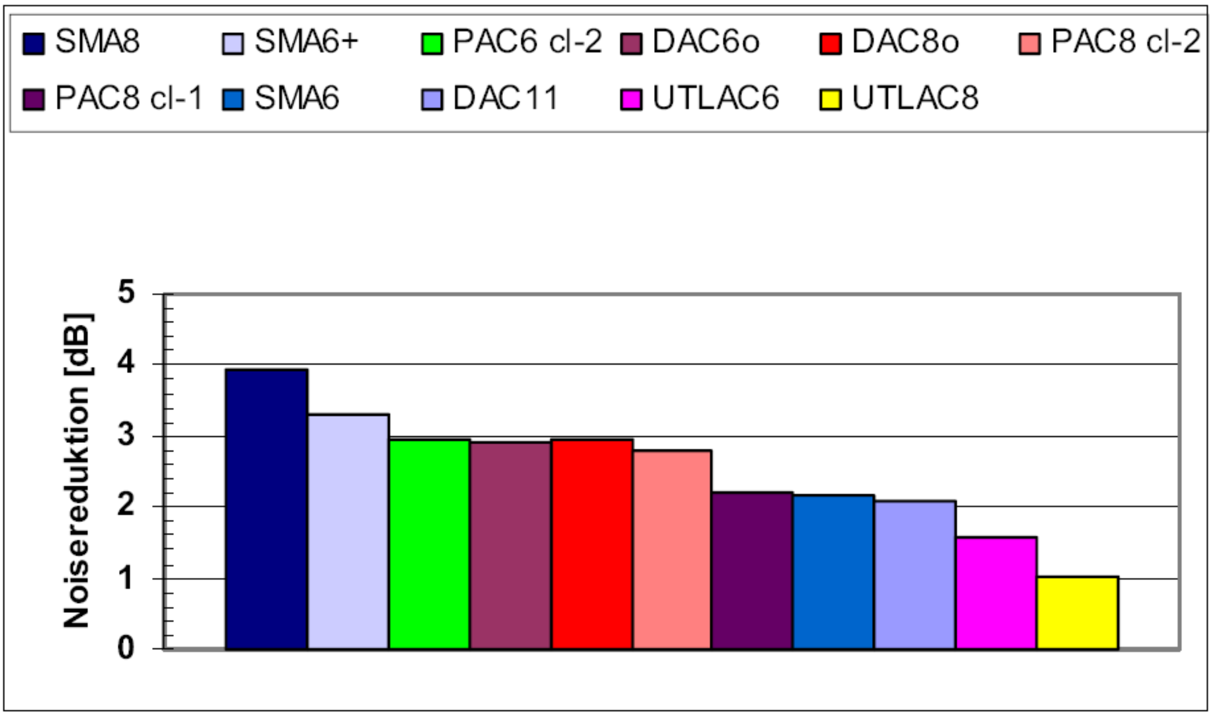


Fig. 8.25. Measured SPB noise reduction for multi-axle trucks at 80 km/h for the trial thin layers in Herning. The reference surface is DAC 0/11 in the M10 Solrød experiment. From [Bendtsen et al, 2007-2].

8.5.4 Concluding remarks concerning thin layers

Finally, it may be of interest here to look at the measured noise levels of various thin layers in the Netherlands (in the IPG program) and Denmark. Fig. 8.26 is reproduced from [Morgan, 2008] and shows such comparisons in terms of measured SPB levels for cars, trucks and a mix of these vehicles. The traffic composition for the mix of traffic is 85 % light vehicles at 115 km/h, 15 % heavy vehicles at 85 km/h. The microphone height is 1.2 m in all cases. Note that the diagram includes only the first generation of Danish thin layers and that the optimized versions are at least 2 dB quieter. Still, there is a 2-3 dB higher noise reduction for the best Dutch thin layers compared to the presently best Danish thin layers.

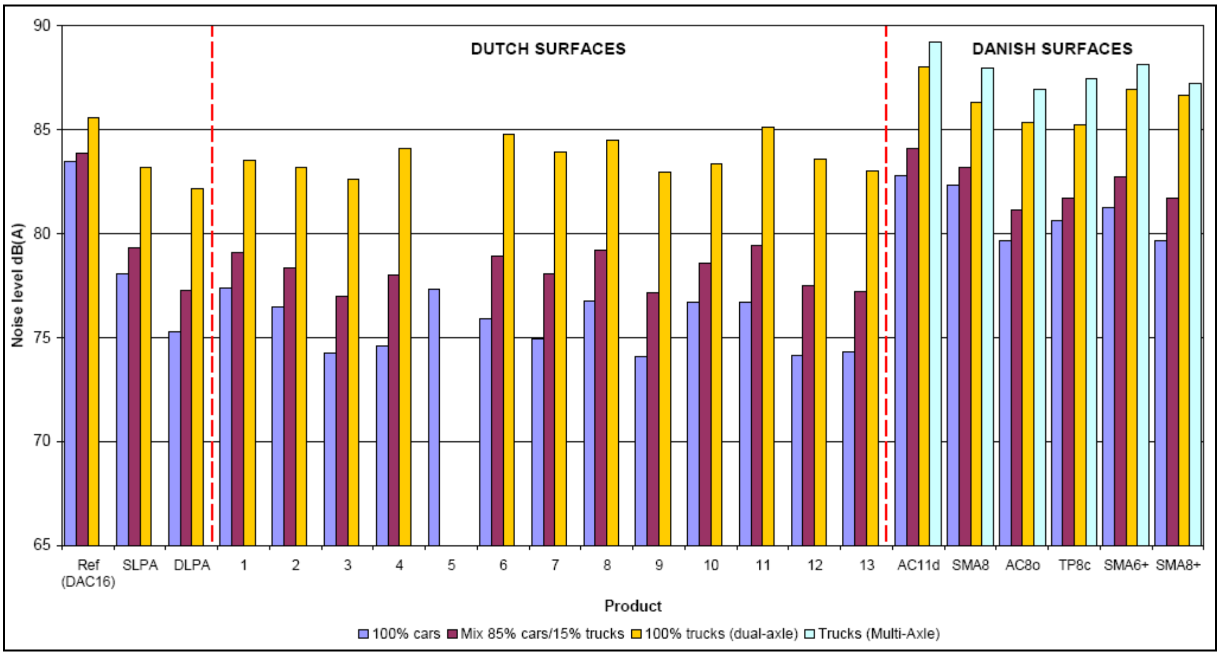


Fig. 8.26. Comparison of measured SPB levels at highway speeds for cars, trucks and a mix of these vehicles between Dutch and Danish thin layers. The Dutch ones are Nos. 1-13. Note that the Danish data do not include the latest more efficient thin layers. From [Morgan, 2008].

The following conclusions can be made concerning the application of thin layers on low-speed and high-speed roads:

- On highways the best DRI thin layers offer a 4-5 dB noise reduction relative to DAC 0/11 and 5-6 dB relative to DAC 0/16.
- These surfaces are also effective for heavy vehicles, albeit the optimum for light vehicles is different from the optimum for heavy vehicles.
- On low-speed roads, noise reduction relative to DAC 0/11 is 3-4 dB for the latest surfaces tested by DRI
- There is a somewhat reduced effect for cars after one and two years, but not so much for heavy vehicles
- The thin layers offer good friction
- TPc, DACo and SMA can be optimized for noise reduction
- Test sections with improved noise-optimized thin layers have been constructed, including thin semi-porous layers and they appear to be the best ones

8.6 Acoustical durability of low-noise road surfaces

In the EU project SILENCE, one task was to study the influence of age and condition of various road surfaces on their noise properties. The aim of this task was to provide models for the effect of ageing on the noise-reducing effect of surfacings. The basis was existing historical data on noise performance and analyses of data available to the work package team from sections of road with a known history. Also, a few dedicated measurements were carried out within the framework of this task at sites where measurements had been carried out in the past.

The task also had the purpose to complement the road surface noise classification dealt with in another SILENCE Task. This latter classification is, namely, based on the initial acoustic performance and must be supplemented by some concern for the longterm properties.

The final analyses were made by computing, by linear regression analysis per measurement site, the initial noise level L_0 = 0 dB at time t_o. For all measurement sites, with a given family of pavement, the time histories were plotted as the change in noise level with pavement age, relatively to the initial noise level. Finally, linear regression analyses were made of all these noise level changes on time [Kragh, 2008].

The results were as follows. In Table 8.6 a summary is given of the slopes to be expected for the time history of vehicle noise levels [Kragh, 2008]. For both light and heavy vehicles, the slope to be expected at dense asphalt surfacings is in the order of 0.1 dB per year of pavement service time. This applies to high-speed as well as low-speed roads. For porous or open-textured surfacings the time history slope for light vehicles can be expected to be in the order of 0.4 dB per year at high-speed roads and 0.9 dB per year at city streets with low vehicle speeds. Heavy vehicle noise levels can be expected to increase with 0.2 dB per year at high-speed roads.

Note that this is an estimation of an overall average from various sources and it has been noticed that the most recent versions of Dutch and German porous asphalt surfaces have a somewhat lower loss of noise reduction with time for at least light vehicles. Note also that the table is not valid for climates where studded tyres are used, since in such cases surface wear and dirt generation are much higher.

Table 8.6. Loss of noise reduction by time: Overall proposed time history slopes, in dB per year of pavement service time. For the lower right cell there is not sufficient data available. From [Kragh, 2008].

Type of vehicles:	Light vehicles		Heavy vehicles	
Vehicle Speed:	High	Low	High	Low
Dense asphalt (DAC and SMA)	0.1	0.1	0.1	0.1
Porous / Open-textured asphalt	0.4	0.9	0.2	-

9. EXPERIENCE IN THE NETHERLANDS

9.1 General information

The world's most comprehensive research program ever in the noise area (IPG) has just been finished in the Netherlands, with a budget of around 54 million Euros in time period 2004-2007. The most prominent feature of the IPG project was the refinement of the double-layer porous asphalt surfacing. Another feature worth mentioning here is that the IPG focused on high-speed roads.

It can be mentioned that Dutch researchers were the first to explore in detail the possibilities of using double-layer porous asphalt concrete (DPAC) for noise reduction in the late 1980's and early 1990's. This interest has prevailed and research on DPAC has been one of the major parts in IPG.

Some words about the terminology: What in this report called is double-layer porous asphalt concrete (DPAC), since it is a preferred European terminology, is in the Netherlands called twin-layer porous asphalt (TLPA). The corresponding terms for the single-layer version are (single-layer) porous asphalt concrete (SPAC or more frequently just PAC), which in the Netherlands is called single-layer porous asphalt (SLPA). In Hong Kong, the latter corresponds essentially to polymer modified friction course (PMFC).

Furthermore, the Dutch are consistently talking about "silent roads". The preferred term in English should be "quiet roads" (the Americans are using "quiet pavements"), since traffic can be silent (= totally quiet) only when it is standing still with engines switched-off or contained in a tunnel. However, this author and British colleagues are normally using the term "low-noise road surfaces".

In Chapter 9 (only), the terms TLPA and SLPA are preferred over the general terms DPAC and PAC, since they are consistently used by the Dutch.

9.2 Low-noise road surfaces on high-speed roads

9.2.1 Focus on double-layer asphalt concrete

The Dutch have almost entirely focused in their R&D on improving the characteristics of TLPA (DPAC). The goal is that this surface shall provide a traffic noise reduction of 4 dB over dense asphalt concrete with maximum 16 mm chippings (DAC 0/16) for a mix of 85 % light vehicles and 15 % heavy vehicles. The 4 dB is the average noise reduction over the life-time of the surface, which is expected to be at least 8 years (as an average), and is the goal for surfaces ready to be implemented as a regular paving material by the end of 2007.

Apart from this goal for surfaces ready to be implemented by the end of 2007, the Dutch have set up a goal of 6 dB, with same conditions as stated above, for surfaces that are developed in the IPG program but may need some further refinement and testing before being possible to implement as a regular paving material.
The TLPA surfaces are primarily intended for the high-volume, high- and medium-speed road network (70 km/h and above), although they may also be useful on the low-speed network

where high horizontal tyre/road forces do not occur. But the only development activities made with special relevance also for the low-speed network are the attempts to reduce ravelling problems where high horizontal forces occur and to reduce clogging problems.

It also seems that the Dutch are well on the way to achieve the goals mentioned above. Already the SLPA with 16 mm max chippings has an initial noise reduction of 3.5-4.0 dB reducing to 2 dB at an age of 8 years. The lifetime average is around 2.5 dB. TLPA of "traditional" design provides an initial noise reduction of 5-6 dB reducing to 3 dB at an age of 8 years, with a lifetime average of 4 dB. The noise reduction deterioration seems to be about 0.25 dB per year. The new and improved designs of TLPA, which are not yet tested over their full lifetime, seem to offer a lifetime average of 5-6 dB if the lifetime is assumed to be 8 years. The noise reduction deterioration seems to have been improved to about 0.2 dB/year.

It shall be mentioned that the above values are relevant to SPB testing at high speeds with a non-standard microphone height of 5 m, which usually means that about 1 dB of noise reduction is lost compared to cases when the microphone is at a height of 1.2 m. The Dutch are unique in using this high microphone position.

The spread in initial noise reduction is commonly ± 1.0 dB around the average, as a result of tolerances and variation between contractors. Higher deviations may occur in case of inexperienced contractors. See Fig. 9.1.

No rutting is observed in the Netherlands on porous asphalt surfaces, due to

- the stone skeleton
- the temperature (the open texture makes the surface somewhat heat insulating)

9.2.2 Construction details of double-layer asphalt concrete

The type of TLPA most commonly applied has the following main data:

Top layer: 25 mm thick, dominating stone fraction 5-8 mm (87-91 %), only quarry material is allowed, minimum PSV value of 58, resistance to crushing LA <15%, voids content target 20 %. As binders (5.2-6.1 %), different types modified bitumen are used: either PMB's with SBS or EVA or mixes of both, or rubber-modified bitumen. Fines are 3-11 % and filler is 2-5 % by weight.

Bottom layer: 45 mm thick, dominating stone fraction 11-16 mm (89-92 %), quarry material or crushed river gravel are allowed, voids content target 25 %. As binders (3.8-4.8 %), different types are used: sometimes pen grade 70/100 bitumen, sometimes PMB (but no RAP is allowed). Fines are 5-8 % and filler is 3-4 % by weight.

Fines and fillers:
Fines: crushed sand < 2 mm
Filler: lime stone filler with hydrated lime, < 0.063 mm
Note: The addition of hydrated lime (HL) improves the bonding effect between the bitumen and the mineral aggregate and HL also influences the bitumen properties in a positive way.

An alternative tried quite extensively is a variation of the above in which the top layer has a dominating aggregate size of 2-6 mm and is 20 mm thick, and where the bottom layer is 50 mm thick. However, this variant does not seem to offer an advantage; except a one dB higher initial noise reduction, since the deterioration with time goes faster and ravelling is more critical.

The acoustic absorption measured with the tube method of such designs show a peak sound absorption coefficient of around 0.97 at a frequency slightly higher than 600 Hz.

9.2.3 Problems with porous asphalt

The lifetime of 8 years or more achieved for porous asphalt surfaces within the IPG is very impressive. Fig. 9.1 shows a compilation of measured noise levels (expressed as SPBI; i.e. for a mix of light and heavy traffic) for TLPA versus the age of the surfaces. It shall be noted that the high durability and long-lasting noise reduction are achieved for high-speed roads, and that the Dutch motorways, on which many of the tests have been made, are generally subject to very high traffic volumes and high heavy vehicle proportions. During peak hours the traffic is so intense that the traffic flow is very slow, when not at stand-still. These are tough conditions for high-speed roads.

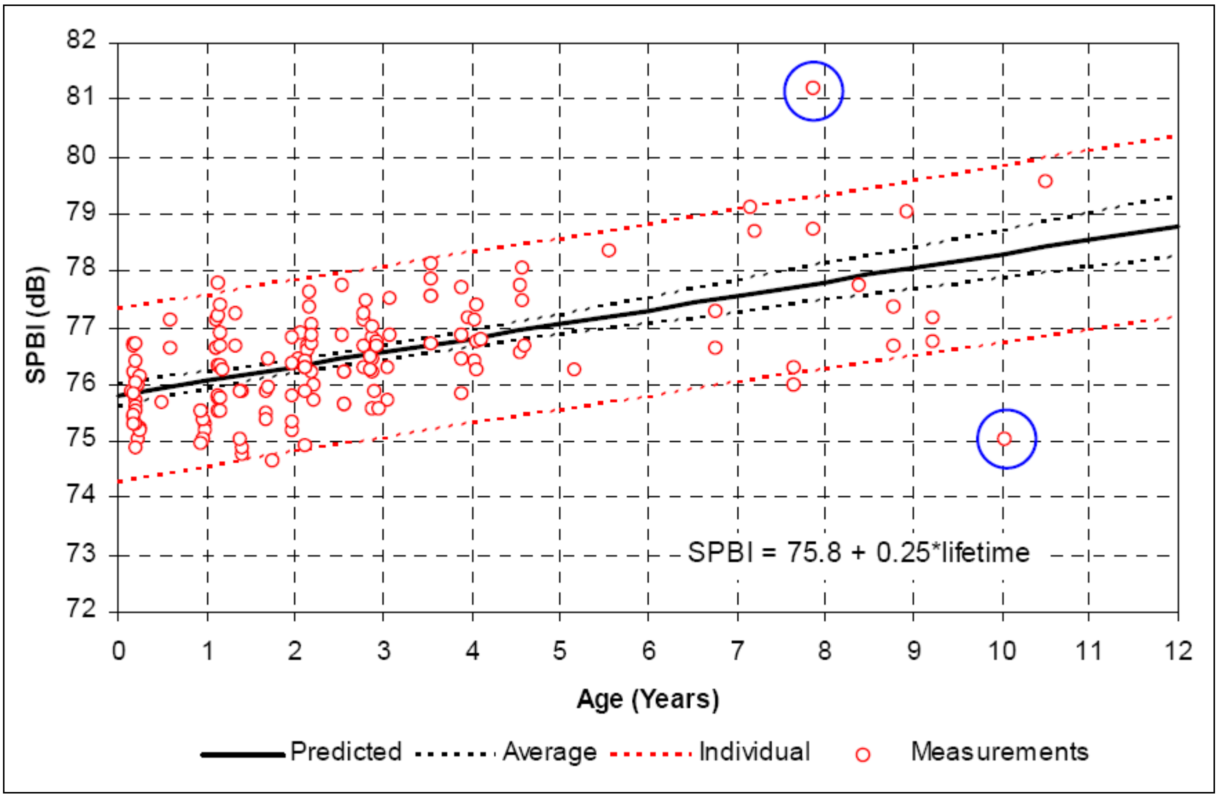


Fig. 9.1. Measured SPB Index (SPBI) on TLPA sections with a 4/8 mm upper layer, as a function of age of the surface. The two circled outliers have not been included in the regression calculation. From [Morgan, 2008-1]. Note that the reference level for the SPBI in this case, representing a middle-aged Dutch DAC 0/16, is at 82.3 dB.

It should also be noted that the TLPA or SLPA are not normally laid where there is an intersection or curve. In the Netherlands there are no longitudinal gradients on roads so this situation is also not considered. Nevertheless, the TLPA and SLPA are subject to moderate accelerations and decelerations at exits and entrances to the motorways, as well as due to the frequent stops in the traffic flow due to peak-hour congestions.

A discussion of the major problems follows:

<u>Clogging:</u> Clogging mainly occurs in the bottom of the top layer and the top of the bottom layer; i.e. the boundary between the two layers creates a kind of soft barrier to the air, water and dirt that are supposed to be transported through the pavement. This is a problem particularly for a top layer with 2-6 mm chippings where the finer material penetrates somewhat down into the bottom layer. This type of TLPA is therefore not allowed any more on motorways. Clogging is less of a problem where self-cleaning by traffic occurs such as in wheel tracks on high-speed roads, but is a problem on the shoulders and on low-speed roads.

<u>Cleaning:</u> Cleaning has not yet been proven to be very effective (see, however Chapter 11.2.4). However, it is believed that the cleaning is easier on the TLPA than on SLPA since the clogging occurs closer to the top on the TLPA and there is a "discharge" volume below. Cleaning in the Netherlands is made only on road shoulders, and two times per year. See also [Sandberg & Masuyama, 2005].

<u>Ravelling:</u> Ravelling is a problem to some extent on all TLPA and SLPA surfaces, but most of all in cases of high horizontal tyre/road forces, such as in sharp curves, small roundabouts, intersections with stoplights, parking bays, bus stops, and on roads with steep grades (thus not so much on high-speed roads). Of course, the problem is worse for heavy vehicles than for light ones. The ravelling problem is most of all caused by the deterioration of the binder due to the exposure of the binders down into the pavement by virtue of its porous nature. The best estimate of the technical lifetime on high-speed roads with the present intervention levels is 8 years, but this is something expected to be improved in the near future.

<u>Laying in bad weather:</u> TLPA shall not be laid in wet or cold weather. If done, it will jeopardize durability. Nevertheless, the Dutch are attempting to make laying at lower temperatures possible. Presently, ambient air and road surface temperatures below 15 ^{o}C shall be avoided and it is preferable that temperatures are about 20 ^{o}C or higher. Thus, this should not be a problem in warmer climates.

<u>Warm-in warm laying:</u> The lower layer must not be cooled down too much before the top layer is laid. Therefore, it is highly desirable to use a laying machine which can lay two layers in the same operation. There are such machines in Japan, Germany and the Netherlands, see [Sandberg & Masuyama, 2005].

<u>Early-life skid resistance:</u> It has been noted that the skid resistance in wet weather the few weeks immediately after laying a TLPA is lower than desirable according to Dutch standards. The development work in IPG has demonstrated a number of improvement procedures; the most effective of which was found to be to add glass slag of the fraction 0/1 mm to the surface [Morgon, 2008-1]. This procedure solved the problem at a negligible extra cost and no significant disadvantages.

Obtaining a high voids content: In the AOT (see Chapter 5.3.3) it was desired to achieve substantially higher air voids contents than the 20 % target commonly used. The contractors employed at the Kloosterzande test track had problems to achieve that, while maintaining a high durability. Later on they succeeded a little better, when putting higher priority to achieving high voids content. However, in Sweden, the contractor Skanska has achieved 25-30 % in surfaces having an acceptable durability, and the German experiment mentioned in 11.2.5 also achieved high voids content, so it should not be a major problem. However, it is likely that there is always some sacrifice of technical durability.

9.2.4 Development and testing of thin layers for high-speed roads

As a parallel track, the Dutch are making comprehensive trials and testing with thin, semi-dense layers. The thickness of thin layers is in the range 15-25 mm, as opposed to the 35-45 mm common for normal dense asphalt concrete and SMA. That they are "semi-dense" means that their initial voids content may be 5-20 %, with the intermediate range most common. The grading resembles that of SMA surfaces but with lower fines content. Most of these thin layers are designed and constructed by road contractors, whose products are then proprietary and their design details not open for inspection. In general, they feature maximum chipping sizes of from 4 up to 8 mm, with a thickness typically 2.5 - 3 times the maximum chipping size. An expected lifetime is 8-10 years, but up to 13 years seems possible.

The thin layers are mainly intended for low- or medium speed roads; i.e. urban areas, but some tests are made also for high-speed roads. The latter have been made within the IPG program. The already existing proprietary[38] thin layers show a noise reduction of 3-5 dB at 50-80 km/h, whereas new types tested in the IPG program at high speeds suggest noise reductions of 4-7 dB in new conditions. See Fig. 9.2 and further the section about low-speed roads later in this report.

The SPBI levels in Fig. 9.2 should be possible to compare with Fig. 9.1 and from this one can see that the initial noise levels of the thin layers is 75-78 dB whereas it is 75-77 dB for the TLPA; i.e. the thin layers are almost as good as the TLPA surfaces in new condition.

These thin surfaces have not been in operation for a long time on high-speed roads when this is written, so it is impossible to tell how fast the noise reduction deteriorates. However, after 8-11 months, the loss in noise reduction had been 0-1 dB with an average of about 0.5 dB for ten measured surfaces, which is very roughly twice as much as for the TLPA surfaces[39].

The performance of the thin layers will be follow-up in the next few years.

[38] “Proprietary” means that the surface is offered on the market by some company as a specific product, using a special protected name.
[39] This author’s calculations from Fig. 4.59 in [Morgan, 2008-1]

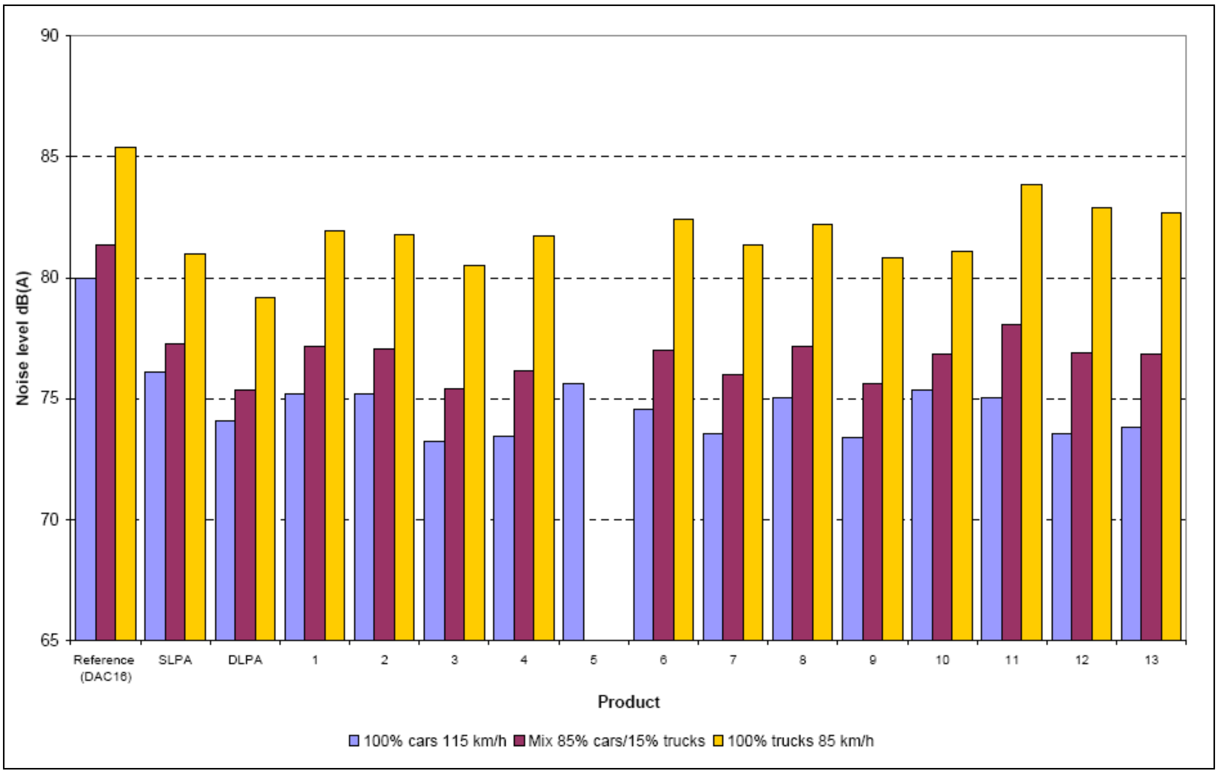


Fig. 9.2. Measured SPB levels (SPBI in the violet bars) on thin layer sections on Dutch high-speed roads, as a function of age of the surface. From [Morgan, 2008-1]. Note that the reference level for the SPBI, in this case (violet bars), representing a middle-aged Dutch DAC 0/16, is at 82.3 dB. However, in this diagram also a reference of a DAC 0/10 (probably new) is indicated at 81.3 dB.

9.2.5 Futuristic low noise road surface constructions - Modieslab

The Dutch have also conducted tests related to the IPG program with three futuristic surface constructions: Modieslab, Rollpave and poroelastic road surfaces (PERS). The two first are the result of the earlier Roads to the Future ("WnT") program.

Modieslab[40] is a prefabricated two-layer porous cement concrete slab pavement laid on piles but it can also be placed on supports created in an existing pavement. It is especially intended for rather common Dutch conditions when a road must be built over non-stable soil or ground and extensive actions must be taken to secure the road structure against a stable sub-ground. A thinner version of Modieslab can also be used to overlay existing concrete pavements.

The slabs can be accurately adjusted to height at the time of construction and can, if ever necessary, be adjusted later. The slabs feature a double-layer porous concrete wearing course for reduction of noise and splash and spray. See Figs. 9.3-9.4. As the slabs are cast upside down in steel moulds in the factory, starting with the fine aggregate top layer, an extremely high surface evenness with low mega- and macrotexture is achieved.

[40] Most of this section about Modieslab is an abridged version of [van Dommelen, 2007]

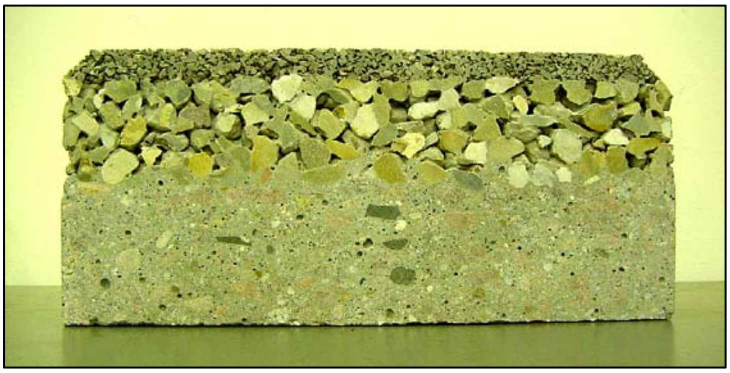


Fig. 9.3. The double-layer porous cement concrete surface of Modieslab. Note that when manufactured these slabs are placed upside-down. Photo from [van Dommelen, 2007].

Fig. 9.4. Construction of Modieslab on the A12 motorway. Photo from [Morgan, 2008-1].

The pile foundation and concrete slabs provide a long-life structure (theoretical design life is 80 years). However, the wearing course is expected to last 10 years, making it necessary to periodically exchange the pavement elements with elements with a renewed wearing course. Due to the fact that the longitudinal joints coincide with the pavement lanes, the slabs can be exchanged per lane.

The use of factory produced pavement elements has a number of advantages, such as independence on weather conditions, better control of tolerances and quality in general, quick replacement of worn-out pavement modules (at least 100 m/hour over the full carriageway width) on the road with a minimum of traffic hindrance, and the possibility of taking used modules back to the factory for recycling, refurbishing or modification.

The initial construction costs of Modieslab are several times higher than those of conventional pavements. However Modieslab can be cost-effective in the long term, especially when road sections have to be constructed in a short time span in areas with large settlements. Normal construction would imply slowly building an embankment with long waiting times to avoid slope instability and to allow the large settlements (up to several meters) to develop. Yet the resulting conventional pavement will usually still not be free from unevenness in the longer term, but the Modieslab can be adjusted for such changes.

After small-scale testing in two motorway access lanes along the A50 motorway and in the LinTrack ALT facility, a first application as a 100 m long two-lane section on the motorway A12 in Oudenrijn was realized in 2006; see Fig. 9.4 and Fig. 9.19. The surface was artificially treated so as to remove the cementitious binder film that initially reduces the skidding resistance of the surface. This resulted in excellent skidding resistance.

The goal was to achieve a noise reduction of 6-7 dB. The present trial achieved 6.1 dB in relation to the Dutch reference surface DAC 0/16 for light vehicles. The results compared very closely with similar measurements on a TLPA surface for both light and heavy vehicles (in new condition). However, it is expected that this surface will have a longer acoustical and technical life-time than TLPA.

9.2.6 Futuristic low noise road surface constructions - Rollpave

Rollpave is a 30 mm thick rollable porous asphalt concrete pavement which is prefabricated in a factory (yard or barn) as a number of 50x3.75 m “slabs”, which are rolled up on reels, brought out on the road, rolled out and glued on the basecourse. The latter is normal dense asphalt. See Fig. 9.5. The rolled asphalt mat, which has a wire mesh (iron gauze) on its underside, can be bonded and unbonded to the basecourse very quickly by an innovative bonding system based on induction by electromagnetic waves. Energy transmitted by the waves (from a machine moving over the surface) is picked-up by induction in the wire mesh which is heated by the currents in the wires. This melts a bituminous bonding layer (a “carrier layer”) around the mesh in order that it can bond to the basecourse, or unbond if the process is used to remove the asphalt mat. See Fig. 9.6.

Fig. 9.5. A roll of Rollpave is laid in June 2006 on the A35 motorway near Twente Canal in Hengelo. Photo from [Morgan, 2008-1].

The width of the rolls first was 2.5 m, but in the later trials they have been 3.75 m; i.e. the width of a normal driving lane.

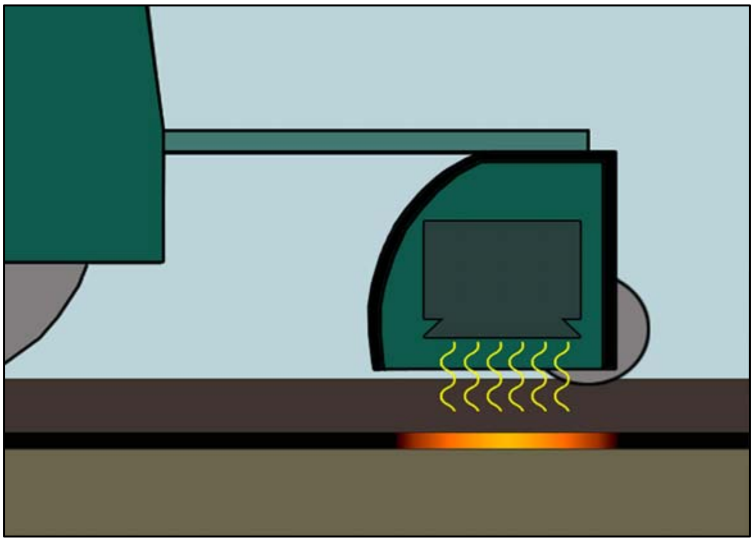


Fig. 9.6. The principle of bonding or unbonding the rollpave mat (dark grey) on the basecourse (grey) by electromagnetic heating of the wire mesh in the bonding layer (black). From [Nauss, 2007].

The advantage with this is that a repaving project can be finished much faster than with the conventional paving method; thus causing less interruption to traffic, plus that the prefabrication should warrant a more uniform and homogene surface. The prefabrication can also use the principle of producing the asphalt mat in an "upside-down" fashion; i.e. the top surface of the final asphalt mat will be the bottom surface facing the floor during fabrication; making it possible to get the stones aligned in order to have their "flattest" surface facing the floor, which will then be the top surface when laid on the road. This should give a "negative" texture with a flot top surface, creating a minimum of tyre vibrations.

The laying speed in one of the latest experiments, on motorway A37 in January 2007, indicated that the required time limit of one day for laying and finishing 430x11.5 m was met as the project was finished in 8 h. This speed at the trial level is much lower than what can be achieved in the future if the equipment and procedures are optimized and with improved experience. The target is to lay 300 m/h [Naus, 2007]. The expectation is that in the future, Rollpave can be laid approximately 50 % faster than single layer porous asphalt and approximately 100 % faster than TLPA (i.e. double the speed) [Morgan, 2008-1].

The original goal was to achieve a noise reduction for the Dutch standard mixed traffic of 7-9 dB in relation to the Dutch standard reference surface[41]. The first small-scale attempt (100x5 m laid in 2001 on an access road to the motorway A50) gave a 6 dB noise reduction; i.e. approximately the same as TLPA. The first full-scale trial was laid in June 2006 on the A35 motorway in Hengelo, where a 480 m long section of the two-lane motorway plus wide shoulder was paved at a width of 12.5 m in one of the directions. See Fig. 9.18. This surface turned out to give a 4.3 dB noise reduction when new and 3.4 dB after one year compared to the Dutch reference [Morgan, 2008-1], which was a disappointment[42].

Later trials in 2007 have shown that the Rollpave is possible to lay also in (Dutch) wintertime (one section was laid at -1 ^{o}C) and in a moderate curve (radius 1000 m) typical of motorway.

[41] This author thinks that this was a much too optimistic goal
[42] This author thinks that 4 dB is totally logical for a 30 mm thick and 15-19 % porous mix.

The porous asphalt material is some kind of mix of an SMA surface, with its open but non-porous structure, and an SLPA with its porous structure, 28-32 mm thick and with a 2/5.6 mm aggregate. The binder is bituminous with several modifications. Voids content became around 19 % in the A35 trial but was targeted a little higher. This is probably due to "self-compaction" of the rolls. The resulting surface is then similar to some of the thin layers of porous nature. Rollpave is actually based on the concept of the proprietary thin layer Nobelpave.

The expected lifetime is 10 years. The cost is projected to be EUR 25 per m^2 [Naus, 2007], which is significantly higher than for a thin layer or for SLPA. However, it is thought that this may be justified in cases where traffic congestion due to repaving becomes too cumbersome and when Rollpave provides a much faster repaving process. Other potential uses include bridge decks, temporary pavements and emergency repairs.

This author thinks that by further development, the Rollpave may become equally quiet as the best thin layers or as an optimized SLPA (of the German type, see Chapter 11).

9.2.7 Futuristic low noise road surface constructions - PERS

Based on promising results from experiments in Japan and Sweden with poroelastic road surfaces (PERS), a cooperation project between the Public Works Research Institute (PWRI) in Japan and the DWW (later renamed to RWS) was started at the end of the iPG project. Within this project three short sections of poroelastic road surface (PERS) materials produced in Japan were glued on the test track at Kloosterzande in the southern Netherlands. This is a non-trafficked test track, so this author considers the experiments as being of limited interest since the challenge is to get this surface operational under significant traffic conditions. A main purpose with the PERS surfaces here was to provide a very soft surface that can assist in determining the influence of surface stiffness on tyre/road noise generation, as part of the AOT project (see below) but it was also considered as a pilot project to see the potential of achieving substantially better performance than the best TLPA surfaces.

These surfaces, which were supplied as 30 mm thick 1×1 m^2 prefabricated panels, were imported from Japan and each used a different mix specification. All of the necessary materials required for laying the PERS surfaces, e.g. adhesives, etc. were also imported from Japan. Fig. 9.7 shows part of the poroelastic surfaces laid at the Kloosterzande test site. The PERS were laid in April 2007, under the supervision of a contractor from the Japanese manufacturers, as 3 m wide sections on a base of SMA 0/11 [Morgan, 2008-1].

Several measurements have been made on the PERS, but with different results. Fig. 9.8 shows the results of CPX measurements made with US equipment and using sound intensity microphones [Rasmussen, 2007]. The pavements are from left to right:

- SMA 0/16
- DAC 0/16 (surface 23)
- The three PERS pavements

It appears that the noise reduction is 7-9 dB compaed to the DAC 0/16. Other measurements with the CPX method have indicated 8 dB noise reduction in April 2007 but 6 dB in October 2007. It is believed that the 2 dB difference is caused by 14 ^{o}C difference in temperature where the colder weather gives a noisier PERS, mainly due to expanding joints [Morgan, 2008-2].

Fig. 9.7. Mounting of the PERS test sections at Kloosterzande. From [Morgan, 2008-2].

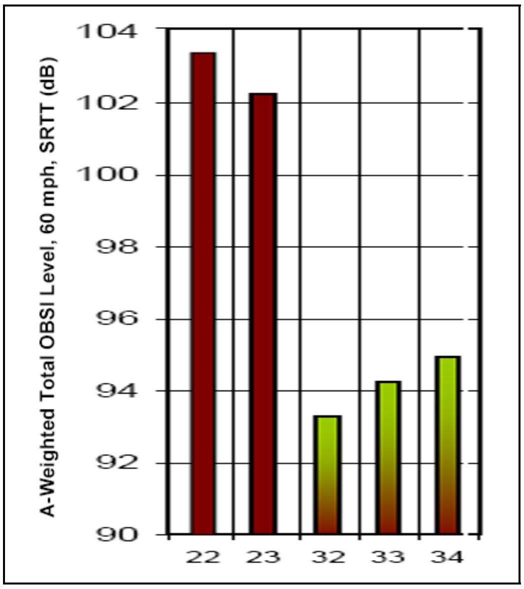


Fig. 9.8. Results of one set of CPX measurements in 2007 on the PERS test sections at Kloosterzande and two reference sections there. Test tyre: ASTM SRTT run at 100 km/h. From [Rasmussen, 2007]. See the text for more information.

CPB measurements (test vehicles passing-by at constant speed) indicated an initial noise reduction of 6.9 dB for passenger cars at a speed of 100 km/h relative to the noise level measured on the DAC 0/16 reference surface at Kloosterzande (Surface 23). This was poorer than previously reported in the Japanese trials but considered to be due to the quality of the joints between the PERS tiles, despite these being laid by experienced Japanese contractors [Morgan, 2008-1].

9.3 Low-noise road surfaces on low-speed roads

9.3.1 General

The IPG program has provided a wealth of information about the use of low-noise road surfaces on high-speed roads. Much of this is also applicable to medium-speed roads (60-70 km/h). However, when it comes to low-speed roads (posted speed 50 km/h and below) in urban areas, things change quite dramatically. It is not just that the medium speed is lower, which seriously affects the selfcleaning of porous surfaces and changes the proportions between tyre/road noise and power unit noise of vehicles. Driving patterns are also different, with more accelerations and braking manouvers; furthermore, urban low-speed roads and streets are crossed by other roads and streets as well as often have parking areas along the road. Streets mostly have kerbstones and pedestrian sidewalks which prevent or at least limit the drainage of water off the carriageway, in this way reducing the positive effect of porous surfaces. These things create not only accelerations and decelerations/braking, but also high lateral forces when vehicles are turning. All this dramatically affects durability, economy and acoustic efficiency.

While the IPG was not of much use for the low-speed case, there have been other major activities in the Netherlands related to the use of low-noise road surfaces in urban areas which are interesting to review here.

9.3.2 State-of-the-art review

First of all, however, there was in fact one study in the IPG which have relevance for low-speed roads; namely a state-of-the-art review concerning TLPA used on local and secondary roads [Goubert et al, 2005]. This means that the posted speeds were 50-70 km/h. The study identified about 40 Dutch roads and 20 roads outside the Netherlands for which there were technical data; for 37 of which there were also noise data measured with the SPB method. However, the SPB data only had reliable data for light vehicles, not for heavy vehicles. There were also about 90 sections found in Japan, but the authors did not have access to relevant data for them. Some of the major findings are summarized below.

The authors calculated statistics of the technical lifetime of the surfaces; see Fig. 9.9. The figure presents the technical lifetimes of both removed sections which had already been replaced and the ages of the existing sections in poor technical condition (which are all Dutch). It turned out that the range is very wide, with an average 7-8 years. It was also found that high traffic volumes meant a shorter lifetime, and vice versa, although the relation was weak. A weak trend for decreased lifetime with smaller aggregate size was suggested by the data.

The study was unable to analyze noise reductions; one reason being that no uniform reference surface existed by that time. However, it was possible to study how the noise levels increased as a function of surface age; see Fig. 9.10. Note that this is the average vehicle noise level at 50 km/h for cars only. The first year meant a loss of approximately 1.5 dB, the second year a loss of 0.5 dB more and the next years still some loss of noise reduction, but the data above the age of 3 years are insufficient for any conclusions. An alternative interpretation of the data, depending on how the regression is calculated, is that there is a loss of 1 dB/year, at least over the first 3 years. Note that this is much higher than for the high-speed roads. It may of course be explained by the poor self-cleaning of porous asphalt at low speeds.

It was also found that the initial noise reduction was influenced by the maximum aggregate size in the top layer; with 4 mm being the best and 11 mm the worst. The total thickness of the porous layers affected initial noise levels too, with thicker being better.

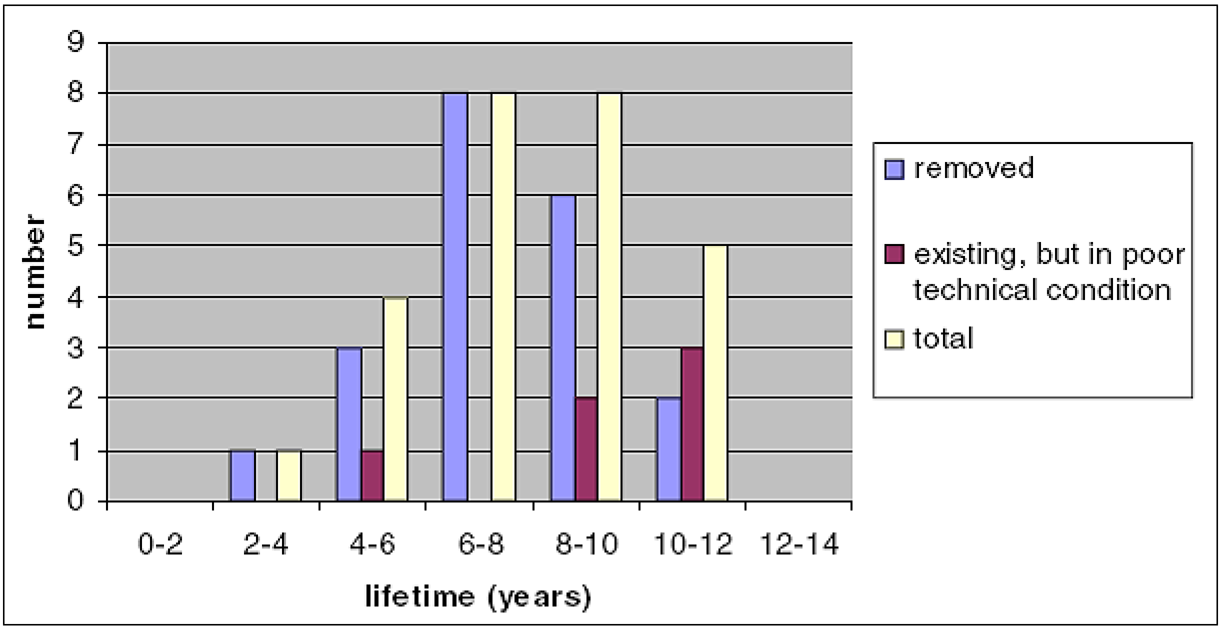


Fig. 9.9. Distribution of technical lifetime of the surfaces in the data set, where blue are the surfaces already removed and repaved and violet are surfaces still in operation although in poor condition and thus needing replacement. From [Goubert et al, 2005].

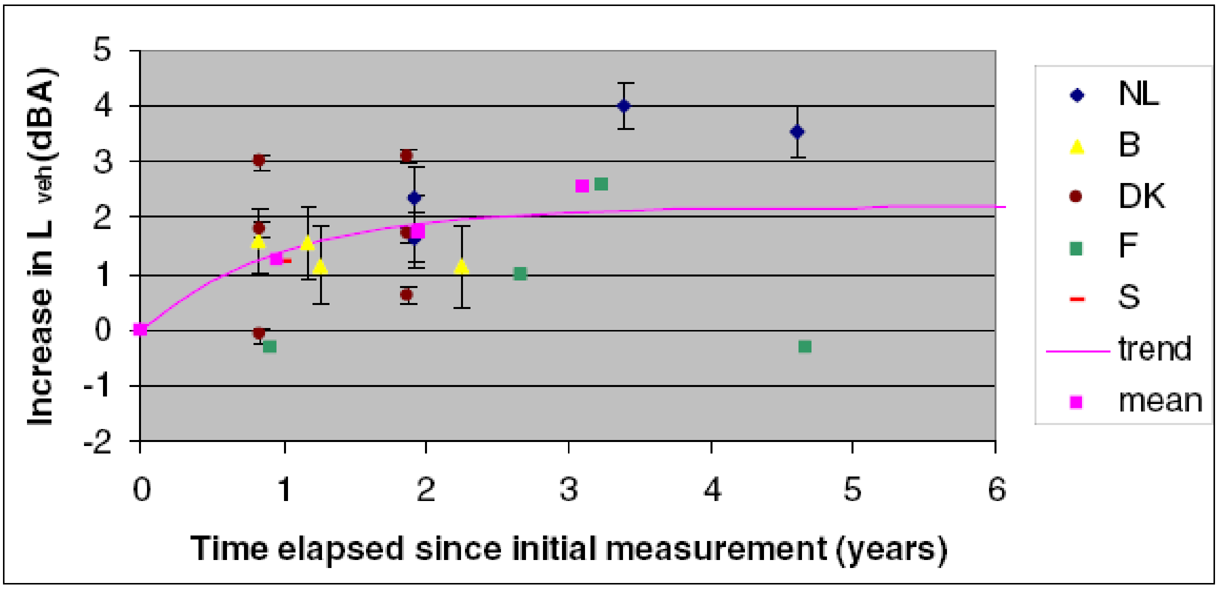


Fig. 9.10. Increase of the SPB parameter L_{veh} (average vehicle noise level) with time elapsed since the measurement of the initial value for L_{veh}. The symbols at the right show which country the data comes from (Netherlands, Belgium, Denmark, France, Sweden). From [Goubert et al, 2005].

9.3.3 Experience in the City of Groningen

In the beginning of the 1990's, double-layer porous asphalt was introduced in the Netherlands as the ultimate solution against traffic noise. Now, there is more than 10 years of experience with the construction, efficiency and maintenance of such surfaces. VANKEULEN Consulting has been involved in evaluating the effect of low-noise road surfaces in the city of Groningen in the north of the Netherlands, and this sub-chapter is based on non-published information from Mr Wim van Keulen of this company [van Keulen, 2008].

Low-noise road surfaces in Groningen are of two types:

- Double-layer porous asphalt (TLPA)
- Thin layers

From 1996 to 2000 five roads of the city network were paved with double-layer porous asphalt in order to reduce traffic noise. The reason was that traffic had intensified significantly and façade isolation and noise reducing asphalt were the only possible options in these cases to bring back noise levels to acceptable ones. Noise-reducing asphalt was found to be more attractive financially; not the least since the Ministry of Environment subsidised the application of porous asphalt in cities and municipalities during this period.

It was recognized that porous road surfaces must have an advanced drainage system when laid in urban areas, which of course introduced extra costs.

Soon after their construction, all surfaces showed damage (ravelling); especially near joints. From 1997 till 2004 major maintenance was necessary annually. Ravelling occurred especially in curves, at intersections and near parking places and the intense heavy traffic worsened these problems. As soon as the first stones were lost ravelling progressed rapidly. At one location the top layer had to be replaced within three years. On the other hand, at one location (only) the porous asphalt seems to function satisfactory after several years and it is estimated that the technical life-time there will be about seven years.

With respect to noise reduction, normally, an initial noise reduction of 4 dB was obtained for light vehicles at 50 km/h[43]. A loss of this reduction of around 2 dB over 5 years was considered as acceptable in the contracts that were established. When this requirement was not met, the contractor had to undertake some measures to restore the noise reduction.

These experiences in Groningen seem to be a little less positive than reported in the previous section. The reason may of course be the intensity of traffic, heavy vehicle content and the number of critical locations such as intersections, curves and parking bays. Nevertheless, the Groningen experience seems to have been a little more positive with respect to the loss of noise reduction, as it was considered to be around 2 dB per 5 years, as opposed to the previous sub-chapter in which 3 dB per the first 3 years was reported.

The other low-noise road surface option was thin layers. The first test with a thin layer surface took place in 2000. The initial noise reduction was found to be 3 dB. Later, the noise reduction decreased by 1 dB per year. At this moment (2008) there is no more noise reduction; however, the surface is technically still in good condition and will probably last some years more.

[43] Compared to a virtual Dutch reference surface being an average of DAC 0/8, DAC 0/11 and DAC 0/16.

Fig. 9.11. Parkwegviaduct in Groningen, paved with noise-reducing thin layer. From [van Keulen, 2008].

In 2002, the first *semi-dense* thin layer was applied on a Groningen road. The initial noise reduction was 3.8 dB. It was expected that such a surface would show better resistance against wear because of the lower air voids compared to porous asphalt. In practise this was found to be the case and, moreover, the noise reduction remained more or less equal. In 2003, on two other roads, semi-dense thin layers were applied and, again, the noise reduction showed only a minor deterioration. Apparently, product development had been successful in improving the quality.

In 2004 it was decided to replace double-layer porous asphalt surfaces at three locations by a thin *open* layer with a (C_{road}) labelled noise reduction of 4.3 dB. This thin layer had air voids almost as high as porous asphalt but was much thinner. The first measurements showed that the actual noise reduction was equal to or better than that of double-layer porous asphalt. In 2004, at four other locations thin layers were applied. The initial noise reduction was 4.6 dB at all these locations.

Financially, the comparison of double-layer porous asphalt (TLPA) and thin layers is very interesting. While the construction cost for TLPA is at least two times the cost of conventional asphalt, the construction cost for thin layers is a little higher than for conventional asphalt. Thin layers cost approximately EUR 17 per m². The smaller amount of material needed due to the thin surface means reduced cost, but the used aggregate and binder are substantially more expensive, so the result is a net increase in cost; albeit not at all as high as for TLPA. Maintenance costs (not requiring repaving) of thin layers are similar to those of conventional asphalt. When it comes to life-cycle costs, TLPA are known to require a lot of maintenance and replacement earlier than conventional asphalt. For example, porous asphalt needs to be cleaned two times per year in order to reasonably maintain its drainage. In Groningen, it was considered that every five years the top layer had to be replaced. For thin layers, producers indicate that the life-time is 8-10 years, which corroborates the latest Groningen experiences. Product development of thin layers continues and a life-time of 10 years now seems realistic for some of the newer products.

It is concluded that in Groningen, double-layer porous asphalt has not been a success. Thin layers appear to be a better alternative. The first years of experience with thin layers in Groningen are positive and seem to confirm that the noise reduction remains longer and costs are lower than for porous asphalt. However, also thin layers are more expensive than conventional asphalt. Therefore, thin layers are only applied where it is necessary in order to meet legal noise requirements[44].

[44] The author is grateful to Mr Wim van Keulen who kindly allowed summarizing findings in this sub-chapter from a much longer manuscript that Mr van Keulen will publish later.

9.3.4 Experience in the City of Ede

The City of Ede in the central part of the Netherlands has been another forerunner in the application of low-noise road surfaces on local low-speed roads. The city has a population of 100 000. In April 2007, a total of 10 km of urban roads posted at 50 km/h were covered with ”quiet” surfaces. The low-noise road surfaces have been laid both on 50 and 70 km/h roads and streets in the central district but mostly along residential areas where traffic noise otherwise would reach unacceptable levels.

The use of TLPA has been found to be too expensive for the city; partly due to its problem with durability, partly with its high initial cost[45]. Therefore, the city has decided to use thin layers instead. They have found that the thin layers could be laid at a total cost of only 5 % higher than for conventional dense asphalt (DAC); however, recognizing that the lifetime will be shorter and thus increase the lifecycle costs somewhat more. For a DAC 0/16 the normal lifetime is considered to be about 12 years; for thin layers 8-10 years.

Normally, the city has not used thin layers closer to major intersections than 50 m. At and near the intersections, conventional DAC or SMA 0/11 is used, in order to avoid problems with ravelling due to high horizontal tyre forces. The thin layers have a thickness within the range 20-30 mm, usually 25 mm. The types used are proprietary thin layers such as Nobelpave from Dura Vermeer Infrastructure, Dubofalt from BAM Wegen b.v., and Microflex from Heijmans Infrastructuur.

The noise reduction is considered to be 3-4 dB at 50 km/h and 6 dB at 70 km/h and new condition. At the end of the lifetime, the noise reduction is typically down at 1-2 dB.

In 2007 the major thin layer sections included for example Klinkenbergerweg having posted speed of 50 km/h with a surface laid in 2006, see Fig. 9.12, and Kasteelenlaan with a surface laid in 2003 having posted speeds of 50 and 70 km/h. The latter one used the surface named Microflex 0/6, see further the next sub-chapter and Fig.9.14[46]. Kasteelenlaan crossed a major intersection where the Microflex surface had been extended over the entire intersection; see Fig. 9.13. Due to the large-area design of the intersection, the vehicles did not turn very sharply, the bends were only “moderately sharp”; yet it was a major intersection with moderate and mostly light traffic. This intersection showed no signs of abnormal ravelling for a 4 year old surface. Significant ravelling was observed only in one (straight) lane as a 20-40 cm wide patch near the joint to the other lane. This must have been a temporary problem with the paving machine. Some cracks due to the basecourse were also observed.

There was also another intersection in Ede paved with a 4 year old thin layer. This one was tighter and traffic there turned sharply at 90 degrees. A third intersection was planned to be paved with a thin layer in the summer of 2007.

Overall, the city was satisfied with the thin layers.

---

[45] All information in this sub-chapter, except where noted, was obtained during a study visit to Ede in April 2007 together with Hong Kong officials.

[46] The author and four Hong Kong officials had the opportunity to visit the thin layer sites in Ede in April 2007 and it was observed at Kasteelaan that at the joint to an adjacent SMA surface one could clearly hear a significant reduction of noise when vehicles travelled from the SMA to the Microflex surface or vice versa.

Fig. 9.12. Thin layer paved on Klinkenbergerweg in a central residential area in Ede; one year old when the photo was shot.

Fig. 9.13. Thin layer "Microflex" paved on Kasteelenlaan (crossing left-right) and its intersection with Koekeltse Boslaan and Veenderweg (in the camera direction) in a central residential area in Ede; four year old when the photo was shot. The lower part of the photo shows Keokeltse Booslaan with its older DAC in poor condition, with the Microflex taking over a few metres ahead. The photo was shot during low-traffic hour and at an occasion when no vehicles happened to disturb the cameraman (the author).

9.3.5 An example of a thin layer: Microflex

As an example of how a thin layer can be constructed with such amazing low-noise properties (noise reduction equal to or better than thick two-layer porous asphalt), a closer look at the Microflex surface will be made. Microflex is a proprietary thin layer constructed and offered by Heijmans Infrastructuur in the Netherlands, with a 6 mm version named Microflex 0/6.

Microflex 0/6 is qualified according to the C_{wegdek} procedure (see 17.3.3) to provide a noise reduction of 4.3 dB for light vehicles at 50 km/h, but also 3.9 dB at 40 km/h and 4.9 dB at 70 km/h [van Loon, 2006]. Some information provided at a study visit to Ede is listed here:

- Maximum aggregate size is 6 mm
- Thickness is approximately 20 mm
- Air voids content is approximately 13 %, when new

A photo of the texture of the surface is shown in Fig. 9.14. A comparison with an adjacent SMA 0/11 surface is shown in Fig. 9.15. Note how smooth and even the Microflex is on its uppermost part, with the larger stone faces directed upwards. Note also the difference between the maximum aggregate in the Microflex (6 mm) versus the SMA (11 mm).

Fig. 9.14. A close view of the surface of the "Microflex" thin layer, as paved on Kasteelenlaan in Ede; four year old when the photo was shot. The coin is 23 mm in diameter.

Fig. 9.15. The surface of the "Microflex" thin layer at the left, as paved on Kasteelenlaan in Ede; four year old when the photo was shot. The surface at the right is SMA 0/11.

The Microflex 0/6 surface in Ede was one of the first of this type to be laid [van Bochove, 2008]. It was designed to provide around 3 dB of noise reduction at 50 km/h. Later versions have been designed to provide 4-5 dB. The increased noise reduction is then achieved with thicker layer, higher voids content, and 2-4 mm aggregate instead of the normal 2-6 mm. The smaller aggregate size and higher voids content compromises structural durability. The type used in Ede, i.e. the first version (Microflex 0/6), provides an optimum balance between high durability and low noise, while the newer version (Microflex 0/4) emphasizes noise reduction more. For the older version, durability is sufficient even for light-controlled intersections and roundabouts, where it is already used at more severe locations than the one reported in Ede. The total length of Microflex pavements presently is around 200 km [van Bochove, 2008].

There are two features which explain why the surface can get such a nice texture, which seems to be close to the optimum low-noise texture, namely [van Bochove, 2008]:

- The flat surface of each stone facing upwards is created by rolling operation, but is enabled by using a special type of crushed stone. The stones are crushed in order to give one relatively large flat surface, which is achieved by a special shear operation, rather than just crushing.

- The open texture is produced by a gap-graded sand (obtained from the sea), which does not include sand in the fraction 0.5-2 mm. In this way the volume between the chippings is not filled totally, but is left rather open.

9.3.6 Porous asphalt versus thin layer: Comparison

The explanation in the previous chapter about the design of modern advanced thin layers is illustrated in Fig. 9.16. The left part illustrates a common porous surface, which is thick (commonly 70-80 mm) and has a relatively high air voids content (20-25 %). It also uses a small aggregate in the top layer to reduce the vibration excitation input to the tyres. These features give such porous surfaces excellent low-noise characteristics. However, it is sensitive to clogging of the voids and to ravelling.

The right part of Fig. 9.16 illustrates a modern very advanced thin layer design (Microflex or corresponding) which has only a thin layer (20-30 mm, but even thinner exists) and a semi-porous structure (10-20 % voids). These two features should be far from sufficient to give the surface a high noise reduction, and clogging would rather fast reduce its efficiency. However, the use a very special aggregate with high flakiness and with the flat surface turned upwards, will create a smooth surface for the tyres to roll on, and thus vibration excitation will be minimal. Also the air pumping will be fairly low since the spaces between the chippings on the surface will provide reasonably good air drainage. The major deterioration with time would be the clogging in the layer which quickly eliminates the sound absorbing effect but if ravelling can be kept low (which is usually the case) the other characteristics should not change very fast. But to keep the chippings in their position over a longer time and without ravelling requires a very strong binder. Since the surface is less open to air penetrating down into the structure, the oxidation of the binder will be less than for the porous asphalt. Such thin layers are not so likely to be durable in a region where studded tyres in winter time would knock loose the chippings.

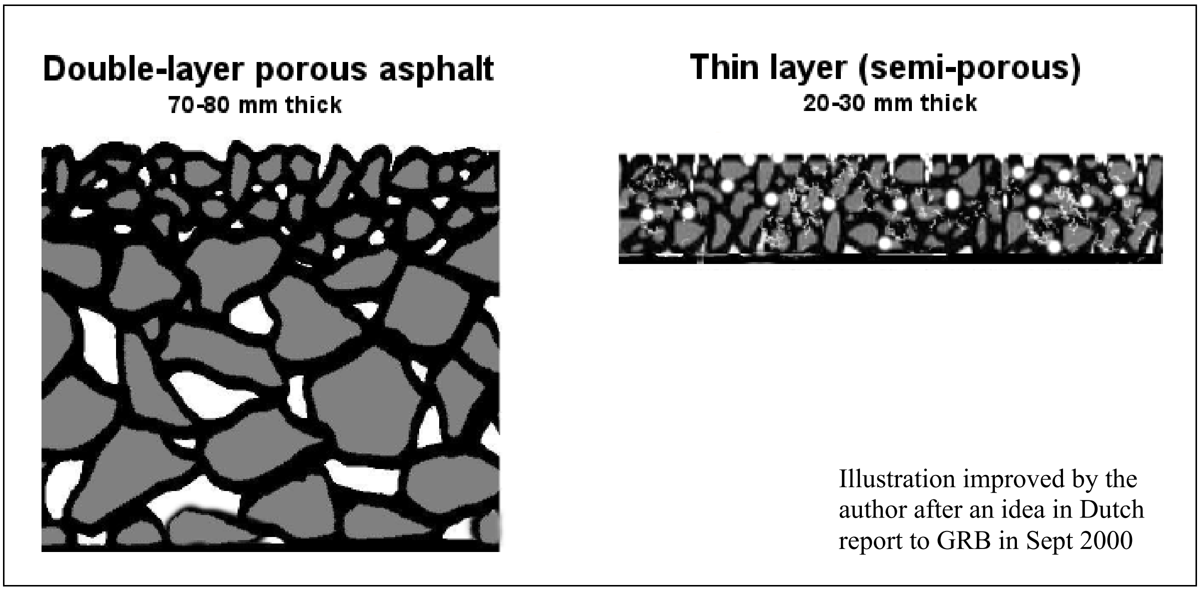


Fig. 9.16. Illustration of the structure of porous asphalt and advanced thin layers.

Such advanced features may explain why some thin layers in Europe provide an amazingly high noise reduction: i.e. their texture is very well optimized for low vibration excitation while at the same time providing an effective drainage to reduce the air pumping mechanism. This of course makes these surfaces rather expensive despite they are so thin, by requiring very special aggregates and binders and more careful paving operations than usual.

9.4 Selected observations from site visits during HK study tour

As part of the study tour in April 2007 to the Netherlands for officials from Hong Kong (see appendix), several site visits were made. A few selected observations from these which are not already presented are reported below.

Ordinary SLPA and TLPA on high-speed roads: The group saw several sections of SLPA of various ages; in fact most of the motorway driving was on SLPA. Most parts were in good condition but some old sections on A50, probably 10 years or older, showed very severe ravelling. There were also several examples of TLPA sections that were passed; with few exceptions they were in good condition. At one place there was a repaired patch of TLPA within a larger area of TLPA.

Porous asphalt in a roundabout, and recycling: Immediately after exit 27 of motorway A12 at Velperbroek in Arnhem there is a roundabout with a large radius, 150 m according to Google Earth, above which the A12 runs. This roundabout originally was paved with double-layer porous asphalt which has been recycled and the top layer exchanged two years ago. Consequently, the present surface is TLPA, probably with max. 8 mm aggregate in the top layer. The roundabout carries high volumes of mixed traffic. This gives an idea of the resistance to ravelling of a TLPA for a case of turning traffic with a moderate-to-high curve radius. The group circled in the roundabout several turns but could not notice any serious deterioration of the surface. See Fig. 9.17. However, there was some ravelling, although not serious but perhaps a little more than normal, on a straight section of the same age. At one place, oil spillage had caused a track of clearly noticeable ravelling. The case shows that at least for a moderate curve radius TLPA is reasonably durable. It also shows that replacing the top layer is feasible.

Fig. 9.17. Roundabout in Arnhem paved with a TLPA surface and still in good condition 2007.

Structural strength of porous versus dense asphalt concrete surfaces: An expert who guided the HK team during the site visits, Mr Jan Voskuilen, said that the Dutch consider the porous asphalt surfaces as having about 80 % of the structural strength of a corresponding dense asphalt layer. Normally, therefore, it is not necessary to lay a strengthening extra layer under a porous surface to compensate for its porosity.

Rollpave: By expert guidance by Mr Robbert Naus, driving force behind Rollpave, the study group visited the location of the full-scale experiment with Rollpave on motorway A35 near Hengelo. The section, one year old at the occasion, appeared to be in very good condition, and it was easy to hear the measured difference of around 4 dB when vehicles passed over the joint between the Rollpave and the adjacent SMA surface (when there were no vehicles in the opposite motorway direction). See Fig. 9.18.

Fig. 9.18. Rollpave, as applied in June 2006 in one direction of the motorway A35 near Twente Canal in Hengelo. Photo shot in May 2007 by the author. The joint in the bottom part of the figure is the end of the Rollpave section.

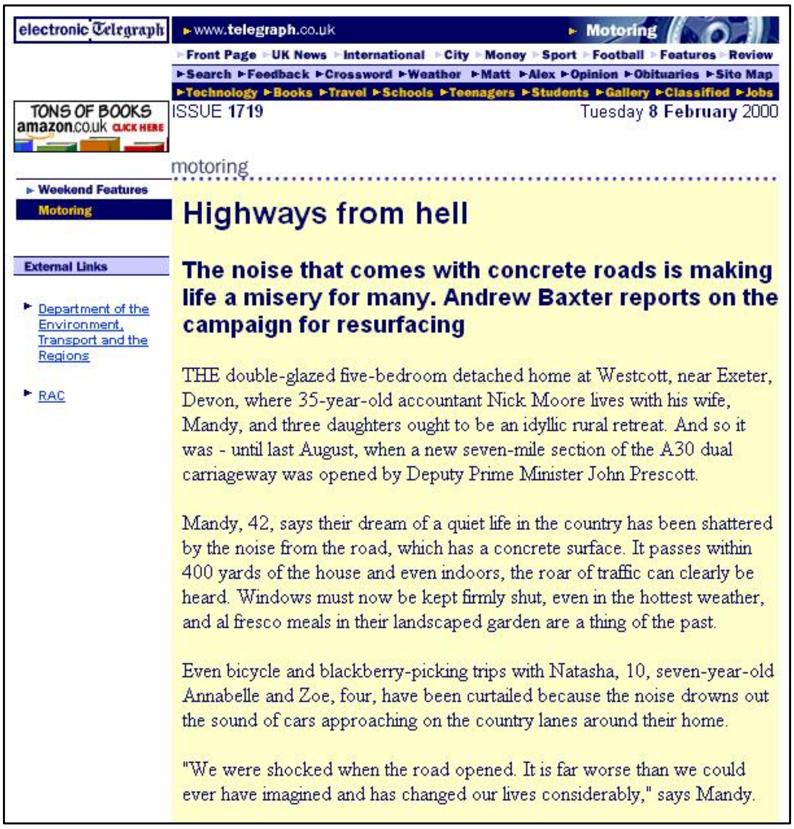
Modieslab: A 100 m test section of this surface had been laid on the A12 motorway near Utrecht in the summer of 2006, which the group drove over. It was unsafe to stop there so only a quick glance could be made. The surface appeared to be in good condition. See Fig. 9.19. The group also visited the site at where Modieslab was tested on the road the first time in 2001; which was on the entrance road from a rest area Ravenstein to motorway A50.

Fig. 9.19. Modieslab, as applied in the summer of 2006 in one direction of the motorway A12 near Utrecht. Photo shot in May 2007 by the author. The Modieslab section which is 100 m long is the lighter one on this side of the bridge.

10. EXPERIENCE IN THE UNITED KINGDOM

10.1 Some historical notes – British forerunners regarding low-noise road surfaces

Traditionally, the most common road surface in the U.K. has been the hot rolled asphalt (HRA) in which chips are added on the surface, either pre-coated with binder or not. In chipped HRA wearing courses, the nominal single size coarse maximum aggregate varies between 14 and 20 mm. On motorways, cement concrete has been used. Since the UK road administrators traditionally have been worried about poor skid resistance; especially in wet weather on high-speed roads, it has been the policy to accept road surfaces only with a high macrotexture depth. This has been one reason why the HRA surface has been so popular, but it has also meant that cement concrete roads have been textured by lateral treatments such as brushing and tining, which used to create "noisy" road surfaces. Fig. 10.1 shows one example of the very strong reactions that may be caused by such surfaces.



electronic Telegraph ▸www.telegraph.co.uk ▸ Motoring

Front Page ▸UK News ▸International ▸City ▸Money ▸Sport ▸Football ▸Features ▸Review ▸Search ▸Feedback ▸Crossword ▸Weather ▸Matt ▸Alex ▸Opinion ▸Obituaries ▸Site Map ▸Technology ▸Books ▸Travel ▸Schools ▸Teenagers ▸Students ▸Gallery ▸Classified ▸Jobs

ISSUE 1719 Tuesday 8 February 2000

TONS OF BOOKS amazon.co.uk CLICK HERE

▸ Weekend Features
Motoring

External Links
▸ Department of the Environment, Transport and the Regions
▸ RAC

motoring

Highways from hell

The noise that comes with concrete roads is making life a misery for many. Andrew Baxter reports on the campaign for resurfacing

THE double-glazed five-bedroom detached home at Westcott, near Exeter, Devon, where 35-year-old accountant Nick Moore lives with his wife, Mandy, and three daughters ought to be an idyllic rural retreat. And so it was - until last August, when a new seven-mile section of the A30 dual carriageway was opened by Deputy Prime Minister John Prescott.

Mandy, 42, says their dream of a quiet life in the country has been shattered by the noise from the road, which has a concrete surface. It passes within 400 yards of the house and even indoors, the roar of traffic can clearly be heard. Windows must now be kept firmly shut, even in the hottest weather, and al fresco meals in their landscaped garden are a thing of the past.

Even bicycle and blackberry-picking trips with Natasha, 10, seven-year-old Annabelle and Zoe, four, have been curtailed because the noise drowns out the sound of cars approaching on the country lanes around their home.

"We were shocked when the road opened. It is far worse than we could ever have imagined and has changed our lives considerably," says Mandy.

Fig. 10.1. News article in British press about extreme noise from a just opened high-way with a "noisy" cement concrete surface.

The problem was recognized very early; especially when the texturing was made with uniform spacing between grooves or tines. The uniform spacing creates a single-tone sound which is usually perceived as extremely annoying. In fact, one of the earliest documents the author has collected on tyre/road noise deals with this problem in the U.K. and was published already in 1971 [Maynard & Lane, 1971]. They concluded that due to noise impact "...it is strongly recommended that transverse grooves, whether formed in plastic concrete or sawn in hardened concrete, should be so arranged that their frequency varies in a random manner". They recommended the spacing between 6 mm wide grooves to vary from 20 to 60 mm.

A typical HRA surface, as used extensively in London and in the whole of England, is shown in Fig. 10.2 in medium worn condition. It is easy to imagine that the large chippings (looks like it may be a 20 mm max aggregate size) and the way they protrude above the base, as well as the relatively large spaces between the chippings and the totally dense surface, cause substantial vibration excitation to the tyres while failing to providing escape channels for air pumping noise.

Fig. 10.2. A typical HRA surface in medium worn condition; the one on this photo being the main surface on Oxford Street in central London. The coin is £1 with a 22 mm diameter.

The British are keen to tell that the porous asphalt surface was invented in the U.K.; albeit it was at that time with the intention to increase safety and not to reduce noise. Applications of porous surfaces were made in the 1960's to military airport runways in the UK and the USA, in order to reduce the risks of hydroplaning. Road trials were made in the early 1970's in the U.K. In contrast to most other countries, the porous asphalt used in the U.K. in the 1970's and 1980's usually had large chippings, 16 or 20 mm max aggregate size, which did not provide a great noise reduction initially, but maintained the noise reduction longer than the surfaces with smaller aggregates.

It is also another historical fact that possibly the first attempt to design and test a low-noise road surface was made in the mid 1970's in England. The pioneers seem to have been researchers at Birmingham University and Fort Dunlop in Birmingham. As early as in 1974, a special surface termed Delugrip that was reported to reduce vehicle cruise-by noise by 3 dB was mentioned [Walker & Major, 1974]. This surface used the principle of texture optimisation and skew as presented in [Sandberg & Ejsmont, 2002]. A look at its texture profile (Fig. 10.3) illustrates its positive properties.

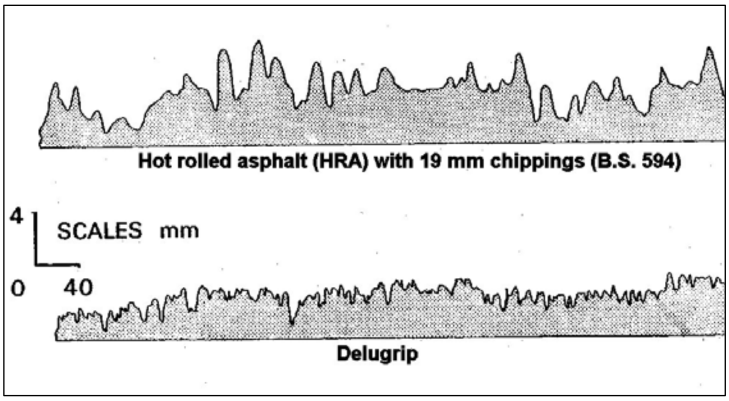


Fig. 10.3. Comparison of texture profile curves of the "normal" UK motorway surface HRA and the Delugrip. Figure edited by the author, based on figure in [Walker, 1981].

The first important feature is the much smaller distance between the peaks of the profile. Although no texture spectrum has been calculated it is obvious that the Delugrip texture spectrum would have much lower levels than the HRA at long wavelengths but probably the contrary at the shorter wavelengths. The second important feature is that the profile of the HRA has a positive skew (texture is "directed upwards", while the Delugrip has a negative skew (texture is "directed downwards").

This surface was applied in 1975 on a major medium-speed road in London, called the Hammersmith fly-over, which is an elevated motorway still in operation (but with another surface). An illustration of the noise-reducing effect appears in Fig. 10.4. It was also laid on a great number of other U.K. sites. In the early 1980's it was also tried in Sweden within a number of test sections checked by VTI. The Swedish result was rather similar to the U.K. experience if the same reference surface was considered.

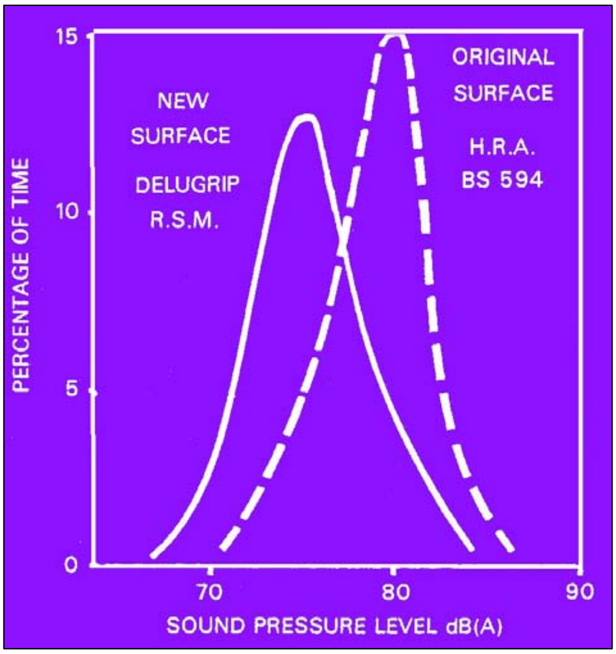


Fig. 10.4. Traffic noise level histogram, measured on the Hammersmith fly-over in London before and after resurfacing the existing HRA surface with Delugrip. Diagram from [Walker, 1981], edited by the author.

Delugrip was a trademark of Dunlop Ltd. It was awarded a "Design Council Award" in 1977. This surface type was marketed as a noise-reducing surface; also outside the U.K.

Due to noise concerns, the U.K. policy is nowadays changing in favour of using SMA and thin layers. With regard to using low-noise porous surfaces, the U.K. policy has been very conservative. Presently, the policy is as follows:

- Porous asphalt is not allowed on high-speed roads (speed limit 70 mph, 113 km/h).
- Porous asphalt is allowed on roads with lower speed limits, but actually used to a very small extent.
- There are some experimental sections of porous asphalt.
- The maximum chipping size in porous asphalt used to be 16-20 mm.
- Thin layers are often preferred to porous asphalt as a "low-noise" surface (provided they are approved according to the HAPAS procedure, see below)

The Highways Agency controls the high-speed roads but controls very few low- or medium-speed roads. The local councils who control all other roads than those of the Highways Agency (which can include some high speed roads) tend to follow the Highways Agency in surfacing policy as they do not do any research themselves.

10.2 Some British studies of road surface noise properties

Based on early studies of noise properties of road surfaces, the U.K. model CRTN for traffic noise prediction, includes a correction table for road surfaces. In CRTN, the correction is expressed as in Table 10.1 [UK DoT, 1988]. It means that the CRTN, here called CRTN1988, needs access to a measured or predicted texture depth.

Table 10.1 Road surface correction according to the U.K. prediction model CRTN. From [UK DoT, 1988].

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

for concrete surfaces

Correction = 10 Log (90 TD + 30) - 20 dB(A);

for bituminous surfaces

Correction = 10 Log (20 TD + 60) - 20 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."

Some years ago, the CRTN1988, was subject to a study with the aim to update the road surface correction [Abbott & Nelson, 2001]. From this study a recommendation was made (for high-speed roads) which is copied in Table 10.2. A later study extended the previous one to low-speed roads [Abbott et al, 2003]. The final result is summarized in Table 10.3.

Whenever introducing new surfaces, a special procedure must be followed to determine the proper correction for these in CRTN. This procedure is outlined in [Abbott & Nelson, 2001].

A compilation of early measurements made according to the HAPAS procedure (high speeds) appears in Fig. 10.5 (see description of the HAPAS scheme in Chapter 17.4.2). The major surface families are indicated as ranges on the RSI_H scale. The ranges illustrate the spread between surfaces within the family. The red indication of "-2.5" is to mark the U.K. minimum requirement for being considered as a "Quieter surfacing".

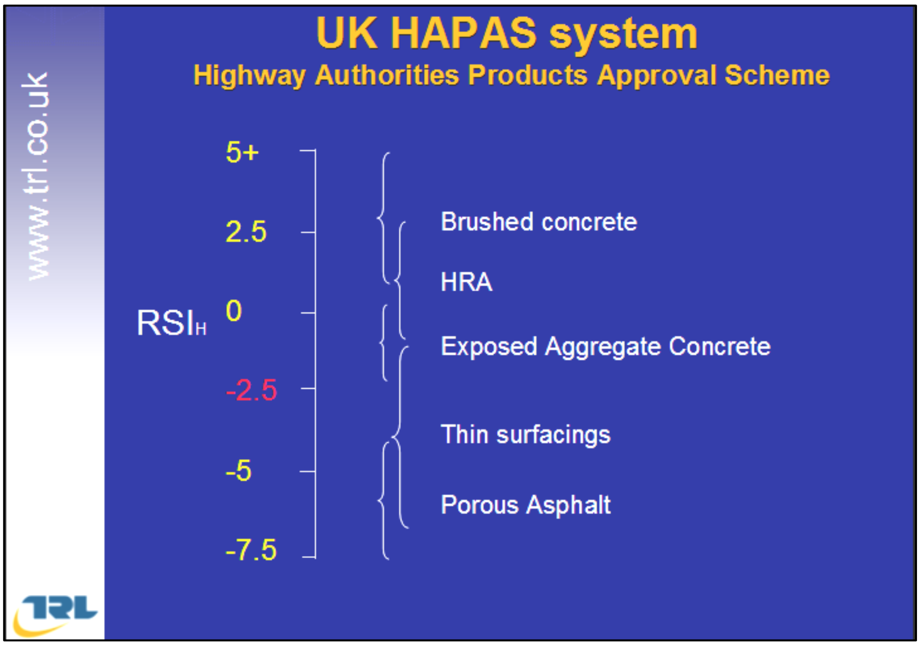


Fig. 10.5. Noise levels of British surfaces, in dB on the RSI_H scale, according to early measurements in the HAPAS approval schemes. Compilation made by TRL Ltd; diagram from [Stait, 2002].

The tables clearly show the negative acoustic properties of the HRA and how much can be gained just be shifting to SMA. It is also worth noting that the Exposed Aggegate Cement Concrete (EAC or EACC) is a better alternative to the brushed concrete. Note especially that on low-speed roads with 30 mph or less posted speed, the difference between the HRA and the thin surfacings is 9 dB! The author finds this remarkable and it is possible that the difference is a little overestimated by the particular measurements on which the table is based.

Evidently, it is interesting to explore more the use of thin layers for noise reduction; especially on low-speed roads.

Table 10.2 Suggested update to the CRTN1988 road surface correction, for high-speed roads [Abbott & Nelson, 2001]

Roads not subject to a speed limit of less than 60 mph.

Different corrections are applied according the type of surface. Table A1 describes the different surface categories and the corresponding corrections to apply.

Table A.1. Surface correction for roads not subject to a speed limit of less than 60 mph

Surface type (aggregate maximum size)	Surface correction for different road types dB(A)	
	Motorways	Non-motorways
Hot Rolled Asphalt (20mm HRA)	+1.8	+2.3
Stone Mastic Asphalt (14mm SMA)	-2.4	-2.8
Porous Asphalt (20mm PA)	-3.9	-3.6
Exposed Aggregate Concrete (11mm EAC)	-0.3	-0.3
Brushed Concrete (BC)	+1.8	+1.9

Roads subject to a speed limit of less than 60 mph.

1 dB(A) should be subtracted from the Basic Noise Level for all surface types.

Table 10.3 Suggested update to the CRTN1988 road surface correction, for low-speed roads [Abbott et al, 2003].

Table 5.3: Surface correction for low speed roads

Surface Type	Surface correction for roads with different speed limits dB(A)		
	50 mph or more than 30 mph		30 mph or less
	Dual	Single	All
HRA	+3.3	+3.2	+3.1
SD	+1.4	+1.0	+0.6
TS	-5.4	-5.5	-5.8
HF[1]	+0.3	+0.4	+0.2

[1] Corrections derived from SPB-BB method

Legend for Table 10.3:
Dual = dual-carriageway roads, Single = single-carriageway roads
HRA = Hot rolled asphalt, max aggr. size 14 mm
SD = Surface dressing (no more information given)
TS = Thin surfacing (called thin layer in other parts of this report), such as SMA (10 mm aggr. size), UL-M (10 mm aggr. size), Safepave (14 mm aggr. size) and Masterflex (6 mm aggr. size) surfaces
HF = High-friction surfaces, surface dressings with small max aggr. size, used at critical locations

10.3 *Early British experience of thin layers*

10.3.1 Early examples: Colsoft and Thinpave

A thin layer named Colsoft, developed by Colas in France, was used rather early in the U.K.. An example was Surrey. According to [Highways, 2001] the Surrey local transportation plan called for treatment of 100 km of road with low noise road surfacing before 2006. They at least initially selected the thin surfacing termed Colsoft that included a substantial rubber content. A 35 mm layer was laid in 1999 and a noise reduction of about 5 dB measured with the SPB method at 64 km/h was reported, in comparison to the normal U.K. HRA surface.

Another thin layer, which has been measured to have a very high noise reduction is Bardon Thinpave 10 mm, which has been measured in 2003 to have an RSI_H of -7.8 dB at an age of 30 months, tested on the A38 Devon Expressway at Heathfield in Devon [HAPAS H048, 2003]. It seems to have been used successfully as an overlay on an old cement concrete surface. A search on the web does not give many hits for this surface, but it is widely used and performs well, according to [Walsh, 2008]. For urban schemes, it uses a slightly different grading and more binder [Walsh, 2008].

10.3.2 Performance of thin layers in the United Kingdom

In 2004, a review was published of experience that far of the use of thin layers in the U.K. since the beginning of the 1990's [Nicholls et al, 2004]. This subchapter is a summary of this, which is essentially adapted from [Bendtsen et al, 2005]. In the paper by Nicholls and his co-authors, the pavements were divided into five types shown in Table 10.4.

Table 10.4 Pavement types as classified in [Nicholls et al, 2004].

Type	Short name	Comment
Paver-laid surface dressing	PLSD	Ultra-thin surfacing developed in France
Thin asphalt concrete	TAC	Generally with polymer-modified binder
Thin stone mastics asphalt	TSMA	Generally unmodified bitumen with fibres
Multiple surface dressing	MSD	Binder and aggregate applied separately
Micro-surfacing	MS	Thick slurry surfacing, generally with modified binder

A number of road sections with these pavement types were followed over a period of up to 12 years. Measurements of skid resistance by the SCRIM measurement vehicle, and texture depth by the sand patch method and laser methods were made. For the different aggregates used, the resistance to polishing (PSV) was determined and it was attempted to correlate skid resistance and the PSV measurements.

The result was a very poor correlation, which the authors explained by the fact that the variations in traffic and the site conditions can destroy any relationship. At the time of writing (2004), both the skid resistance and the texture depth for most of the sections indicated good performance of the pavements. Also, visual inspections by engineers from TRL were carried out. Table 10.5 shows the point scale used.

From the visual assessment, the tentative ranking of Table 10.6 was derived for the average service life until the thin layer reached three of the "medium" visual condition marks in Table 10.5. It appeared that the thin SMA and the thin asphalt concrete surfaces performed well.

Table 10.5 Basic 7-point scale for visual assessment [Nicholls et al, 2004].

Mark		Description	
E	Excellent	No discernible fault	Termed satisfactory
G	Good	No significant fault	
M	Moderate	Some faults but insufficient for serious problem	
A	Acceptable	Several faults would usually be just acceptable	
S	Suspect	Seriously faulted but still serviceable in the short term	Termed unsatisfactory
P	Poor	Requires remedial treatment	
B	Bad	Requires immediate remedial treatment	

Table 10.6 Average time to reach three of the visual conditions marks in the previous table [Nicholls et al, 2004].

Type of surface	Moderate	Acceptable	Suspect
Paver-laid surface dressing (PLSD)	4½ years	8 years	11½ years
Thin asphalt concrete (TAC)	7½ years	14½ years	25 years
Thin stone mastics asphalt (TSMA)	11½ years	-	-
Multiple surface dressing (MSD)	4 years	6 years	7½ years

10.4 Example of recent applications of low-noise thin layers

10.4.1 UL-M

The Ringway company is one of the major contractors using the UL-M family of surfaces. Developed in France by the company Eurovia, UL-M has proven its durability and versatility over the last decade in new-build and maintenance applications in England [Ringway, 2008]. UL-M's properties are claimed by Ringway to be:

- Durable – incorporates a polymer-modified binder
- Versatile – suitable for new construction or maintenance work
- Safe – high skid resistance and reduced spray in the wet
- Quiet – noticeably lower noise levels
- Economical – can be laid from 15 mm to 40 mm thick
- Driver-friendly – ultra-smooth riding quality

Rather than a single material, UL-M is a family of thin surfacings, all HAPAS approved[47] with the same tried and tested polymer-modified binder, Evatech. More than 14 million m^2 of UL-M have been laid at over 2,000 sites, ranging from urban roads to motorways such as the M25, M60 and A1/M1 Link in the U.K.. Assuming an average width of paved road of 14 m, this would amount to about 1000 km of road, which is quite a substantial length of road and should mean that it is one of the most used thin layers in the world.

[47] See Chapter 17.4.2 for more details about the HAPAS noise approval of UL-M.

10.4.2 Ultraphone

In November 2007, a 500 m section of the A26 road (Cornwallis Avenue) at Tunbridge Wells, a commuter route near Tonbridge in Kent (south of London), was repaved with a new thin layer called "Ultraphone"[48], which since then has received "rave reviews" by the residents along the road for being quiet[49]. This work in Tunbridge Wells is part of a countywide micro-surfacing contract awarded the road construction company Ringway [Modern Asphalt, 2008].

The posted speed was 40 mph (64 km/h), but actual speeds during noise measurements were around 50 km/h [Scott, 2007], and statements and photos in the article [Modern Asphalt, 2008] seem to suggest that it should be a two-lane (one per direction) "busy urban road" in a residential area. Traffic counts on this 2x2 lanes road has shown an AADT of 21 700 (predicted from actual counts in 2004), with 5 % heavy vehicles [Walsh, 2008]. Texture depth is around 1.2 mm.

Noise measurements were made a couple of weeks before repaving, on the existing old HRA surface, and on the new Ultraphone surface two days after paving works had finished. Supplementary measurements were made on an adjacent SMA surface. Results are reported in [Scott, 2007]. Measurements were made by the SPB method, but also as "shortened CRTN" measurements; i.e. continuously measuring the noise level over three consecutive hours of traffic exposure and calculating the L_{A10} level.

The results are summarized in Table 10.7. The references were an HRA 35/14 with 20 mm aggregate and an SMA with 10 mm aggregate size; both with a texture depth around 1 mm [Walsh, 2008]. It is not a big issue that the SPBI and the CRTN measurements give slightly different results, since they are made with slight differences in vehicle composition and with different measuring principles. The author thinks that it is likely that part of the high noise reduction (maybe 1 dB) is due to measurements being made already two days after resurfacing. If one would distinguish between light and heavy vehicles, such as is made on SPB measurements, the noise reduction of Ultraphone would be approximately halved for heavy vehicles, but increased by approximately 2 dB for light vehicles, as compared to the overall SPBI levels. This may be due to a combination of contribution by unchanged and unaffected power unit noise from the heavies and a lower sensitivity to road macrotexture of truck tyres. In summary, compared to a nearby section of recently laid conventional SMA surface (the age difference may have been unimportant in this case), overall noise levels were reduced by 5-6 dB according to these measurements.

Table 10.7. Results of noise measurements, as reported in [Scott, 2007] and additional information from [Walsh, 2008].

Surface type, aggr.size, and age	Notes	Noise level (SPBI)	Noise level (L_{A10})
HRA 20 mm (several years old)	A26 before repaving	72.5 dB	73.9 dB
SMA 10 mm ("recently laid")	Site on adjacent road	71.6 dB	72.4 dB
Ultraphone 6 mm (2 days old)	A26 after repaving	66.8 dB	66.0 dB
Noise reductions			
Noise reduction of Ultraphone vs HRA		5.7 dB	7.9 dB
Noise reduction of Ultraphone vs SMA		4.8 dB	6.4 dB

[48] The author believes that this was originally a UL-M but with the steel slag aggregate it was renamed to Ultraphone. The latter does not yet appear to be HAPAS-approved.
[49] The main part of the information about the Ultraphone surface is taken from [Modern Asphalt, 2008].

The noise reducing properties of the Ultraphone surfacing are due largely to the 6 mm single size aggregate, derived from slag sourced from a nearby steelworks [Modern Asphalt, 2008]. Around 78 % of the Ultraphone thin surfacing material content is steel slag, to which crushed rock fines are added, along with a polymer modified bitumen binder. The slag particles are sharp and angular, giving the asphalt a high void content and an open texture that helps to absorb tyre/road noise. It also helps to meet targets of using recycled materials and is expected to provide a very durable surface. The Ultraphone is 22 mm thick as most thin surfacings with 6 mm aggregate and needs a strong and even base, such as an SMA surface on which a so-called Gripclean bond coat is used to ensure a strong bond between the layers.

An earlier version of this thin surfacing material was laid on a section of the Oxford Ring Road around the city of Oxford seven years ago [Modern Asphalt, 2008]. Road traffic noise dropped and led to research into ways in which further noise reduction could be achieved. Use of steel slag in the latest generation of the material has, according to Ringway, had the desired effect.

10.4.3 Thin layers partly made of recycled materials

Thin surfacing materials require greater use of high-specification aggregates than traditional materials and the available reserves in the UK are diminishing. The Ultraphone surface mentioned above is an example of a thin layer using recycled material. However, more commonly, reclaimed asphalt offers major cost savings for road construction, and trials by TRL Ltd to recycle asphalt have shown that it is feasible to recycle thin asphalt into new thin surfaces with up to 30 % reclaimed asphalt, as long as the plant is able to add the milled material [World Highways, 2008]. However not all asphalt plants are capable of adding this proportion and more stringent testing needs to be adopted when increasing the amount of reclaimed asphalt to be added to the mixture, particularly in terms of how to treat the residual binder. There is a need for more design guidance, particularly with regard to the quantity and grade of binder to be added, however the findings from the trials are now being used for a best practice guide.

10.4.4 MASTERpave

Another example of a recycling project, resulting in a pioneering thin layer is a Highways Agency project conducted jointly by companies Tarmac and Mouchel, in which 800 tonnes of existing porous asphalt road surface has been recycled to constitute 25 % of a new road surface called MASTERpave, having a 14 mm max aggregate size [Mouchel, 2007]. This surface was laid over an area of 30 000 m^2 at “junction seven” on the busy M25 motorway near Redhill in Surrey.

MASTERpave is a thin surfacing system for highways, approved by HAPAS, used in connection with a polymer-modified bond coat “Mastertack” to enhance the adhesion to the substrate and laid in thicknesses of 20 to 40 mm [MASTERpave, 2001]. There are at least four versions of different grading: with 6 mm, 10 mm, 14 mm and 20 mm maximum aggregate size. The HAPAS certificates show that MASTERpave 14 mm gave a noise level RSI_H of -3.7 dB at an age of 2 months, while the other versions do not seem to have be tested with respect to noise.

10.4.5 UL-M and other thin layers laid in Central London

The Transport for London Road Network (TLRN) accounts for about 5 % of London's roads but carries 33 % of London's traffic. London's 33 local authorities manage the other roads, apart from motorways, which are the responsibility of the Highways Agency. Traditionally, the surface used in London has been HRA with maximum 14 or 20 mm chipping size. However, in the last 10 years, SMA surfaces have gained in popularity; not the least the version with 10 mm maximum chippings. Noise is a consideration in the design and choice of pavement materials which has been one reason why the HRA surface type is rarely laid any more.

TLRN has also used the proprietary UL-M thin layer as approved by HAPAS for a few years; possibly also some other thin layers. There have been problems with all thin surfacings, particularly in high stressed areas where they have been laid in small areas or by hand [de Souza, 2008]. Nevertheless, the London Asphalt Specification (see subchapter 10.7) states that if the pavement has been properly designed, and it is avoided to lay the surface by hand, there should not be any durability problems with thin surfacings.

The author has during recent visits studied an application of UL-M 10 mm at a very central location in London where traffic stresses are severe. This location is where Cumberland Gate meets Bayswater Road at Marble Arch. A newly laid UL-M 10 mm surface covers Cumberland Gate and the eastern 100 m of Bayswater Road until the latter intersects with Edgware Road; and extends about 50 m in on Edgware Road too. On part of the surface, vehicles stop and go at a light-controlled intersection, and there are also considerable side forces due to turning vehicles. There are many heavy London busses passing this very busy location.

The surfacing was laid during the second week of March. Figs. 10.5-10.6 show photos from the following week. Note the alignment of the top aggregate with usually the largest flat surface facing upwards; yet a rather open texture, almost looking as porous asphalt. An SMA 10 mm would probably look a little similar. So far, only half of the junction has been resurfaced. The second portion is programmed to be paved in the mid to late summer 2008 [de Souza, 2008].

The next two photos, Figs. 10.7-10.8, show the surface three months later (June 2008) after a substantial rainfall. Evidently, this rainfall has saturated the semi-porous surface with water. The photo in Fig. 10.8 was taken near the kerb where water had collected and almost covered the surface asperities. There were a few drains along the kerbstones but they were too far apart to be able to drain away the water from standing on the surface.

It can be concluded that in times of rainfall with intensity sufficient to saturate the wearing course, the UL-M surface is ineffective. It was impossible for the author to hear a noise reduction when vehicles drove over from the adjoining HRA surface to the UL-M in this condition. In dry condition when the author was there, a slight noise reduction could be heard when listening carefully to passing light vehicles, but no difference was audible for passing heavy vehicles. It must be recognized that the location is unsuitable for hearing small noise differences due to the noise from all heavy busses on Bayswater Road and Oxford Street masking the noise of the passing vehicles.

No damages such as ravelling could be seen at any of the visits (March and June 2008).

Fig. 10.5. UL-M thin layer in new-laid condition in March 2008 at Marble Arch (at north-eastern corner of Hyde Park). Note the controlled stoplight at the bus, where vehicles stop and go. The wet track behind the light truck is leakage from a previously passing truck.

Fig. 10.6. Surface close-up view of the UL-M thin layer with maximum 10 mm aggregate size in new-laid condition in March 2008 at Marble Arch in London. Coin diameter is 22 mm.

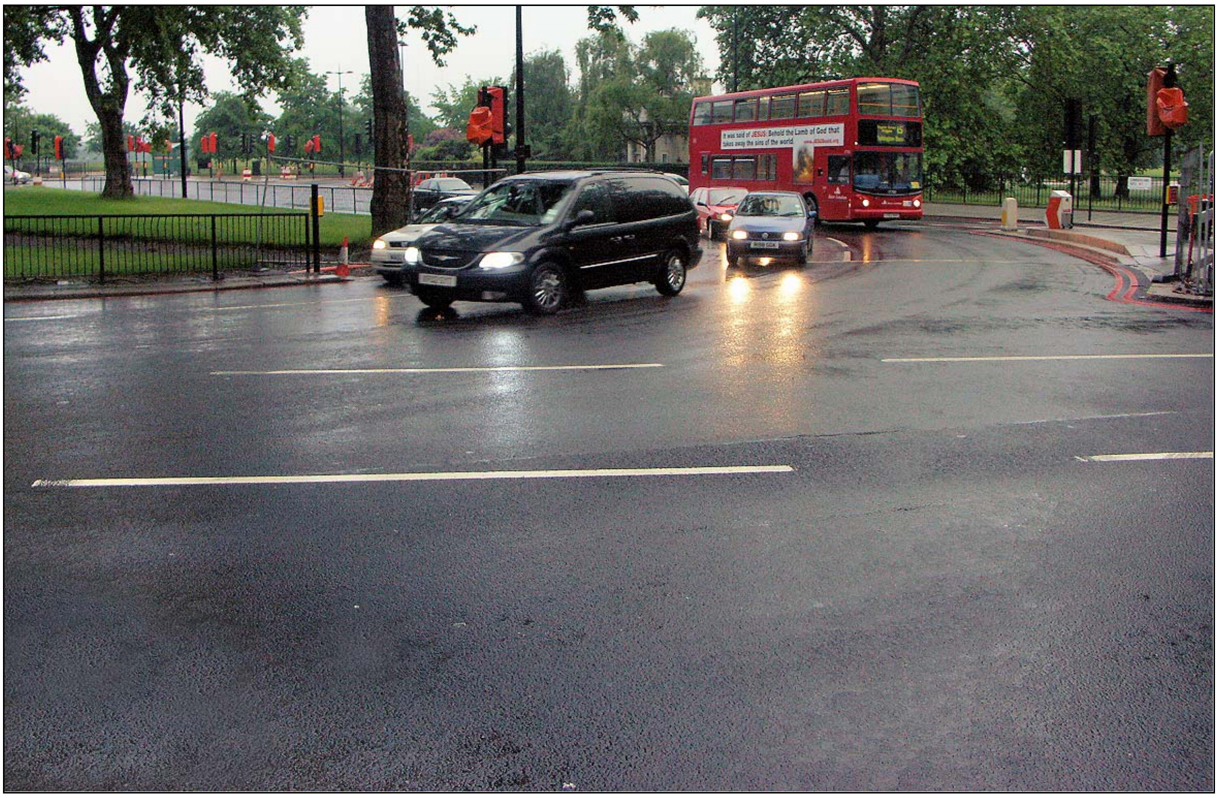


Fig. 10.7. UL-M thin layer three months old (June 2008) at Marble Arch in London, after rainfall. Note the stoplight where vehicles stop and go. Same location is in Fig. 10.5.

Fig. 10.8. Surface close-up view of the UL-M thin layer with maximum 10 mm aggregate size at Marble Arch, three months old in June 2008, after rainfall. Same scale as in Fig. 10.6.

10.4.6 Thin layer laid in Feltham near Heathrow Airport

Recently, the authior noticed a low-noise surface, very similar to the UL-M 10 mm, laid in an urban location in Feltham, on the A312 which is an access road to Terminal 4 at London Heathrow Airport (LHR) running through a residential area in Feltham. According to a local taxi driver, the surface was laid in May 2008. The subjective impression was that the surface was clearly effective in reducing tyre/road noise. One end of the low-noise section is at the light-controlled intersection with A30, running to LHR. The surface extended over the busy intersection where speed limit was 40 mph. The A321 at this location had a posted speed limit of 40 mph (64 km/h) and there were two lanes in each direction, widening at the intersection with to up to five lanes (of which three were turning lanes) in one of the directions. Figs. 10.9-10.10 illustrate a part of this low noise road section.

Fig. 10.9. Low-noise surface on A321 through residential area in Feltham near Heathrow Airport; being access road to air cargo and Terminal 4 at the airport.

Fig. 10.10. Low-noise surface on A321; closer look at the texture (surface a few weeks old).

10.5 High friction surfacing (HFS)

High friction surface (HFS) treatments are ultra thin layers based on a variety of binders, both thermosetting and thermoplastic which are intended for application where a higher level of skid resistance than elsewhere is required. Depending on the type of binder, high PSV[50] aggregates - most commonly chippings of calcined bauxite approximately of the size 1-3 mm - are either broadcast over a pre-applied binder film or pre-blended with binder, and the mixture applied. For large areas this process is normally machine applied but resins capable of being mixed and applied by hand are now available. The resin binders used at present for broadcast systems are epoxy, polyurethane and acrylic all of which are thermosetting. The binders used for screeded systems are rosin esters which are thermoplastic [HD 37/99, 1999]. The thermoplastic resin and calcined bauxite aggregate is premixed in poly bags and then heated in a large "boiler" to the required temperature. The calcined bauxite aggregate is usually imported from China or Guyana. A concern has been recent price increases in China.

The HFS treatments are not primarily intended for noise reduction, but it has been found that they may as a bonus provide a substantial noise reduction if they are laid on a smooth basecourse. The mechanism is a macrotexture with peak energy at texture wavelengths of 4-5 mm, which has been found to be favourable for noise reduction [Sandberg & Ejsmont, 2002].

Situations that may require HFS treatment are approaches to pedestrian crossings[51], and some junctions, islands and bends; especially if combined with a downhill grade. It is also common to apply a similar treatment to the surface of bus stop bays. Such sites need the highest possible skid resistance available and the surface must be able to withstand very high lateral tyre/road forces; for example from braking or accelerating busses and trucks.

HFS treatments are very common in the UK. Figs. 10.11-10.13 show a couple of examples pictured by the author.

Fig. 10.11. HFS treatment on bus stop bay on Edgware Road in central London. Coin 22 mm.

[50] PSV = Polished Stone Value; measure of friction provided by individual stones and their resistance to polishing
[51] In the UK and Ireland referred to as Pelican Crossings

Fig. 10.12. HFS treatment on bus stop bay on Edgware Road in central London.

Fig. 10.13. HFS treatment “Tyregrip” on bus lane on motorway M4 from Heathrow Airport to London.

HFS treatments are recommended only if they are HAPAS approved and laid by companies responsible for such approval. Some HAPAS-approved HFS treatments are named Suregrip, Spraygrip, Safetrack, Duragrip, Truegrip and Tyregrip. The latter has also been applied on Sydney Harbour Bridge in Australia and on one of USA's busiest interstate roads, known locally as 'death alley'. This is the I75/I85 connector ramp, north of downtown Atlanta, Georgia, which has a difficult camber, regularly causing motorists to misjudge the bend and run off the highway.

Other similar surfaces, not HAPAS approved, include for example Shellgrip and EP Grip. Another surface of the same type, albeit not HAPAS approved, but used in Italy and USA is Italgrip, consisting of milled steel slag aggregates (1-4 mm) bound in a layer of epoxy resin [Sandberg & Ejsmont, 2002].

As far as the author has found, no noise measurement has been published for a HAPAS approved HFS treatment.

10.6 The most recent research on low-noise road surfaces

10.6.1 Surfaces with medium or rough texture

TRL Ltd was commissioned by Leicestershire County Council to examine the noise levels of various surfaces laid on different roads located within the County. A report was issued in 2005 [Balsom et al, 2005]. The surfaces measured included several sections of hot rolled asphalt (HRA), surface dressings, stone mastic asphalt (SMA) and close graded macadam. The main objectives of the study were to obtain information on the relative noise levels of different surface types at different test speeds and to investigate how the noise levels change over time on selected surfaces to establish information about their acoustic durability. It was hoped that this data could then be combined with data on texture and skidding performance to help inform future surfacing and road maintenance strategies.

The study only included surfaces with medium or rough macrotexture. There were no thin layers included in the tested sample.

Measurements were made with the CPX method (representing only light vehicle tyre/road noise) at 50 and 80 km/h in 2002 and 2004. The most important results indicated the following:

- The quietest surfaces were a close-graded macadam 0/14 and an SMA 0/10 while the noisiest were HRA 0/20 and SMA 0/14, the range noisiest-quietest being approximately 3 dB. However, HRA 0/20 surfaces varied over a range of approximately 1.5 dB.

- There was a significant correlation between noise level and texture depth.

- There was no significant correlation between noise level and wet skid resistance.

10.6.2 TRL projects

TRL Ltd in the UK recently conducted or is conducting two research projects, sponsored by the Highways Agency, that were investigating the acoustic properties of low-noise road surfaces. Information in this subsection is from [Stait, 2007][Morgan, 2008-3].

The first project concerned the feasibility of using double-layer porous asphalt on the (high-speed) road network. This project was completed in the beginning of 2008 and reviewed other countries experiences of double-layer porous asphalt and provided recommendations to the UK Highway Agency on how the surface could fit in with existing maintenance and noise policies. In August 2008 the report for that is still unpublished.

The second project is examining the acoustic performance of thin surfaces over time. This covers 6, 10 and 14 mm maximum aggregate surfaces, together with other common surfaces (e.g. Hot Rolled Asphalt) found on the UK road network. The project is due to run from October 2007 until the end of 2009 and will cover both new (<1 year old) and old (>5 years old) surfaces. This project will also trial the SILVIA methodology on several of the test sections. TRL has recently finished the first year of measurements on that project.

In addition, the use of 6 mm thin surfacing on the (high-speed) road network is being studied in more detail by a separate project, and noise measurements have been undertaken on some test sections as part of this project.

10.6.3 Asphalt rubber trials

The first UK trial for using dry process rubber crumb from used tyres for a road surface (the dry process mans adding rubber granules as a supplementary aggregate) has begun on a 7000 m^2 area on a road in Salisbury, under the jurisdiction of Wiltshire County Council in partnership with road contractors Ringway and Mouchel [Gillespie, 2008]. To test compatibility with European standards, 3-4 % rubber crumb mixes were tested in a wheel tracking facility and proved to perform best. Greater percentages had a detrimental effect on performance.

For the trial Ringway laid 135 tonnes of cold lay “microsurfacing”, incorporating cement, additive, retarding agent, emulsion and 6 mm high PSV aggregate, plus (probably) 3-4 % rubber crumb. The mix was laid by a standard method, and operator feedback indicated that the mix was easier to lay than the standard one [Gillespie, 2008].

The trial will run for two years to assess the general performance of the surface. This author thinks that a surface of this type will have low noise properties, although it is uncertain whether the amount of rubber is enough to give any extra noise reduction.

10.7 Major design and practice guides

A major design guide used in the U.K. is the Design Manual for Roads and Bridges, Volume 7: Pavement Design and Maintenance – Bituminous Materials, published in 1999, which contains chapters related to the bituminous surface types commonly used in the Kingdom [HD 37/99, 1999].

The Highways Agency (HA), Quarry Products Association (QPA) and Refined Bitumen Association (RBA) all appreciate the need to maximise the durability of asphalt pavements. Therefore, one of the tasks in a jointly funded research project at TRL entitled Performance and Durability of Asphalt Roads was to produce a Best Practice Guide on Durability of Asphalt Pavements [Nicholls et al, 2008]. The aim of the Best Practice Guide was to encourage everyone working in the asphalt industry to contribute to making pavements as durable as practical.

The main aspects that lead to durability were found to be [Nicholls et al, 2008]:

- the control of water (getting it away from the structure if not actually stopping it ever entering);
- limiting the number of and sealing joints (both vertical and horizontal); and
- adequate compaction (particularly at joints).

These aspects are likely to rise in importance with the predicted changes from global warming, with hotter, dryer conditions in summer but more intense rainfall, and possibly more of it, in the winter. Such conditions will exacerbate the potential for unwanted water to penetrate into the pavement [Nicholls et al, 2008].

Very recently, The London Technical Advisors Group (LoTAG), through its subgroup Highway Maintenance Steering Group, has published a specification for design and use of bituminous surfaces called "London wide asphalt specification: Guidance on the selection and recommendations for the use of road surfacing materials and European Standards for Asphalt" [LoTAG, 2007]. This includes also an "Appendix 7 - Summary of selected asphalt layers by Road Type".

The report provides[52]:

- A translation of all the names of all asphalt mixtures used in London from the old obsolete British Standards to the new nomenclature. It has been assured by the supply industry that the use of these materials will be cost neutral.
- A core list of preferred mixtures. Increased use of these will lead to improved quality and help to keep costs down.
- Additional specification clauses, and draft Appendix 7/1 clauses and Bills of Quantities
- Notes for Guidance on the selection of materials for the various Road Classes.
- Useful background Notes for Guidance on pavement maintenance issues such as sustainability, skid resistance and tyre/road noise.

The document is also claimed to be an indispensable aid to implementation of the new European Standards.

It is interesting to note that in the summary table with "Preferred options for materials selection", Option 1 (the preferred option) is thin layers of 14 or 10 mm maximum aggregate size for all road types. Furthermore, there is a summary table of properties of the various materials, in which the noise property (RSI according to HAPAS) is listed as in Table 10.8. Note that "microasphalt" is a proprietary slurry surfacing (very thin).

[52] See http://www.lotag.com/lotasphalt2.htm

Table 10.8. Overall assessment of the road surfaces considered in [LoTAG, 2007] as related to noise and durability. Table values taken from [LoTAG, 2007]; the original table includes several other parameters.

Surface type	Noise (RSI in dB = noise reduction)	Durability (the more stars, the better)
Surface dressings	+2	***
Microasphalt	-4	**
Thin surfacing, thickness 25-30 mm	-3	****
Thin surfacing, thickness 35-40 mm	-2.5	****
Hot rolled asphalt, thickness 45-50 mm	0 (reference)	****

It appears that the thin surfacings 25-30 mm (aggregate size 10 mm) come out very favourably, which is also the case when considering the other parameters in the original table. It is recommended to study this table (copyrights prevent this author from reproducing it here). The thin surfacing with max 10 mm aggregate is recommended to have a thickness 25-35 mm and is suitable for all sites and all road types. The 14 mm variant (35-50 mm thick) is considered to have similar uses but is not considered suitable in roundabouts or where sharp turns may occur. The 6 mm variant (15-22 mm thick) is not considered useful on low-speed roads or where braking and turning occur frequently, but is suitable on medium and high speed roads. This author thinks that the reason for not using the 6 mm variant on slow-speed sites may be that on such, frequent braking and perhaps also turning occurs. It is also considered unsuitable for laying on an existing road surface; probably since the latter may contain significant rutting which this very thin layer may not fill adequately.

A performance guarantee period of five years is foreseen for thin surfacings with 10 or 14 mm maxmum aggregate size but it is also stated that a good, thin, HAPAS-approved surfacing may perform well during at least ten years.

SMA surfaces are considered in the London specifications to belong to the thin surfacing type, but are not generally recommended as they are not subject to the strict requirements that the regular, proprietary thin surfacings must fulfil in the HAPAS system.

11. EXPERIENCE IN OTHER EUROPEAN COUNTRIES

11.1 Austria

Austria is a mountainous country where significant road gradients are common. The presence of road gradients can lead to increase vehicle noise emission. For a given speed, steep gradients can lead to noise level increases of 3 dB or higher [Haberl et al, 2003]. However, measurements have shown that a low-noise road surface such as porous asphalt concrete or a noise-reducing thin bituminous surfacing have similar benefits in areas where a gradient is present as on a level surface; see Fig. 11.1. Note that it is measured at a motorway, which means rather high speeds and that only cars are considered in the figure. Had trucks been considered, the low-noise road surface benefit would probably have been small. Note that the thin layer appears to work fine on such a substantial gradient as 6 %.

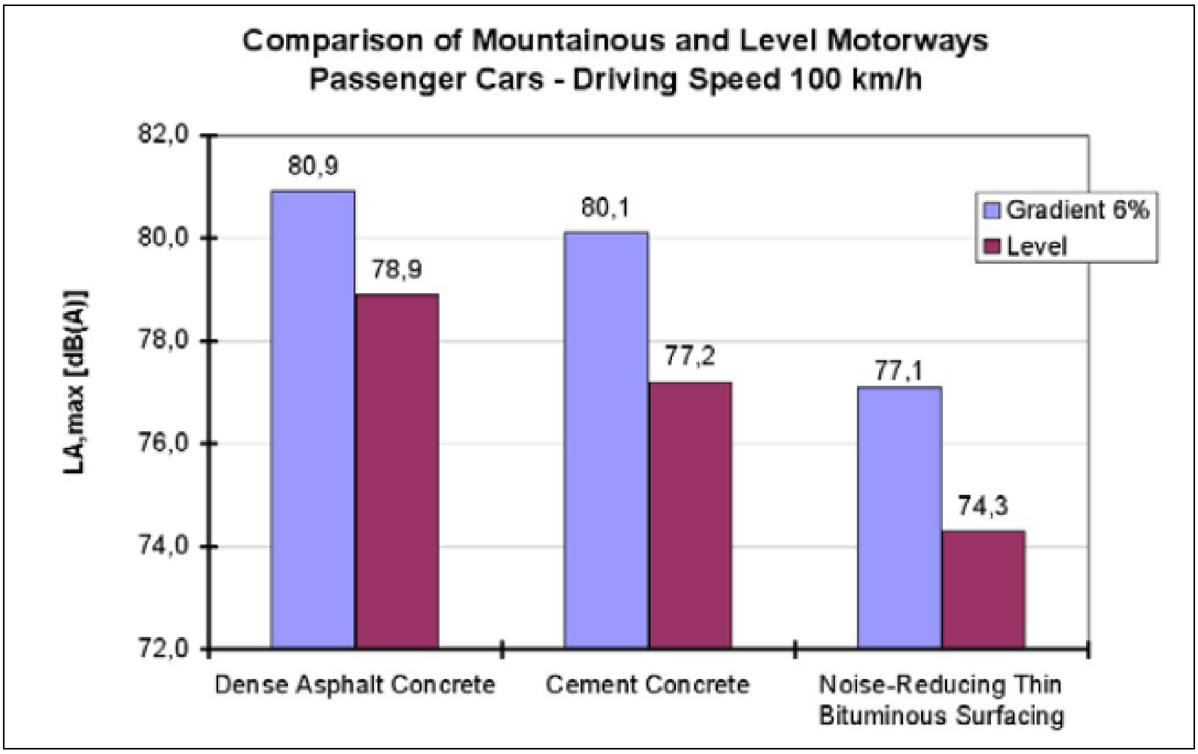


Fig. 11.1. Sound pressure levels on an average mountainous motorway in Austria for passenger cars on different road surfaces and with a gradient of 6 % compared to a level road [Haberl et al, 2003].

As far as the author has found, low-noise road surfaces have never been tried on low-speed roads in Austria. In Vienna exposed aggregate cement concrete (EACC) has been laid on many roads [Haberl, 2008]; although even within the city of Vienna these roads are not normally low-speed roads. An example is a section on the motorway A2 near the big shopping centre Vösendorf with a posted speed limit of 90 km/h which was measured by Transtec in Texas, USA, during a European tour. They found this surface to be a little louder than the average of cement concrete surfaces measured in the USA [Rasmussen, 2008].

Yet, it shall be acknowledged that the Austrians have more experience with noise-reducing exposed aggregate cement concrete (EACC) surfaces, what in German is called Waschbeton (washed concrete, WB), than probably any other country. It was first used in highway applications in Belgium, but the Belgians have generally used larger aggregates and thus not achieved so high noise reductions. When the Belgian and Austrian experience was transferred to and applied in the U.K., the surface became known as "Whisper concrete". A comparison between U.K. and Austrian specifications, as well as the practical experience in the U.K. is reported in [DoE, 1999]. The differences in specifications are shown in Table 11.1.

Table 11.1 Key differences between specifications for EACC ("Whisper concrete") in Austria and the UK [DoE, 1999].

Differences between Austrian and UK Whisper Concrete (Upper Layer)		
	UK	Austria
Chipping Size	6-10 mm	4-8 mm
Texture Depth	1.5 mm ± 0.25 mm	1.00 mm
Construction	CRCP	URC
Polished Stone Value	60/70	50/55

Nevertheless, there are some really interesting recent measurements in Austria on high-speed roads; some of which may be considered interesting also for low-speed roads. To begin with, Fig. 11.2 shows results of measurements according to 100 km/h according to Austrian standard RVS 11.06.64, which means a kind of CPX method using a PIARC ribbed tyre, at different ages of the road surfaces. The diagram is from [Haberl, 2008] but the surface description was improved by this author.

The use of the PIARC ribbed tyre may give results which are not entirely comparable to roadside measurements, but the following trends should be reasonably true:

- The porous asphalt gives superior noise reduction during its first two years but after that it deteriorates until at an age of 6-10 years it approaches the noise properties of the SMA and dense asphalt. Clogging and ravelling are believed to be the causes of this.
- The thin layer LDDH 8 and the SMA with rubber added (LSMA 8) give a medium noise reduction in new condition (approx. 4 dB) but maintain it (at approx. 2 dB) over a period of at least 6-10 years. This author thinks that 1-2 dB of this noise reduction may be explained by lower aggregate size (8 versus 11 mm)
- The WB GK 8, which is an EACC surface, has a 1-2 dB advantage over the SMA 0/11. This author thinks that this may be explained mainly by its lower aggregate size (8 versus 11 mm). It shows that a cement concrete surface does not have to be noisier than an asphalt concrete surface with a proper treatment.

There is no explanation as to the dramatic change in noise level with age, 3 dB increase from new condition to an age of 6-10 years, of the AC 11 surface.

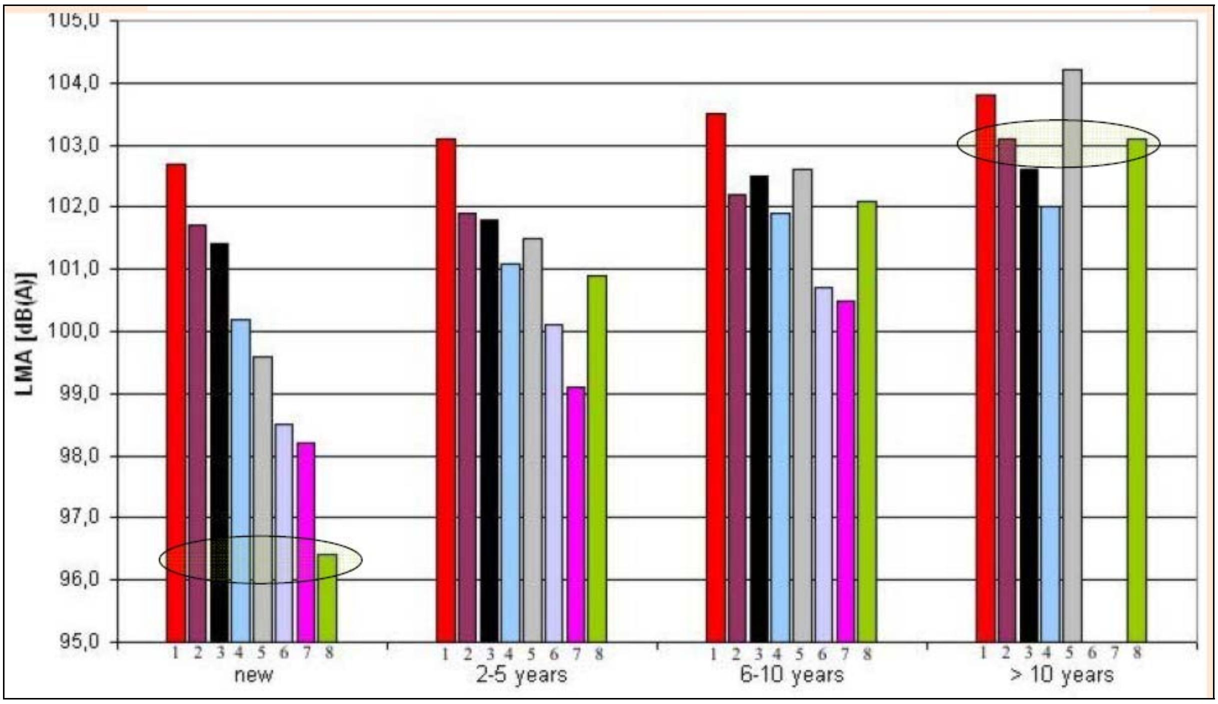


Fig. 11.2. Comparison of tyre/road sound levels measured at 100 km/h according to Austrian standard RVS 11.06.64 with a kind of CPX method using a PIARC ribbed tyre, at different ages of the road surfaces [Haberl, 2008]. The surfaces were (from left to right in the figure):

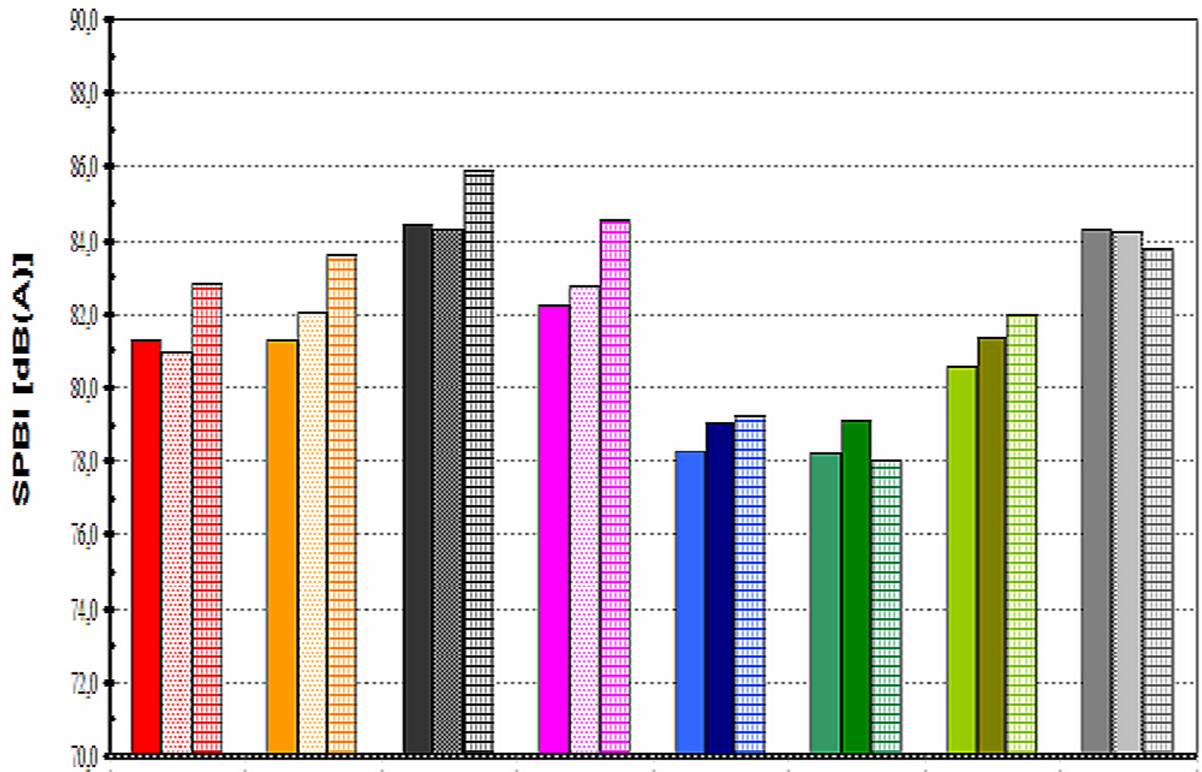
- Griproad (surface dressing laid on cement concrete roads)
- EP-Grip (surface dressing laid on cement concrete roads)
- SMA 0/11 Stone Mastic Asphalt with max 11 mm aggregate
- WB GK 8 Exposed aggregate cement concrete (EACC) with max 8 mm aggregate in top layer
- AC 11 Dense asphalt concrete with max 11 mm aggregate
- LDDH 8 Thin layer, noise-reducing, max 8 mm aggregate
- LSMA 8 SMA with rubber added to the binder, max 8 mm aggregate, ~10 % voids
- Porous asphalt, single layer, max 11 mm aggregate

The next set of data is for eight surfaces laid on the A12 motorway near Innsbruck, some of which are innovative. They have been measured according to ISO 11819-1, i.e. as SPBI sound levels at 110 km/h for cars and 85 km/h for trucks. Measurements were made at three occasions; at the surface ages of 6, 11 and 24 months. The results are presented in Fig. 11.3; from [Haberl, 2008]. A description of the surfaces follow; again from [Haberl, 2008] with Austrian designation at the left:

LSMA 8, rubber modified bitumen, so-called "noise-reducing stone mastic asphalt"
LSMA 11, rubber modified bitumen, so-called "noise-reducing stone mastic asphalt"
SMA 11, stone mastic asphalt, polymer modified bitumen
LSMA 11, polymer modified bitumen, so-called "noise-reducing stone mastic asphalt"
ZDA, double-layer porous asphalt with polymer modified bitumen
ZDA, double-layer porous asphalt with rubber modified bitumen (CTS bitumen)
DA 8, single-layer porous asphalt with rubber modified bitumen (CTS bitumen),
pmAB 11, asphalt concrete, polymer modified bitumen

More detailed data are presented in Table 11.2. It is interesting to note that the rubber-modified LSMA surfaces (the two first ones in the list) has a total weight of rubber of 1 % of the mix, which means that it is about 15 % of the binder amount. This is somewhat similar to the asphalt rubber surfaces used in Arizona (see the Chapter about USA), although only half the rubber amount. Air voids of 10-11 %, which is substantially higher than for conventional SMA surfaces, mean that the surface has a porosity which might influence noise a little. This voids content suggests that the grading is somewhere in-between of the gap-graded and open-graded versions of asphalt rubber surfaces.

The kind of rubber which is blended into the binder, the commercial product ASAplex M100 developed for this purpose, seems to be something in-between of fine granules and powder.



	LSMA 8 Rubber mod. 30 mm 0/8 10 % voids	LSMA 11 Rubber mod. 35 mm 0/11 11 % voids	SMA 0/11 35 mm 0/11 4 % voids	LSMA 11 Polymer mod 35 mm 0/11 11 % voids	Double PA Polymer mod 25mm 4/8 45mm 11/16	Double PA Rubber mod 25mm 0/8 45mm 0/16	Single PA Rubber mod 45mm 0/8	AC 0/11 Polymer mod
6 Monate	81,3	81,3	84,4	82,3	78,3	78,2	80,6	84,3
11 Monate	81,0	82,1	84,3	82,8	79,1	79,1	81,4	84,3
24 Monate	82,8	83,6	85,9	84,5	79,2	78,0	82,0	83,8

Fig. 11.3. Comparison of SPBI sound levels measured at 110 km/h for cars and 85 km/h for trucks, according to ISO 11819-1, on 8 surfaces at the ages of 6, 11 and 24 months [Haberl, 2008]. For each surface the left bar is for 6 months, the middle bar for 11 months and the right bar for 24 months of age. The diagram has been supplemented with surface description by this author.

Table 11.2 Some key data for the test surfaces. Table compiled by this author from [Haberl, 2008].

Surface type	Thickness of layer	Air voids	Binder amount	Binder additive	Notes
LSMA 8 rm	30 mm	10 %	6.2 %	1 % rubber	% by weight of total mass
LSMA 11 rm	35 mm	11 %	6.0 %	1 % rubber	% by weight of total mass
SMA 11 pm	35 mm	4 %	6.3 %	Cellul. fibres	
LSMA 11 pm	35 mm	11 %	5.7 %	Cellul. fibres	
ZDA pm	25+45 mm	23+23 %	6.0+4.9 %	Cellul. fibres	
ZDA rm	24+45 mm	25+28 %	6.5+4.5 %	CTS bitumen	See note*
DA 8 rm	45 mm	25 %	6.5 %	CTS bitumen	See note*
pmAB 11 pm	35 mm	3 %	5.4 %		

* It is not reported what the amount of rubber is in the porous asphalt, but this author believes that it is a much smaller amount than in the LSMA surfaces

From the diagram, one may draw the following conclusions:

- The most effective surfaces for noise reduction are the double-layer porous asphalt surfaces
- Polymer or rubber modified binder does not seem to give a significant difference on the double-layer surfaces
- Second best is the single-layer porous asphalt. However, the difference compared to the double-layer ones may be an effect of the thickness difference (the values in new condition fit very well the noise reduction predicted by Fig. 9 in [Sandberg, 2008-1])
- The double-layer surfaces show a little lower deterioration in noise reduction at 24 months of age than the single-layer one. This may be an effect of the higher amount of voids due to the greater thickness in the double-layer surfaces
- The LSMA surfaces with 1 % rubber seem to give 2-3 dB noise reduction compared to the baseline SMA
- The LSMA surface without rubber gives approx. 1 dB less noise reduction than the one with rubber (11 mm max aggregate assumed)

Depending on the development with time, after the 25 months studied so far, it may or may not appear that the LSMA surfaces will be more cost-effective than the porous surfaces. They do not, at least when in new condition, give as high noise reduction, but they are probably much less expensive. Fig. 11.2 gives a basis for an optimistic view about this. However, they may be challenged by some noise-optimized thin layers, see the section about these surfaces in the Netherlands, Denmark and Poland. It will be interesting to study the future of the LSMA surfaces.

Due to the positive experience so far, LSMA is already used on about 9 % of the Austrian high-level road system (highways and motorways). Mr Haberl thinks that it is the "surface of the future" in Austria [Haberl, 2008].

11.2 Germany

11.2.1 LeiStra2

As reported in Section 5.3.2, intensive research has been and is being performed within the German research programme LeiStra2. Some recently reported results are summarized in the following, which is adapted by the author from a text by [Lorenzen, 2008].

The researchers are looking for methods to prevent a porous asphalt layer from becoming clogged. Two ideas from the subject of nano technology are under investigation, both with the aim to enhance the self-cleansing abilities of the pores. One idea is to make the surface of the pores hydrophobic[53] and the other idea is the opposite: to make the surface hydrophilic[54]. The first idea is well known as the "lotus effect" where a polymeric paint is used to cover the pores. The lotus effect increases the contact angle between a water drop and the surface and thus makes it easier for water drops to flow down under the surface. In doing so, small dirt particles are supposed to be collected by the water drop while flowing through the porous layer rather than sticking to the walls of the pores, since the hydrophobic paint rejects the water. See Fig. 11.4 for an illustration of the lotus effect. Various polymeric substances are being tested for this purpose.

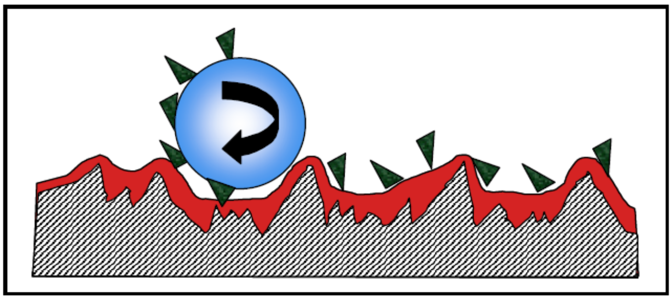


Fig. 11.4. Illustration of the so-called "lotus effect" (in this case on a dense surface). Hydrophobic paint (red) covers the surface. Dirt particles are picked-up by water drops, the latter of which are rejected by the paint. From [Lorenzen, 2008].

To make the surface hydrophilic, polymeric additives are used to modify the bitumen. Due to the Marangoni[55] effect the polymer migrates to the surface of the bitumen so that the contact angle between a water drop and the surface is reduced. Water thus penetrates underneath the dirt particles and by attraction to hydrocarbons in the bitumen spreads out on the bitumen surface, see Fig. 11.5. Thus, dirt particles are prevented from sticking to the bitumen surface and are transported through the porous layer, according to the idea.

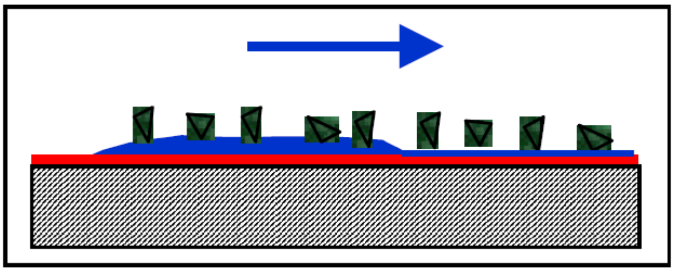


Fig. 11.5. Illustration of the hydrophilic effect (in this case on a dense surface). Formation of a hydrophilic surface (red) due to the Marangoni effect and surface tension. Water (blue) penetrates underneath dirt particles (green/black). From [Lorenzen, 2008].

[53] Hydrophobic means that there is an apparent repulsion between water and hydrocarbons
[54] Hydrophilic means that there is an apparent attraction between water and hydrocarbons (which oil/bitumen contains)
[55] The Marangoni effect is the mass transfer on or in a liquid layer due to surface tension differences (Wikipedia)

The findings so far are that it is relatively easy to cover the surface of the void fraction of the asphalt layer to achieve a substantial lotus effect. For the opposite measure, however, a substantial amount of polymeric material has to be added to the bitumen in order to achieve the desired effect and so far this seems not to be practical.

In laboratory experiments, porous asphalt layers have been artificially clogged with a suitable dirt mixture and then exposed to artificial rain followed by drying periods. These experiments are in progress and various different combinations of porous asphalt layers with and without polymeric modification are on the program.

The flow of water through a porous asphalt layer is investigated to gain a deeper insight into the drainage effect. Numerical simulations of the flow field through a cubic space 30x30x30 mm have been conducted. These calculations show that sufficiently high water velocities (for transporting dirt) are achieved only in about 40 % of the void fraction. In about 20 % of the voids the velocities are already fairly low and will hardly contribute to a dirt transport through the layer and in another about 40 % the water velocities are practically zero. These are dead or recirculation zones of the flow field.

The possibilities to clean clogged porous layers are also part of the program to improve porous asphalt. The layer is soaked with a suitable water solvent mixture and an alternating suction and compressing process is applied. These investigations have been started recently.

Furthermore, computer tomography is used to gain a deeper insight into the porous layers. A distinction between the solid material of the porous layer and (certain) dirt particles can be made. Acoustic and flow measurements as well as chemical analysis of the dirt found in real porous asphalt layers are performed. In particular, these studies include the flow resistance of new and clogged porous asphalt layers, their sound absorbing ability and analysis of the environmental impact of the various substances and chemicals used in the project, e.g. tensides for cleaning the porous layers.

Five highways (BAB) and trunk roads (B) are used in order to verify the research results in 2008:

- BAB 61 near Jackerath: Testing of exposed aggregate cement concrete
- BAB 61 near Kerpen: Testing of Gussasphalt
- B 56 near Düren: Testing of low-noise stone mastic asphalt (SMA)
- BAB 24 near Neuruppin: Testing of improved porous asphalt
- Test section in Bavaria: Testing of improved porous asphalt

The LeiStra2 is planned to be finished in 2009. It is rather probable that the results will influence the development of guidelines and standards and those pavements which prove to be acoustically advantageous will be used more often in the future.

11.2.2 Bavarian experience

In Bavaria ("Bayern"), which is the southernmost state in Germany, low-noise porous asphalt surfaces have been used since 1992. In 2006, approximately 140 lane-km were paved with such surfaces [Rodehack & Beckenbauer, 2006]. There are firm plans to build much more of these surfaces for the purpose of reducing noise; for example along roads where the residential areas are so close that noise barriers would have to be very tall in order to be efficient.

It is reported that single-layer surfaces give an initial noise reduction of 8 dB(A) while double-layer surfaces offer 9 dB(A). After 6 years of operation, it is reported that it is common that 5 dB(A) of the noise reduction remains on a single-layer porous asphalt, although on one road 7 dB(A) noise reduction remains after 8 years of operation. It may be noted that a reduction from 8 dB(A) initially to 5 dB(A) after 6 years, means a deterioration of 0.5 dB(A) per year. The Bavarian single-layer porous surfaces have a maximum of 8 or 11 mm aggregate, and the double-layer one is usually a top layer of 8 mm on a bottom layer of maximum 16 mm aggregate.

However, it is not reported which surface that is the reference. This author assumes that it is a burlap dragged cement concrete which is the reference since this surface is commonly used on German motorways. It might also be a common German surface called "Gussasfalt" (mastic asphalt). Both the mentioned surface types are a little noisier than most references used in other European countries. The author also assumes that the surfaces are used exclusively on high speed roads (80 km/h or higher).

In wintertime, the experience is that much more salt is needed for de-icing than on dense asphalt and there are occasions when not even this is sufficient. It has also been noticed that in case of animals killed in accidents, the blood will make the surface deteriorate so much that repairs are often necessary. Road markings are not without problems either.

On the Bavarian roads, a lifetime of porous asphalt of 7-14 years is normal; compared to 15 years for an SMA and 25 years for a DAC surface. However, repaving often takes place earlier, normally after no more than 6-10 years, since the acoustical efficiency is poor after such a long time. It is believed that the ongoing development work will increase the acoustical efficiency to maintain a noise reduction of 5 dB(A) up to a lifetime of 10 years.

Due to the shorter lifetime the costs are about three times as high as for an SMA.

Measurements are made extensively by means of a CPX trailer. Fig. 11.6 shows a summary of results measured on all the porous surfaces. It is claimed that there is no clear correlation between noise level and year of construction, implying that the range is about 10 dB(A) between the best and worst one, and that this range is not determined or much influenced by surface age.

The information above is summarized from [Rodehack & Beckenbauer, 2006].

An explanation for the large range of noise reduction values is given in [Weissenberger et al, 2006], where grading curves for the pavements are compiled; see Fig. 11.7. It appears from Fig. 11.7 that the gradings differ substantially and it is natural that this causes a large range of porous and thus acoustical characteristics. The reference even offers a scheme for determining what the desirable grading of the asphalt mix shall be, given a desired noise reduction of 8 dB when new and with a loss of max 3 dB after 6 years.

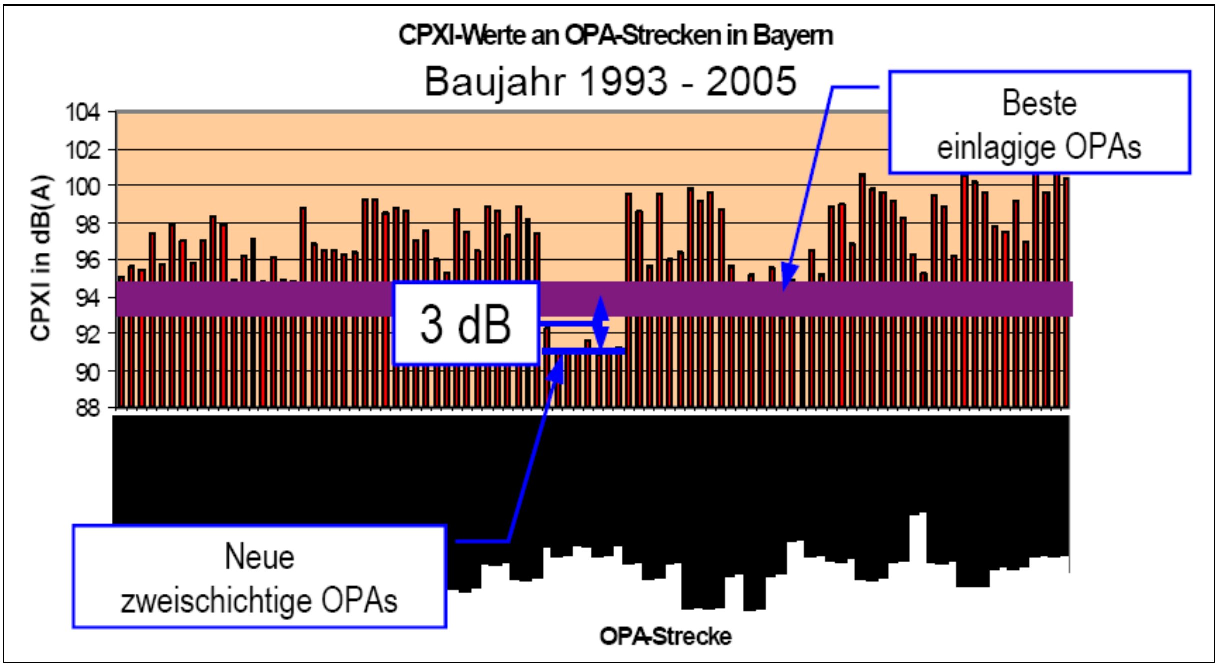


Fig. 11.6. Measured noise levels (CPXI index) for all porous asphalt surfaces in Bavaria, built 1993-2005. The violet ribbon indicates the values of the best single-layer surfaces whereas the blue thin line shows the values of the new double-layer surfaces, which lies about 3 dB(A) below the single-layer ones. From [Rodehack & Beckenbauer, 2006].

11.2.3 Other German experience – High-speed roads

German studies of low-noise road surfaces have focused on two major topics:

- High-speed roads; mainly highways and motorways with posted speeds from 90 km/h and upwards (some motorways have free speeds)
- The use of single-layer porous asphalt with 8 mm maximum chipping size, generally designated OPA or PA 0/8

The first topic is common to the Dutch focus, but the second one is quite unique. And this author thinks that it has been rather successful. The problem with the German results is often the uncertainty with respect to the reference surface used. In the German noise prediction model RLS-90 three types of surfaces are considered as references and having a "0 level" correction, namely:

- Non-grooved Gussasphalt
- Asphalt concrete (dense)
- SMA

However, the variability between and within these three groups is considerable, which makes the reference vague, unless it is well defined in the particular experiment.

Typically the newer German PA 0/8 has the following features: thickness 45 mm, maximum aggregate size 8 mm (some oversize up to 11 mm may occur), voids content target 22-28 %, actually > 22 %, modified binders used. Example of grading curves appear in Fig. 11.7.

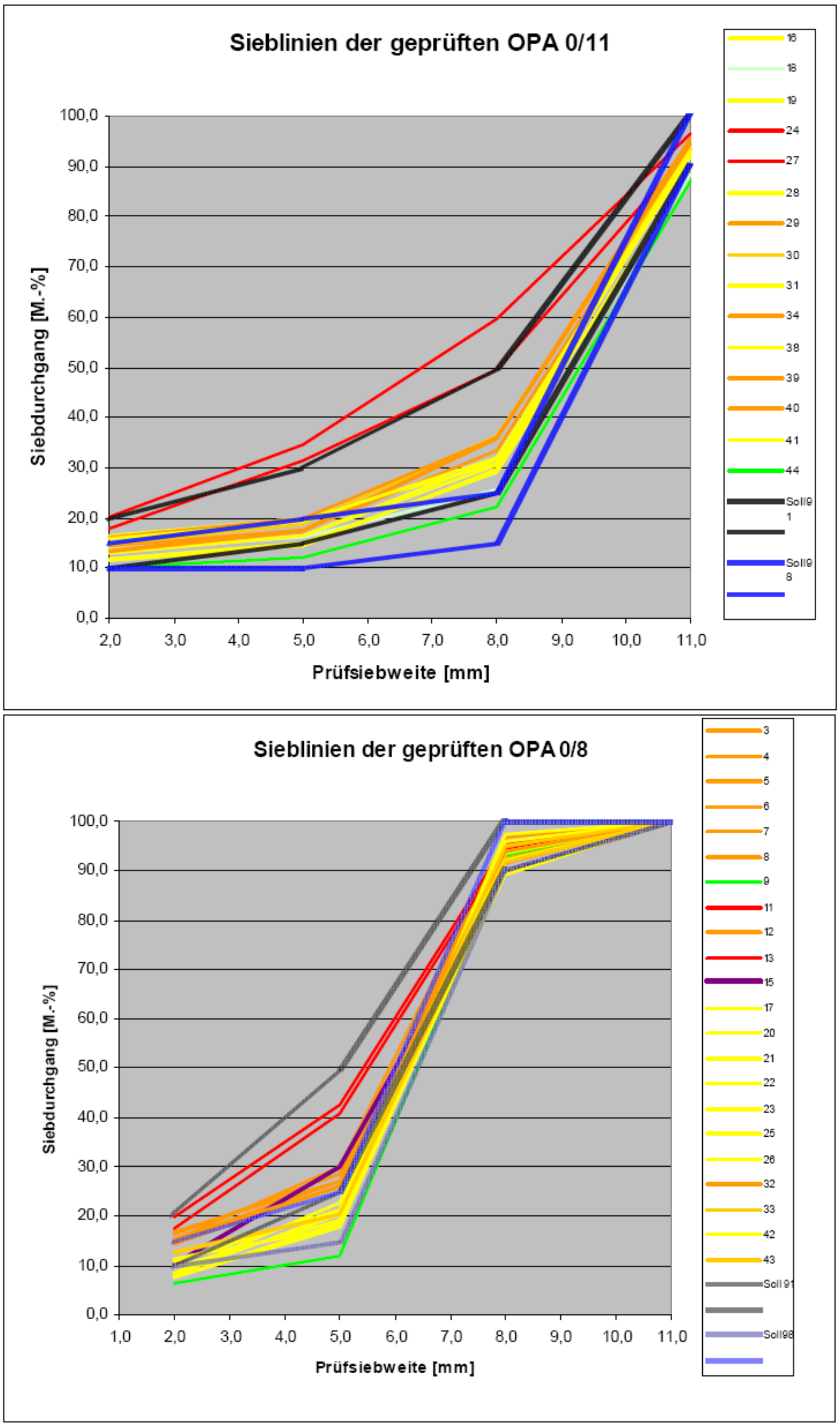


Fig. 11.7. Grading curves for the tested porous asphalt pavements in Bavaria. The upper diagram is for OPA 0/11, i.e. the variant with maximum 11 mm chippings, and the lower one for OPA 0/8; i.e. for maximum 8 mm chippings. The vertical shows the % by mass passing and the horizontal shows the sieve size. Note that sieves varied in steps of 2 mm. From [Weissenberger et al 2006].

A summary of the results measured so far for PA 0/8 is shown in Fig. 11.8 [Bartolomaeus, 2008]. The diagram shows a large spread of noise reduction values for essentially the same type of surface. The three colours, red, blue and green, denote various generations of surfaces, with red being the first ones tried and the green ones the latest generation. Although belonging to the same type of pavement, these generations differ in terms of (for example) grading, achieved voids content and binder used. The straight horizontal line at 5 dB is the "political" target value: 5 dB over a 6-year time period. Note that the results are valid only for cars travelling at 120 km/h and expressed as SPB values (ISO 11819-1). This is somewhat limited way of reporting results since the German motorways are becoming more and more chocked up with truck traffic; albeit the speed of the trucks is about 85 km/h, so that the cars emit approximately as much noise per vehicle as the trucks.

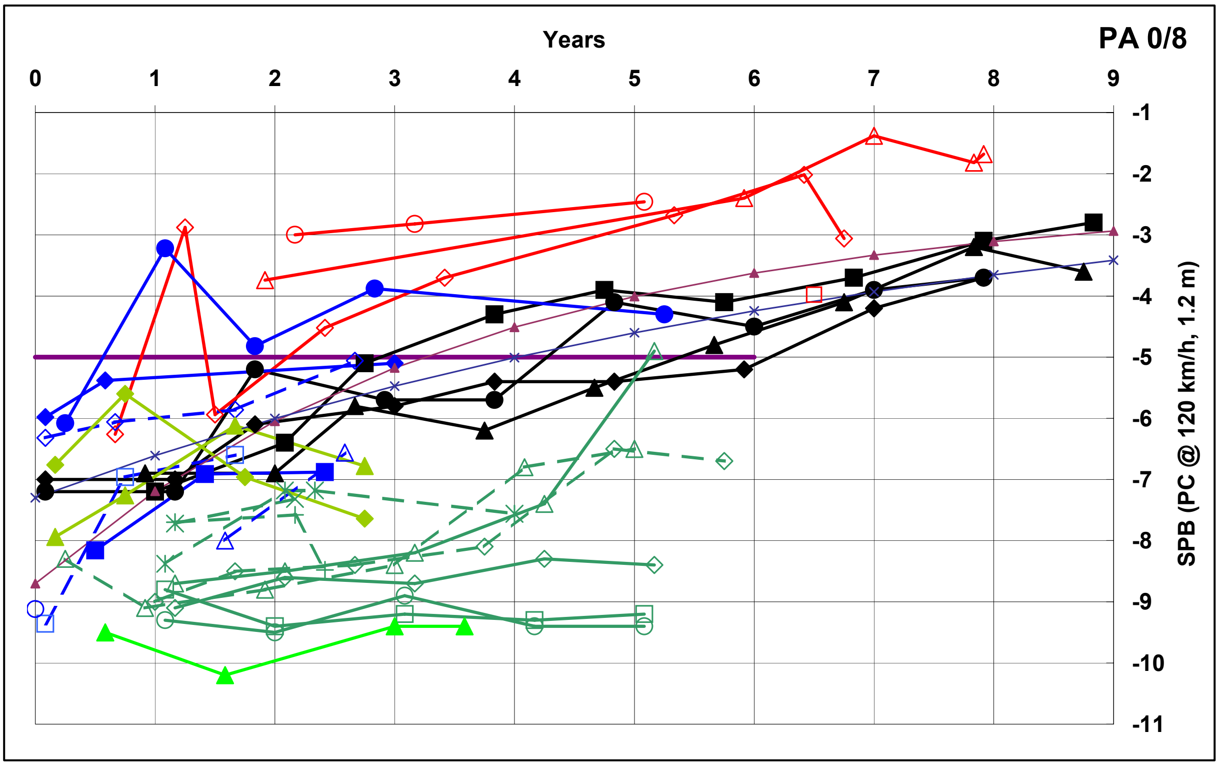


Fig. 11.8. Noise reduction measured for a large number of German single-layer porous asphalt surfaces PA 0/8, as a function of the age. Measurements with the SPB method, for cars at 120 km/h. The colours of the data lines show different generations of PA 0/8 surfaces, with the newer ones at the bottom and the older generations at the top. Diagram from [Bartolomaeus, 2008].

The results show the following interesting features:

- The first generations of surfaces had difficulty in meeting the target value (5 dB)
- They showed a decay in noise reduction of 0.3-0.4 dB/year
- The spread in noise reduction within the entire group is approx. ± 3 dB
- The spread in noise reduction within the latest generation is approx. ± 2 dB
- The latest generation of PA 0/8 surfaces give an average of 8 dB of noise reduction
- The decay with time is very small for these newer generation surfaces (appr 0.2 dB/yr)

Just judging from the numbers, the German results seem to be better than those of the Dutch IPG programme for the much more expensive double-layer porous asphalt surfaces. However, one must remember that the Dutch and the Germans use different references. A "Dutch-German noise translator" was calculated earlier and according to this one the German values shall be reduced by 2.6 dB to correspond to the Dutch ones [Roovers & Doorschot, 2005]. The author thinks that this value may be somewhat exaggerated and that it should not be higher than 2 dB. If so, the German results for the PA 0/8 of the latest generation give a noise reduction of 6 dB which is approximately the same as for the Dutch TLPA 4/8 surfaces (double-layer porous asphalt). The decay of noise reduction with time is also comparable.

According to Fig. 11.6, new double-layer surfaces are 3 dB better than the single-layer ones. It is not clear how this would relate to the data in Fig. 11.8; i.e. if one could expect 11 dB of noise reduction for German double-layer surfaces. Probably one cannot compare the figures in this way.

Another recent report may bring some more information about the performance of double-layer versus single-layer German porous asphalt surfaces [Altreuther & Bartolomaeus, 2008]. A total of 16 such surfaces of various age were tested with both the CPX method at 80 km/h and the SPB method (for cars only) at 120 km/h. See a compilation of results in Fig. 11.9.

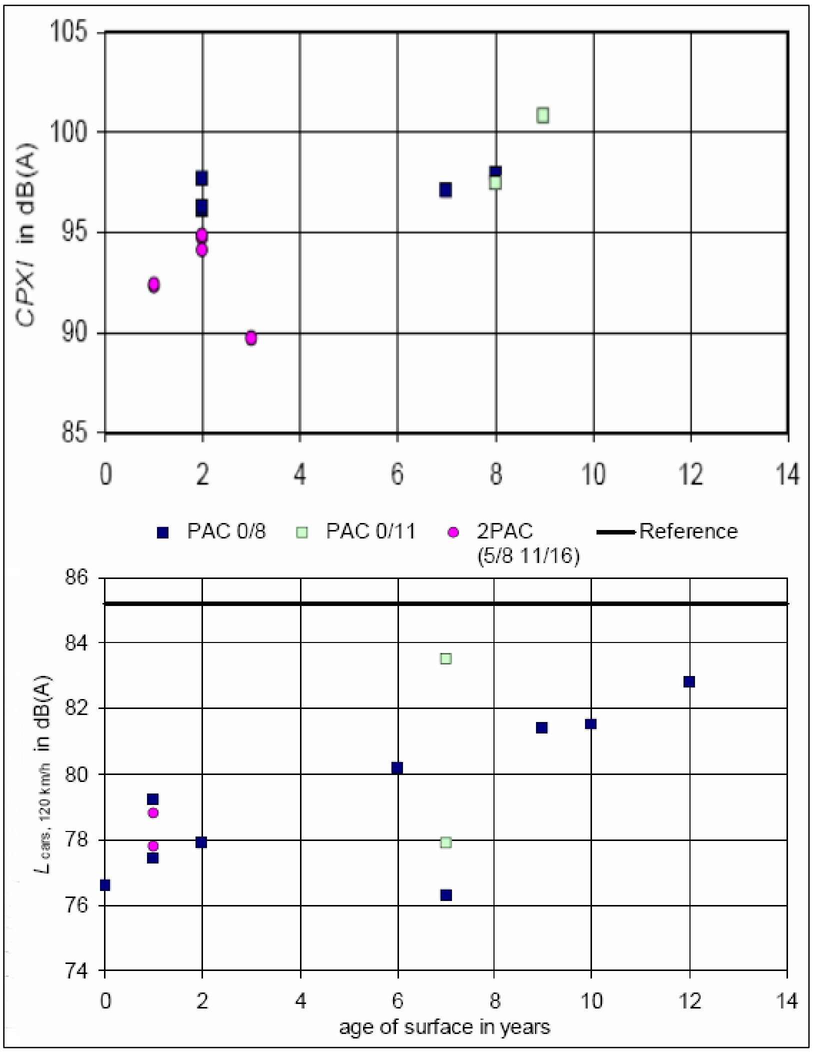


Fig. 11.9. Noise reduction measured for several German single-layer (PAC 0/8 and PAC 0/11) and double-layer (2PAC 5/8 11/16) porous asphalt surfaces, as a function of their age. Measurements with the CPX method for Tyres A and D at 80 km/h in the top diagram and with the SPB method for cars at 120 km/h in the bottom diagram. The line at 85.2 dB shows the German reference level representing a mix of dense surfaces. Note that the noise level scales of the two diagrams are somewhat different. Diagrams from [Altreuther & Bartolomaeus, 2008], but resized to more harmonised scales by this author.

The results suggest that the double-layer surfaces are no better than the single-layer ones for the SPB measurements at 120 km/h (only cars); although the CPX measurements at 80 km/h with two tyres representing a mix of light and heavy vehicles indicate an advantage of about 4 dB for the double-layer surfaces. How can such deviating results occur? Neglecting the fact that both measurement methods have substantial errors, the difference is logical. Other results have indicated that the advantage of the double-layer surfaces is greater at lower speeds and vice-versa (at lower speeds the traffic noise spectral peak fit better with the rather low frequency of peak absorption for double-layers); furthermore, the lower peak absorption frequency of double-layers should be more efficient for heavy vehicles with their lower frequency peak, and when heavy vehicles are neglected as the Germans do in SPB measurements on motorways, differences like the ones observed here may appear.

Two more things may be noted from Fig. 11.9. The decay of noise reduction with time is approximately 0.4 dB/year (the data include some of the older generation PA, so this value may be better for the newer generation as written above). The other thing is that the German standard requirement for a PA for use as a noise abatement measure; i.e., to maintain for 6 years a 5 dB noise reduction relative to the reference level of 85.2 dB, seems to be met by this group of surfaces.

11.2.4 Other German experience – Clogging and cleaning

There are some interesting data related to the clogging and cleaning of porous asphalt surfaces reported from Germany. Fig. 11.20 shows the results of noise monitoring four times per year by Müller-BBM with the CPX method on a 500 m test section which was repaved with double-layer porous asphalt [Beckenbauer, 2006]. The noise level is plotted versus the distance along the road from a reference point before the beginning of the test section. Each curve represents one measurement, and the curves together represent such repetitions over a time period of a couple of years. The brown curve was measured before the repaving, on a dense asphalt surface, and thus the noise level is similar along the entire section.

Then the red and blue curves represent the first measurements after the repaving (the exact month for each measurement is not known to the author). One can see that the "steady-state" noise reduction, between 400 and 750 m, is high during the first measurements but is becoming lower and lower with time; something which is due to clogging. One can also see that the noise reduction does not change from 0 to the full reduction (approx. 6 dB) immediately, but it changes gradually over a distance 150 m from the joint between the dense and the porous surface (corresponding to approximately 180 to 330 m on the scale in the diagram). This has been observed also by CPX measurements in Sweden and Norway, so it is not just by chance but it is a systematic observation on porous surfaces, which probably shows clogging by dirt which is pulled in by traffic from the dense to the porous surface. On a dense surface such dirt will have to blow away to the roadside, but on a porous surface some of it gets stuck in the porosity. Potentially, there may also be another contributing effect in some cases; namely the adjustment of the paving machine and the asphalt mix it uses which is not optimal during the first metres but is improving until the desired "equilibrium" is reached.

Assume that the effect of this surface had been measured with the SPB or CPB method at the point 230 m in the diagram (equal to 50 m from the start of the porous section). The conclusion would have been: "Noise reduction when new was 3 dB, after half a year it was down to 2 dB, after two years it was down to 1 dB". But had the measurement been made at the point 500 m, the conclusion would have been: "Noise reduction when new was 6 dB, after half a year it was down to 5 dB, after two years it was down to 3.5 dB".

This "gradual change effect" is important for three reasons:

- It reduces the noise reduction over a relatively short distance, and it means that it is not very effective to lay a porous surface on only a short section (like 100-200 m).
- When measuring the noise reducing effect of porous asphalt, the effect is underestimated in cases where the measurement is made within approximately 100-150 m from the joint between the dense and the porous surface; in the direction of the traffic.
- Short test sections (say 100-200 m) will not show the true noise-reducing potential of the surface. In cases where one may get extra clogging from two directions, test sections should be even two times larger.

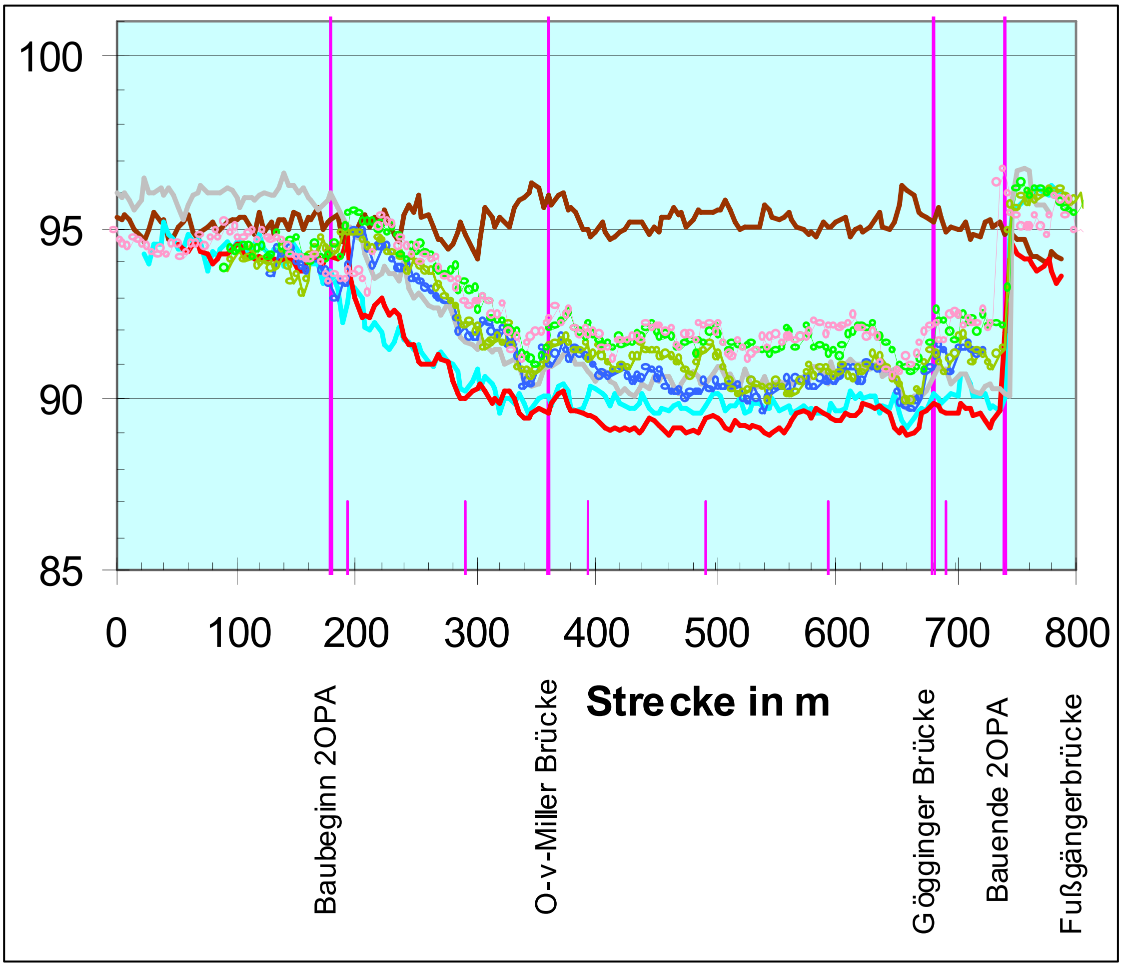


Fig. 11.10. Tyre/road noise level measured along a German road repaved with a double-layer porous asphalt surface. Measurements were made with the CPX method repeated at time intervals of approximately a quarter of a year. The horizontal scale is distance in metres from a reference point approx. 180 m before the beginning of the porous section. Diagram from [Beckenbauer, 2006].

This "gradual change effect" has probably affected many trials during the past years. It also shows how important it is to monitor the noise reduction over the entire road section, or at least over several hundreds of metres after the joint between a dense and a porous road surface.

Fig. 11.11 shows another clogging effect presented in [Beckenbauer, 2006]. The connected yellow points show the noise reduction measured at various times, approximately repeated at 3 months intervals over a three-year period. Occasions approximately half a year apart when cleaning had taken place are indicated. Cleaning was made with a "normal" high-pressure water ejection and suction machine. One can see that the cleaning operations generally "pull down" the curve, while the curve has a positive slope between the cleaning occasions. From this, Mr Beckenbauer concluded that clogging gives a loss in noise reduction of approximately 1 dB per year, while the repeated cleaning (two times per year) compensates for approximately half of this deterioration.

This is one of very few cases outside Japan when cleaning really has been demonstrated to be reasonably effective.

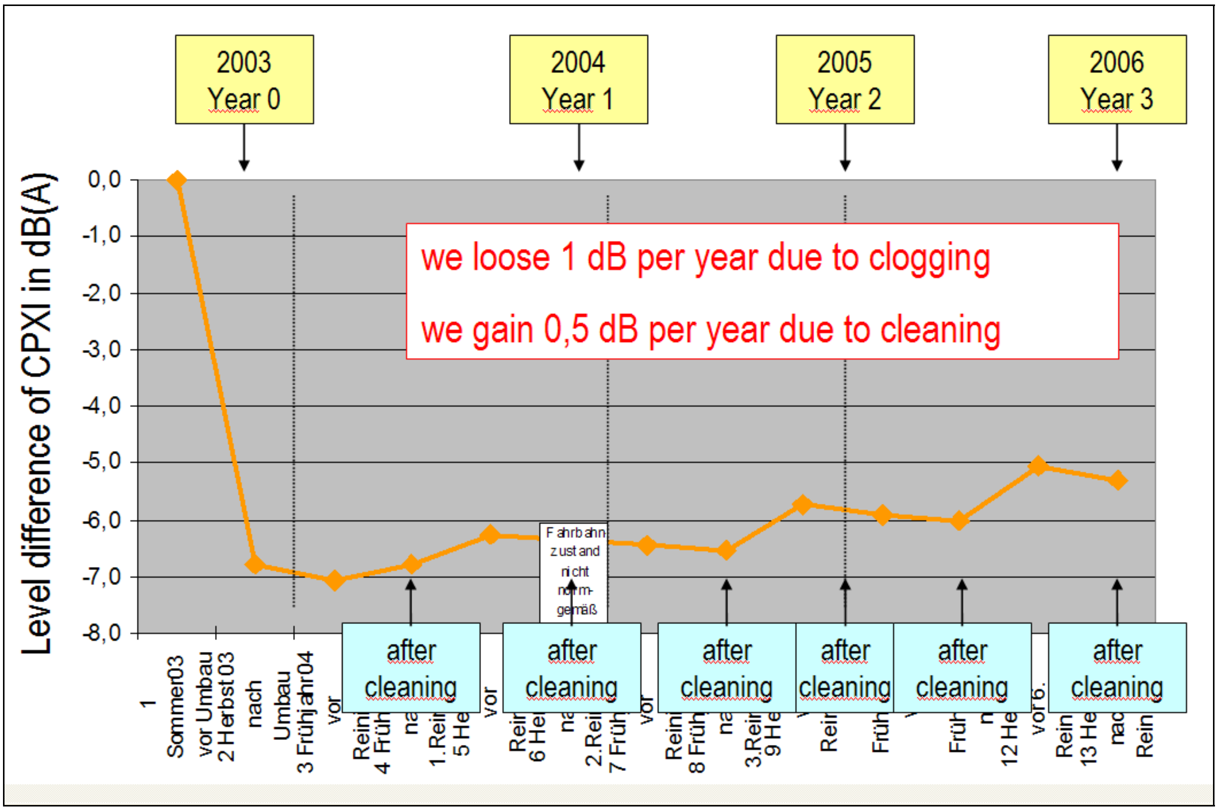


Fig. 11.11. Tyre/road noise reduction as a function of time as measured on a German road repaved with a porous asphalt surface. Measurements were made with the CPX method repeated at time intervals of approximately three months. Times when cleaning was made are indicated. Diagram from [Beckenbauer, 2006] (but this author has processed the diagram to "clean away" some information which is less relevant for this report).

11.2.5 Other German experience – Low-speed roads

Two experiments with double-layer porous asphalt surfaces on low-speed innercity roads (posted speed 50 km/h) have been conducted in Augsburg and Ingolstadt in southern Germany [LfU, 2008].

First, in 2003, an innercity part of the main road B17 through Augsburg (posted speed probably 50 km/h) was repaved on a 560 m long section with double-layer porous asphalt. To take care of the expected problem with drainage from the wearing course on an innercity street, an advanced drainage system was constructed at the side of the street; see Fig. 11.12 [Beckenbauer, 2006]. The noise reduction results are probably seen in Fig. 11.10[56].

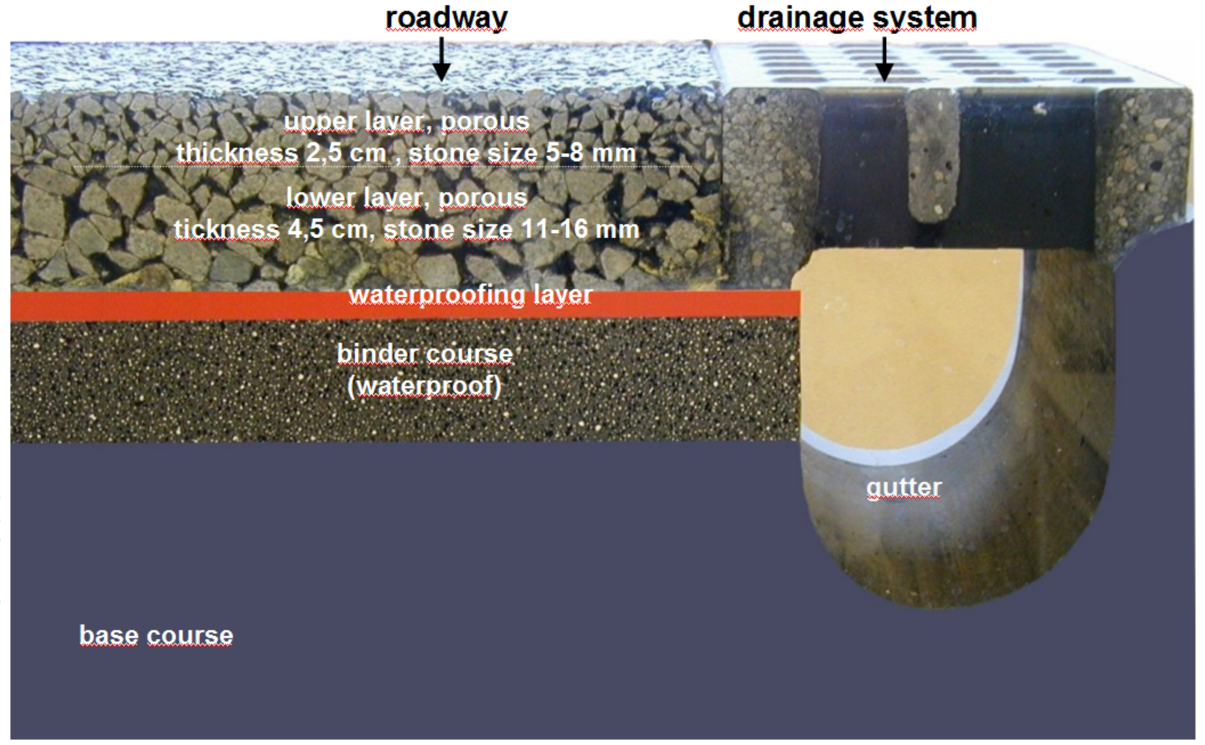


Fig. 11.12. The construction of the double-layer porous asphalt and its base-course and advanced kerbside drainage system on the innercity part of highway B17 through Augsburg. The waterproofing layer is probably a so-called SAMI. Diagram from [Beckenbauer, 2006].

A similar project was then conducted from 2005 on 1200 m of the western ringroad of Ingolstadt in southern Germany. This is a 50 km/h posted speed street having three lanes (two in one direction and one in the other direction) with a residential area on one side and a recreational park on the other side, with at least one light-controlled intersection (one-sided). The proportion of heavy vehicles is 3.6 %[57]. There are some light curves and a small longitudinal gradient on this section. The transverse design gradient was 2.5 % and a drainage system similar to the one in Augsburg was constructed on one side of the street. See Fig. 11.13.

[56] The author thinks that this section may be the same as is reported in Fig. 11.10, but this is yet unconfirmed. The author has not found any documents describing the Augsburg experiment in more detail.

[57] The author has not yet been able to find out how high the traffic volume is.

Fig. 11.13. The western ringroad in Ingolstadt, with porous asphalt one year old. A noise barrier has been built on the side of the road facing the residential area to obtain the desired noise reduction in combination with the low-noise road surface. Total paved width is 10 m. Photo from [Ingolstadt, 2007].

Noise reduction was measured with the SPB method on both cars and trucks with average speeds around 50 km/h, and the results are summarized in Table 11.3. The data have been compiled by this author from [LfU, 2006][LfU, 2007]. The surface before repaving was probably a "non-grooved" Gussasfalt, which is a mastic asphalt which is probably 1-2 dB noisier than a DAC 0/11 or SMA 0/11; rather close to the German reference surface described above.

Some construction data:

- Top layer 25 mm thick with 5/8 mm chippings "Diabas Edelsplitt", binder CTS special modified bitumen 6.5 % (by mass), air voids on Marshall cores 25 %. See Fig. 11.14 for grading curve.
- Bottom layer 40 mm thick with 11/16 mm chippings "Diabas Edelsplitt", binder CTS 4.5 % (by mass), air voids on Marshall cores 32 %. See Fig. 11.14 for grading curve.
- SAMI layer 10 mm (bitumen 2.5 kg/m^2, chippings 11/16 mm).
- Several layers under this, of which one 400 mm thick layer is for frost protection.
- Total thickness, including the frost protection: 810 mm.

Note the extremely high voids contents of both layers, which is obtained by the extremely steep grading curves.

Table 11.3. Compilation of results of noise measurements on the double-layer porous asphalt laid in 2005 on a low-speed road in Ingolstadt, Germany. The data have been compiled by this author from [LfU, 2006][LfU, 2007].

Measurement point and vehicle type considered	Measurement in 2004 before repaving	Measurement in 2005 after repaving	Measurement in 2007 at age of two years	Noise reduction in 2007 (at age of two years)
Meas point 1 Cars	70.7	61.9	62.9	7.8
Meas point 1 2-axle heavies	77.7	70.8	70.1	7.6
Meas point 1 >2-axle heavies	80.0	74.2	73.8	6.2
Meas point 1 SPBI (mixed traffic)	72.4	64.7	64.9	7.5
Meas point 2 Cars	73.0	64.6	64.3	8.7
Meas point 2 2-axle heavies	78.7	73.8	72.6	6.1
Meas point 2 >2-axle heavies	81.3	76.9	75.0	6.3
Meas point 2 SPBI (mixed traffic)	74.3	67.5	66.6	7.7

The surface is cleaned in spring-time and in autumn-time. It has been noticed that the drain holes on top of the drain get clogged, thus they are cleaned too. The cleaning of 1 km of 10 m width took 5 hours in 2006, the cost of which was EUR 8800. After two years (2007), some minor ravelling had been noticed at the light-controlled intersection, which is recommended for further observation; albeit it was still acceptable after two years [Ingolstadt, 2007].

The results are so far, after two years of operation, very positive, with noise reductions high from the start and still after two years with no significant deterioration. It is reported that the cost of this measure, including a 3-4 m tall noise barrier, is only about half of the expected cost of an SMA surface combined with a noise barrier tall enough to give the same total noise reduction [Ingolstadt, 2007].

The expected lifetime is 8 years, with the expectation that at least 5 dB of noise reduction shall remain after 6 years (i.e. the German requirement for a low-noise road surface).

Comments by this author: Note that one side of this road faces a park area, which potentially could cause some extra dirt generation. However, the very small noise reduction loss after two years can probably be assigned to the following facts:

- *Both layers have extremely high voids content, able to accommodate more dirt than usual*
- *Regular cleaning is performed twice per year*
- *An advanced drainage system is employed at the roadside, which avoids dirt staying permanently on the surface. Also, the transverse gradient is as high as 2.5 %.*

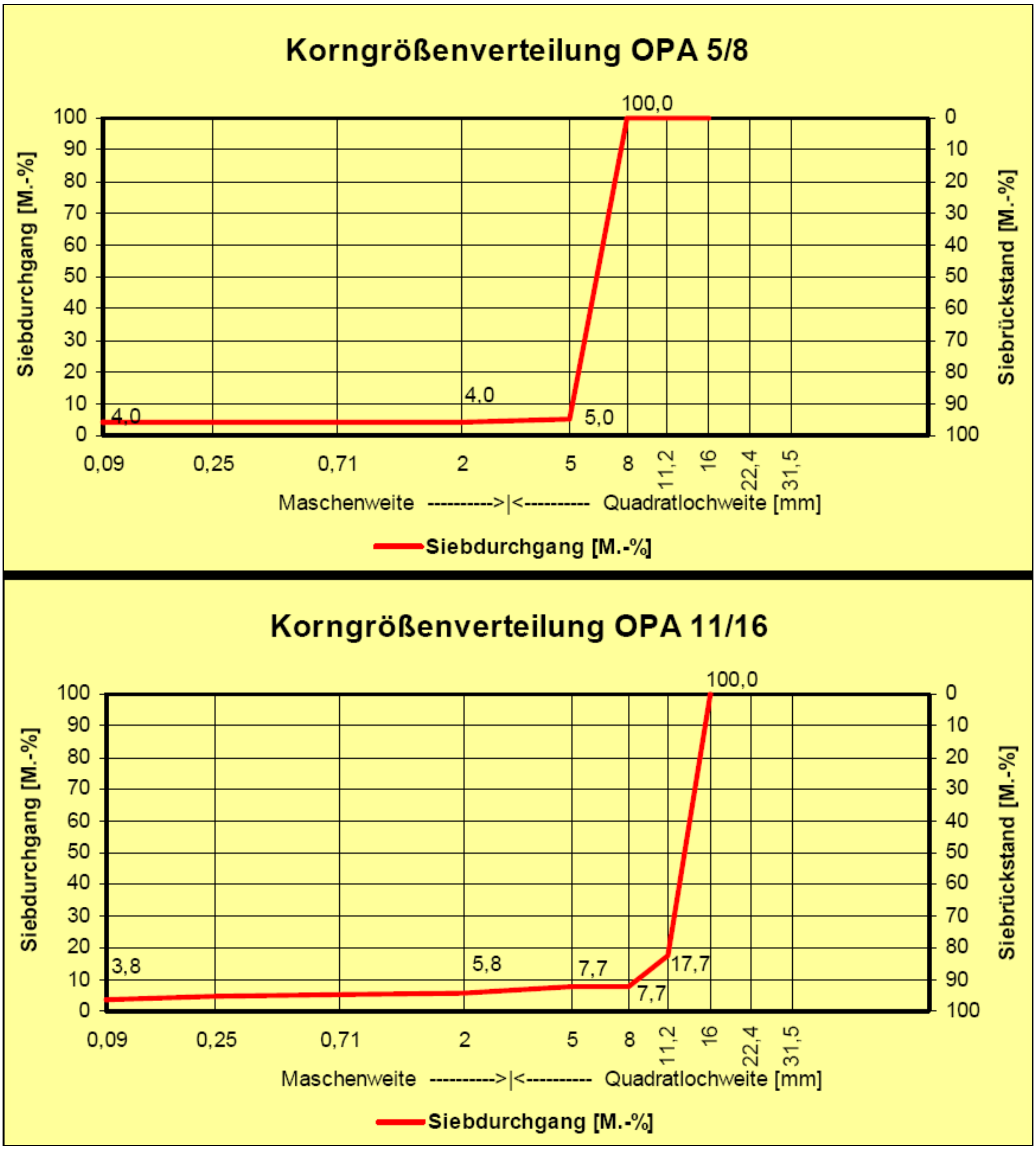


Fig. 11.14. The grading curves of the upper layer (top part of the diagram) and the lower layer (bottom) are shown above. The vertical scale shows percent passing by mass and the horizontal scale shows sieve size in mm. Diagrams from [Ingolstadt, 2007].

11.3 Switzerland

A survey in 2004 showed that there were then 131 km of porous asphalt (PA) surfaces in Switzerland. There has been positive but also some negative experiences with PA in Switzerland. The quality of porous asphalt surfaces among the 8 of the 26 Cantons in Switzerland which use PA is very heterogeneous. Canton Vaud is known as one of the leaders with respect to their promoting and using porous asphalt. As a result of their positive experience, currently, 1/3 of the Vaud motorways are covered with porous asphalt and the use of PA will be extended to most of the motorway surfaces in the Canton Vaud up to an altitude of 600 m. In addition, there are several bridge trial sections with PA [Poulikakos et al, 2006].

The Swiss standard recommends that only polymer modified binders be used. Typical voids content by volume of cores is 20-24 %. Maximum aggregate size is most frequently 11 mm but also 8 mm exist (top of double-layer PA).

An observation which is typical of Alpine countries is that noise emissions were significantly increased due to extensive raveling caused by the use of snow chains by trucks in winter. This resulted in one surface laid in 1991, increasing its noise emission (which initially was 4-6 dB below the DAC reference) substantially until it was repaved in 2005 when ravelling had become too severe. Where such problems do not occur it is expected that the acoustical lifetime could be up to 15 years [Poulikakos et al, 2006]. This would be for high-speed roads.

Poulikakos et al showed one example of how noise reduction changes with age of the surface; see Fig. 11.3. Two sites were monitored over 7-9 years. Amazingly enough (this author's comment) noise reduction remained at the initial high level or even increased somewhat with time.

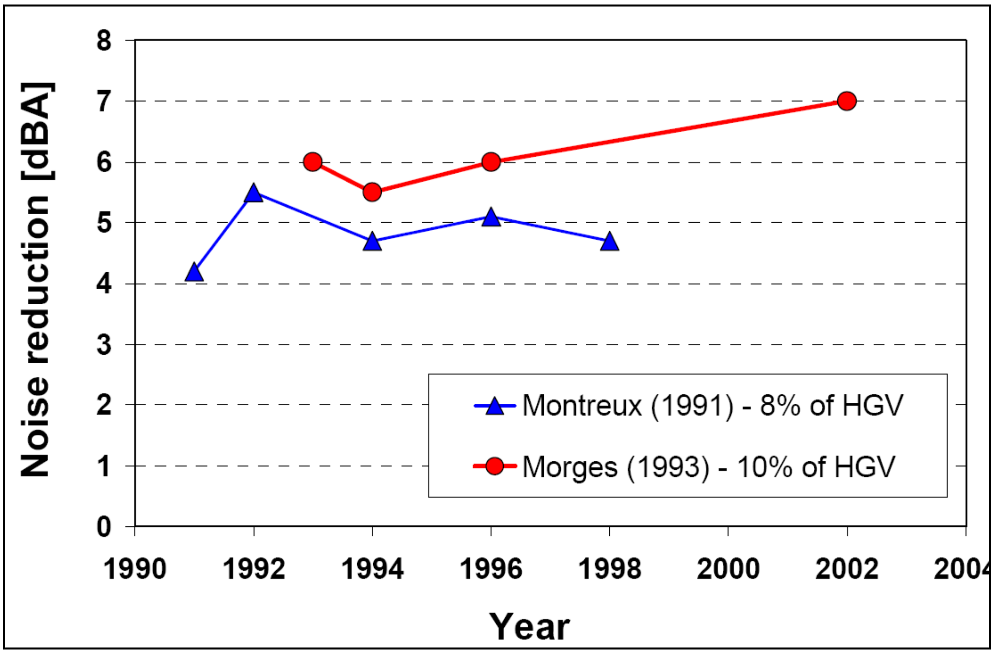


Fig. 11.3. Change in noise reduction of PA versus DAC, as a function of time, on two Swiss sites [Poulikakos et al, 2006].

Several Swiss research projects on porous asphalt have been conducted recently or are ongoing. One is on LNRS for urban areas, which means in this case traffic at speeds under 60 km/h. The final results of this project are reported in [Angst et al, 2008]. Selected results from this project are presented below.

Over a three-year period, tyre/road noise and pavement texture were periodically measured on a series of 21 full-scale sites situated in urban areas with a speed limit of 50 km/h. The study involved a wide range of supposedly noise-reducing asphalt mixtures, including for example “semi-dense macro rough asphalt (AC MR)” and porous asphalt (PA).

It was shown that the acoustic performance decreases asymptotically with time, as a function of traffic volume. For PA the decrease can be delayed if clogging can be avoided. For the research project, urban pavements were defined as “low-noise” if they achieve an initial noise reduction of at least –3 dBA for mixed traffic, compared with the reference pavement of the Swiss standard noise calculation model STL 86+, and if they retain a noise reduction of at least –1 dBA over their intended lifetime.

Fig. 11.4 shows a summary of all measured A-weighted overall levels expressed as SPB Index for a mix including 8 % of heavy vehicles and a reference speed of 50 km/h. The values are noise reductions compared with the Swiss STL-86+ noise prediction model model, which is based on “an average reference pavement which is neutral in acoustic terms”.

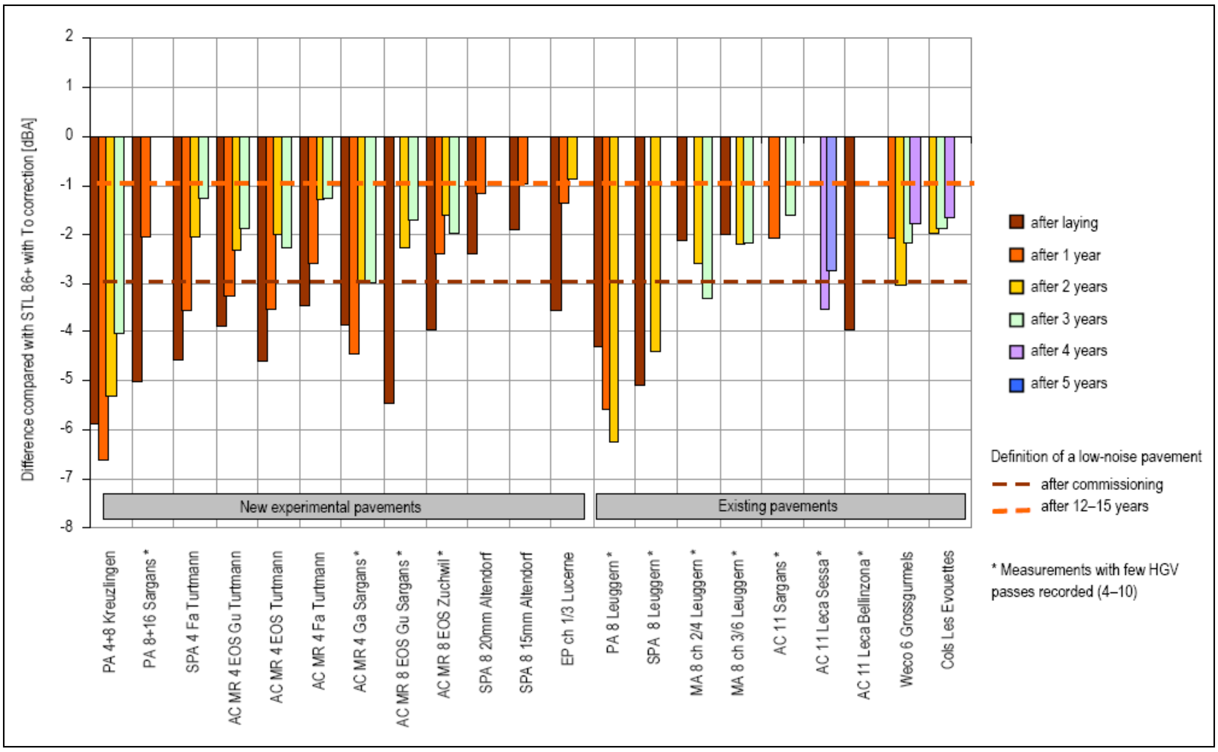


Fig. 11.4. Results of the 2004-2007 measurement campaigns in Swiss urban areas [Angst et al, 2008]. Some notes regarding the road surface terms: PA = porous asphalt, AC = asphalt concrete, MR = “macro rough” (means gap-graded), EOS = electric furnace (steel) slag, Leca = expanded clay of type “Leca”, MA = mastic asphalt, SPA = “aggregate asphalt”, Gu = rubber, Cols = Colsoft 8. The surfaces marked with an * means that on these sites there were only 4-10 heavy vehicles included in the SPB calculations.

The figure shows that the porous asphalts offer superior acoustic performance; up to 7 dB noise reduction for the double-layer PA with 4 mm aggregate in the top and 8 mm in the bottom layer. This is still 4 dB after 3 years of operation; nevertheless it was observed that the surface was clogged by that time. Similarly, the single-layer PA with 8 mm max aggregate offers 4 dB noise reduction initially and 6 dB after two years. The latter should offer very good cost/beneft ratio.

However, also the thin layers offer good results. The AC MR surfaces generally offer 4-5 dB noise reduction initially which is reduced to 1-3 dB after 3 years, depending on the location.

The double-layer PA (4+8 mm) was clogged after three years. Cleaning with high-pressure water was tried but there was no improvement observed.

Fig. 11.5 shows a compilation of the noise reductions as a function of the cumulative traffic load. The latter is taken as the number of vehicle passes since opening of the test section, based on average daily traffic (ADT) measurements. It appears that most pavements deteriorate approximately at the same rate, which is 3 dB per 8 million passes, but with an asymptotic approach to approximately the -1 dB level.

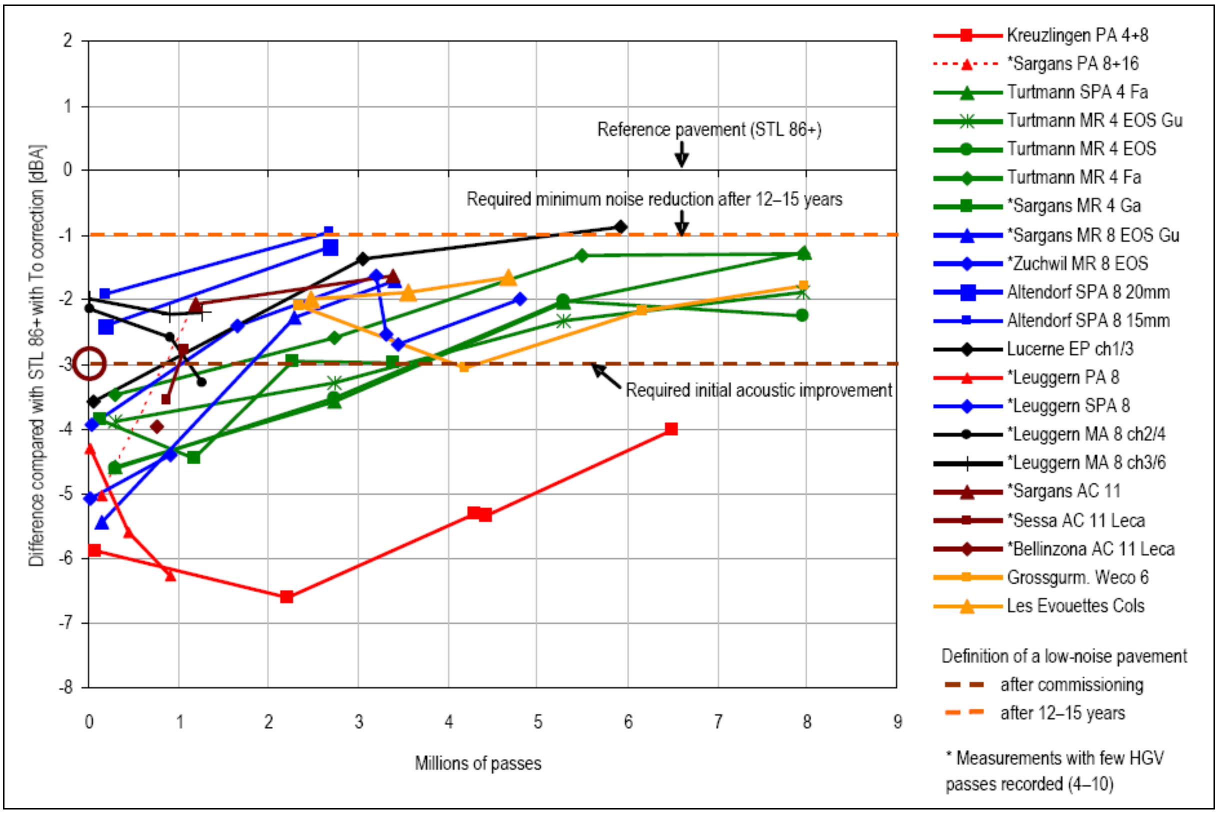


Fig. 11.5. Acoustic performance of the Swiss urban pavements as a function of the cumulative traffic load with mixed traffic (8 % heavies). The number of vehicle passes since commissioning was calculated on the basis of ADT. From [Angst et al, 2008]. Colour legend: Red: porous pavements. Green: max aggr size 4 mm. Blue: max aggr size 8 mm. Brown: max aggr size 11 mm. Black: "gravels" (mastic asphalt). Orange: special proprietary pavements.

The preparation of very fine-grained thin-layer surfaces with gap-grading, such as AC MR 4 or even PA 4 (4 mm max aggregate) was difficult but feasible. Stringent requirements must be imposed on the regularity of the grain size distribution of the 2/4 aggregate. Some of these surfaces used uncommon additives such as rubber granules and electric furnace slag (EOS), but none of these uncommon materials constituted any problems.

It was concluded that the PA pavements studied were superior to dense pavements in acoustic terms, even here in urban areas [Angst et al, 2008]. However, they do impose stringent requirements. Laying PA pavements is very demanding and they are more expensive than dense or semi-dense pavements. In addition, they are highly sensitive to shear stresses (snow chains, intersections, exits and entrances, roundabouts), and this makes their acoustic lifetime more uncertain (ravelling is the major problem). Moreover, they require special maintenance, such as winter service and cleaning. The technical lifetime of this type of surface in urban locations remains to be optimised.

PA pavements are recommended to be laid only in special situations, for example on by-passes with continuous traffic or on sections with especially stringent acoustic protection requirements. General use of PA pavements in urban areas is currently not recommended.

It was further concluded that AC MR shows promising acoustic and structural performance for use in urban areas. AC MR in urban areas may achieve acoustic lifetimes of up to 10 years depending on the traffic volume. These are asphaltic thin layers with a special gap-graded aggregate which gives a "macro rough (MR)" texture, despite the low maximum aggregate size. The version with maximum 4 mm aggregate (AC MR 4) is nominally 15 mm thick and the version with 8 mm aggregate (AC MR 8) is nominally approx. 25 mm thick.

Thus, the following recommendations were presented [Angst et al, 2008]. First, the following pavements were recommended, as one "safe and proven" solution, and as one "promising" solution:

- *A proven solution, without risks and with good acoustic performance:*
Standard material AC MR 4 or AC MR 8 according to Swiss standard SN 640 431-1b-NA (valid from 01.02.2008) with a voids content of 6 to 10 % by volume.

- *A promising solution, potentially with excellent acoustic performance:*
Non-standardised material AC MR 4 or AC MR 8 with a higher voids content of 10-13 % by volume.

It is further recommended to use a special binding layer under the thin layer:

"*Thin-layer pavements require a stable, smooth substrate. This can be guaranteed by using an appropriate pre-laid binding layer. This also meets the requirements for trouble-free periodic replacement of the thin-layer pavement.*"

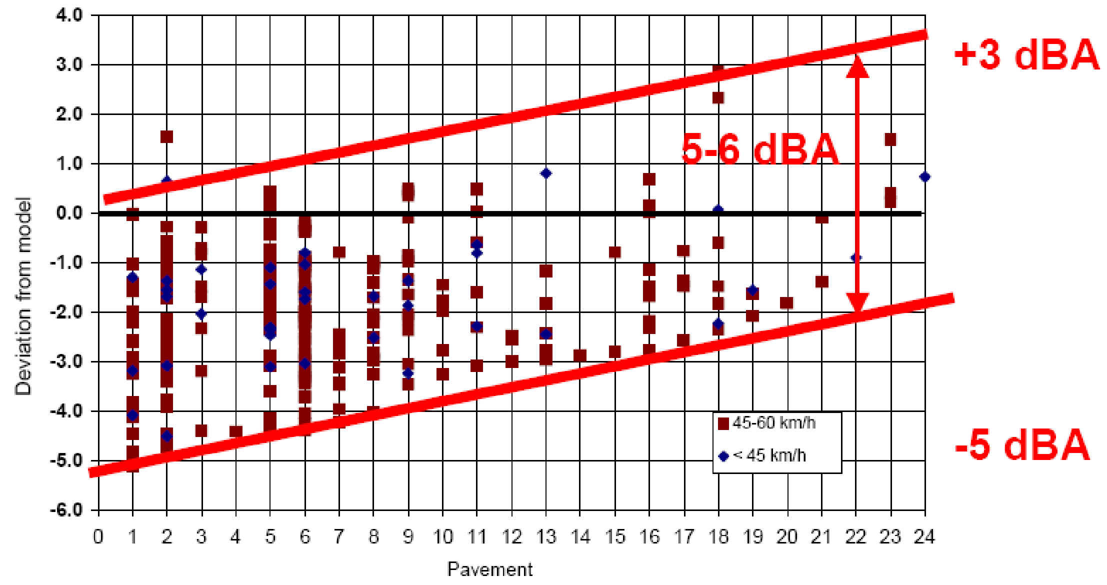
Consistent use of thermosilos for trucks used in the paving process is recommended. Compaction must take place immediately behind the production unit, using smooth, non-vibrating rollers.

Finally, it is also stated [Angst et al, 2008]:

"*The recommended pavements achieve good to very good initial acoustic performance. The 3-year observation period, however, does not allow any conclusive statements to be made regarding their long-term acoustic performance. The pavement design with a binder layer and a thin-layer surface, however, allows simple, economical replacement of the thin-layer surfaces as soon as their acoustic performance no longer meets the requirements. The time for possible necessary replacement of the wearing layer is determined by acoustic monitoring, which is obligatory with the use of low-noise pavements as a remediation measure according to the FOEN/FEDRO guidelines*."

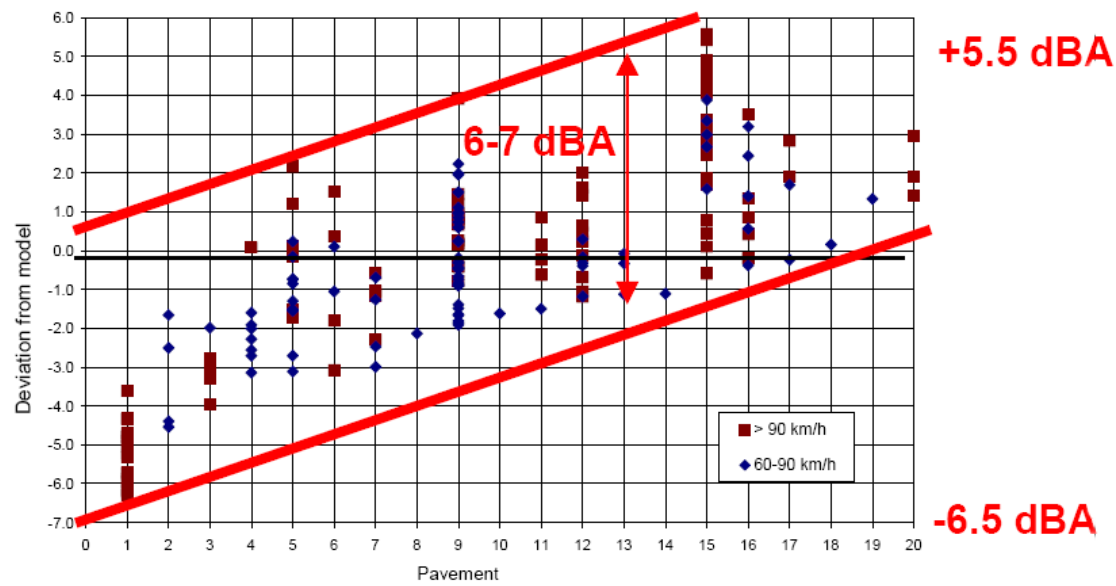
In Switzerland, the two Governmental offices responsible for roads and the environment (FOEN/FEDRO) wish to encourage the large-scale use of this type of pavement. According to the foreword in [Angst et al, 2008] they intend to proceed with a research and awareness-raising programme, incorporating all interested parties, in order to extend knowledge of the long-term performance of these road pavements.

A presentation of Swiss noise measurements, related to the Swiss classification procedure for LNRS, gives further insight into the effect of LNRS in Switzerland [Schguanin, 2008]. Figs. 11.6-11.7 show the variation in noise levels between different pavement types, as well as the spread within each pavement type. Pavements here include both conventional ones and LNRS. The latter is measured at different sites and with pavements in different condition. Fig. 11.6 is for urban low-speed roads and Fig. 11.7 is for high-speed roads. It appears that the variation within each pavement type is equally large as the variation in noise between pavement types. This is especially for low-speed applications; for high-speed applications, the difference between pavement types is greater.



	1 SPA6	6 SMA8	11 TA16	16 TA10	21 OB 6/11
	2 SPA8	7 Monok. 6	12 SMA10	17 OB	22 MR8
	3 SPA11	8 AB11	13 SMA6	18 AB16	23 Beton Concrete
	4 MR6	9 AB10	14 HMT16	19 MR11	24 PflasterCobbles
	5 SMA11	10 GA	15 OB 3/6	20 OB6/10	

Fig. 11.6. Spread in noise levels between different pavement types, as well as within each pavement type. For urban low-speed roads. From [Schguanin, 2008].



	1 PA11	5 AB10	9 SMA11	13 TA10	17 TA16
	2 SPA6	6 SPA11	10 OB10	14 OB	18 OB 6/11
	3 PA10	7 MR11	11 SMA8	15 Beton	19 GA11
	4 AB11	8 HMT	12 GA	16 AB16	20 SMA16

Fig. 11.7. Spread in noise levels between different pavement types, as well as within each pavement type. For high-speed roads. From [Schguanin, 2008].

12. EXPERIENCE IN USA

12.1 Introduction

In USA the focus with regard to noise properties of pavements have been on either on reducing the high-noise properties of most Portland Cement Concrete (PCC) pavements, or on the low-noise properties of asphalt rubber pavements. Porous asphalt with high voids content, and especially double-layer porous asphalt, as well as thin layers, have hardly at all been researched in the US. More about the two focus areas later. Initially, it is worth noting that all research on quiet pavements[58] (or quieter pavements as is currently the preferred term in the US) have been made on high-speed roads; mostly with speed limits of 55 mph or higher (90 km/h or higher).

Current noise abatement policy of the Federal Highway Administration (FHWA) does not allow the use of pavement type or surface texture as a noise abatement measure. As Arizona Department of Transportation (ADOT) has identified asphalt rubber pavements as a major noise-reducing measure (in relation to the conventional pavements used in Arizona) the ADOT has asked the FHWA for an exemption to the above policy, i.e. for approval to implement a Quiet Pavement Pilot Program (QPPP), specifically to use asphalt rubber friction courses on selected freeway segments in the Phoenix area to reduce noise. The FHWA approved ADOT's QPPP in June 2003. More about this policy can be found in Secition 17.5.

Apart from the QPPP project in Arizona, research is ongoing at the FHWA and the Volpe Center for assessing options for implementing into the Traffic Noise (prediction) Model (TNM) the effects of pavement on tyre/road noise. There is a study called "TNM Pavement Effects Implementation Study (TNM PEI Study)" performed with Mrs Judy Rochat as project leader. This project is focused on four pavement types for proof of concept, namely open-graded rubberized asphalt (asphalt rubber), dense-graded asphalt (DGAC[59]), longitudinally tined PCC[60] and transversely tined PCC. Measurements and evaluations are made not only for locations close to the road (in the USA, the standard position is 15 m from the middle of the nearest lane rather than at 7.5 m in other countries) but also for locations at about 100 m or more away from the road. The project was (2008) in a final phase.

Apart from the above, major research on quiet pavements has been made by Transtec in Texas, not only in Texas but, moreover, in a number of other states, such as Iowa and Colorado. The Transtec research has had a certain focus on PCC (but not only). Other major research has been made and is being made in Washington State (including asphalt rubber and open-graded asphalt) and also at the National Center for Asphalt Technology (NCAT) in Alabama. Finally, maybe one shall mention that a lot of trials with asphalt rubber have been made also in other states, not the least in New Jersey.

[58] In other parts of this report the author uses Low Noise Road Surfaces (LNRS) as the preferred term, as this would be preferred in British English, but as the Americans use ”Quiet pavements” this is the term preferred in this chapter about USA.

[59] As would be designated DAC in other parts of this report – DGAC is the preferred term in USA.

[60] PCC = Portland Cement Concrete. There is no major difference between "Portland" and cement concretes used in road construction in other industrialized countries; the term is used for historical reasons.

12.2 Asphalt rubber in Arizona

12.2.1 General remarks

Traditionally, motorways and major highways in Arizona have used Portland Cement Concrete (PCC) as wearing course. This is the case also in most other states. To reduce the risk of hydroplaning, these surfaces have mostly been produced with transversal tining. This type of wearing course and the texture it gets due to the tining is generally one of the most noisy road surfaces that is commonly used. People in the US frequently complain about the noise emitted from traffic on such surfaces; especially if the tining is regular (periodic) in which case the noise is perceived as extra annoying due to the tones created by the tyres rolling across the tines. In Europe surfaces with such textures were abandoned in the 1970's and 1980's due to the noise characteristics but in the US they continue to be widely used even today.

Following the successful resurfacing in the early 1990's of a 18 km stretch of US 60, the 'Superstition Highway', Arizona Department of Transportation (ADOT) in 2002 launched an asphalt rubber resurfacing project worth $34 million encompassing 172 km of freeways paved with PCC in the greater Phoenix area. These new pavements have been received extremely well by the public; people have noticed a remarkable reduction of traffic noise[61] and there have been requests to repave virtually all other roads by asphalt rubber. Since 1988 Arizona has paved one third of its road network (3,600 out of 11,100 km) with asphalt rubber overlays and the state has now begun to use asphalt rubber as a material also for new roads [Aspro, 2005]. The overlays have performed amazingly well. As an example, the first full-scale non-experimental overlay south of Tucson, constructed in 1988, still in 2006 had sections in acceptable condition [ADOT, 2006].

Although asphalt rubber first was used widely as an overlay on PCC, ADOT has extensive positive experience using asphalt rubber mixtures to overlay also asphalt roads; actually more experience than overlaying concrete [Nodes, 2005].

A wealth of information on asphalt rubber, including an on-line library, can be found at the website of the Rubber Pavements association (RPA): http://www.rubberpavements.org

12.2.2 Material, construction and laying of asphalt rubber pavements

Asphalt rubber is different from conventional asphalt mainly because it contains a substantial part which is small rubber granules ("crumb rubber"); see Fig. 12.1. Instead of mixing the bitumen binder directly with the aggregate as in conventional asphalt, crumb rubber is first mixed with the bitumen to create a modified binder. The process can include a portable asphalt rubber plant, consisting of a mixing unit and two tanks. As the bitumen is heated, the crumb rubber is mixed in. After curing, the mixture is mixed with the aggregate in the normal way.

Today, rubber content is generally around 20 percent by weight of the total (modified) binder. The amount of binder needs to be higher than normal; generally around 6.5-10 % of the total asphalt mix, which means that the total rubber content is typically 1.3-2.0 % by weight of the total mix leaving the plant. This process of mixing bitumen and crumb rubber together is

[61] Author's remark: not unexpected, since the PCC pavement replaced is extremely noisy

called the “wet process”, as opposed to the “dry process” in which the rubber granules are added to the mix as a supplementary aggregate[62].

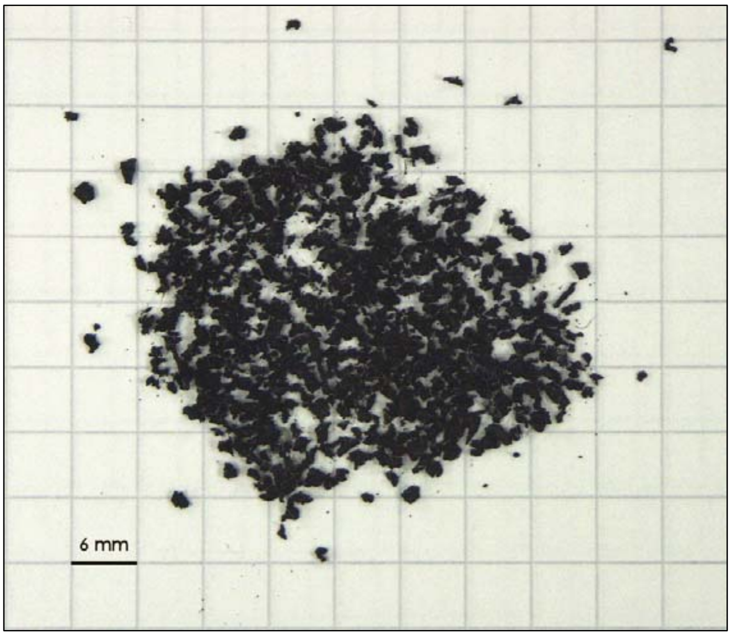


Fig. 12.1. Crumb rubber for use in the Arizona asphalt rubber pavements. Square mesh of background is 6 x 6 mm. The maximum size of the rubber granules is 1.2 mm. Such particles are mixed with the bitumen before this mix is used as a binder.

As regards the aggregate, generally, there are two variants: gap-graded and open-graded, either of which allows more room for the rubber/bitumen binder to penetrate and fill the voids in the aggregate, so that the resulting mixture has a thick binder film[63]. The gap-graded one, which is used as a structural layer, has an aggregate size distribution rather similar to an SMA surface and the voids content achieved is also similar to that of an SMA; i.e. very low; typically around 5.0 to 5.5 %. The gap-grading is necessary to allow space for the rubber chunks in the binder. Binder content is 6.5-8.0 % and nominal thickness would be approx. 50 mm [Nodes, 2005]. The maximum aggregate size is generally 3/8” which is equal to 9.5 mm [ADOT, 2006].

The open-graded variant, on the other hand, has a grading curve which is similar to that of open-graded asphalt; i.e. a little less open than porous asphalt, and is used as a wearing course. Voids content is generally in the range 15-18 %. It is quite similar to many of the thin layers used in Europe with voids contents 15-20 %. However, it is important to note that asphalt rubber, in contrast to porous asphalt or open-graded asphalt is not pervious. Water cannot so easily run through it, since the thick and “fat” binder will close the pores. Typical binder contents range from 9.0 to 9.8 % [Nodes, 2005]. Yet there is a relatively high voids content, but the voids/pores are mostly closed. In this way, this author thinks that they together with the binder may form a kind of “air cushion” which may increase the softness and flexibility of the surface. As an overlay on asphalt pavements it is typically placed with a nominal thickness of 12.5 mm and on concrete pavements with a nominal thickness of 25 mm. Thus, it may be considered as what we in Europe call a thin layer.

The asphalt rubber binder in these mixtures uses PG64-16 (low-elevation desert locations), PG58-22 (middle elevations) or PG52-28 bitumen and is required to contain a minimum of 20 % ground tyre rubber by weight of the asphalt cement. The exact amount of rubber required is

[62] To read an example about the use of the dry process, see Section .10.6.3
[63] See a description of the differences at http://www.asphaltrubber.org/library/difference.asp

a function of the development of other tested properties (viscosity, penetration, resilience and softening point). The gradation of the rubber will also impact the amount of rubber required to meet the specific properties. The DoT does not allow the use of extender oils or rubber from sources other than tyres in their asphalt rubber binders [Nodes, 2005].

Laying the asphalt rubber mix differs slightly from laying conventional asphalt. Pneumatic-tyred rollers cannot be used since they pick up rubber from the mix, so steel-wheeled rollers are used for compaction throughout. It is important to realise that asphalt rubber is less forgiving than conventional asphalt in terms of timing and temperatures. The technique is essentially the same – there is just less margin for error [Aspro, 2005]. When these surfaces were first laid in Sweden in 2007, it took the paving crew one or two km of adjustments and trials until the first very inhomogene and patchy, "fat", surface could be avoided. The first lane-kilometres had to be milled in some lateral tracks due to them becoming too smooth and "fat".

When looking at the surface after laying, compared to a conventional asphalt mix, the asphalt rubber looks "fatter"; the aggregate is covered more effectively by the binder. Within the structure of the mix, the binder (and its rubber) embraces the chippings to a larger extent than in conventional asphalt and a kind of "cushion" is covering the chippings; making the surface somewhat softer than conventional asphalt. See an example in Fig. 12.2. A typical application is shown in Fig. 12.3.

Fig. 12.2. Asphalt rubber pavement of type ARFC newly laid on a tined cement concrete pavement. The max. aggregate size is 9.5 mm. At this location the layer thickness was appr 25 mm; normally it would be 12.5 mm. May 2007, Interstate I10 through Phoenix.

12.2.3 Terminology

The two different types of mixtures with asphalt rubber are designated in Arizona as follows. The gap-graded one is called Asphalt Rubber Asphaltic Concrete (ARAC), or just Asphalt Rubber (AR), and the second they call Asphalt Rubber Asphaltic Concrete Friction Course (AR-ACFC) or just Asphalt Rubber Friction Course (ARFC).

Fig. 12.3. Typical application of ARFC pavement: Interstate I10 through Phoenix has a newly laid ARFC in one direction. The other direction, being temporary closed for paving, still has a tined cement concrete pavement.

12.2.4 Durability

It is the experience that durability is one of the most important, if not the most important, positive property of asphalt rubber. Not only have the asphalt rubber surfaces in Arizona needed a minimum of maintenance; they are also self-curing on top of cracked PCC. The author has seen AR surfaces in Phoenix laid on PCC where the joints between the PCC slabs are reflected through the wearing course as severe cracks, but where traffic is running (i.e. in the normal lanes) the cracks have become automatically "filled" and the cracks can be seen only on the shoulders where traffic is not running. This proves that the mix stays flexible enough to be able to continuously fill such cracks.

Dr Nodes believes that they get such good durability from these mixtures because they typically contain at least 2 % more binder than one would get in similar mixtures using asphalt cement. In addition, they restrict the aggregate absorption to 2.5 % water absorption and 1.0 % asphalt absorption. They also require the use of asphalt cement as a tack coat before application of asphalt rubber mixtures (in traditional mixtures SS-1 1:1 dilute emulsion is more commonly used) [Nodes, 2005].

12.2.5 Noise properties

As early as 1981 a Belgian study found that an open-graded asphalt rubber pavement reduced noise by 8-10 dB[64]. Nominally high noise reductions always impress journalists and people who are not so good noise experts. It must be pointed out that the Belgian result was in comparison to an extremely noisy cement concrete surface. This author thinks that this is what could be expected also from conventional porous asphalt. The Arizona Department of

[64] See http://www.asphaltrubber.org/library/noisereduction.asp

Transportation (DoT) conducted a noise study of Interstate 19 after resurfacing and found that noise had been reduced by 7 dB [Aspro, 2005]. This author thinks that also this is what could be expected from conventional porous asphalt when it is compared to a normal tined PCC.

As part of the Arizona QPPP (see 12.1 and 17.5), noise is being measured over time to evaluate the noise-reducing capabilities of ARFC as the pavement ages. Throughout the project area, source measurements taken with the OBSI method (a US variant of the CPX method) have shown reductions from transversely tined PCC to be on average 8 dB when the pavements were new and stabilized at 6 dB after a few years of service [Rochat, 2009]. Wayside measurements taken adjacent to the highway, 15 m from the nearest lane, at select research sites have shown noise reductions from transversely tined PCC to be on average 9 dB after one year of service; see Figs. 12.4 and 12.5 [Rochat, 2007]. With regard to the effect of age, limited data show an average decrease in reduction of about 1 dB per year over a few years time [Rochat, 2009]. Note that the spectra of the ARFC in Fig. 12.5 indicate that there might be some sound absorption between 800 and 1600 Hz which would be typical for a thin porous pavement. The acoustic longevity of ARFC will be evaluated as the program continues through the life of the pavement.

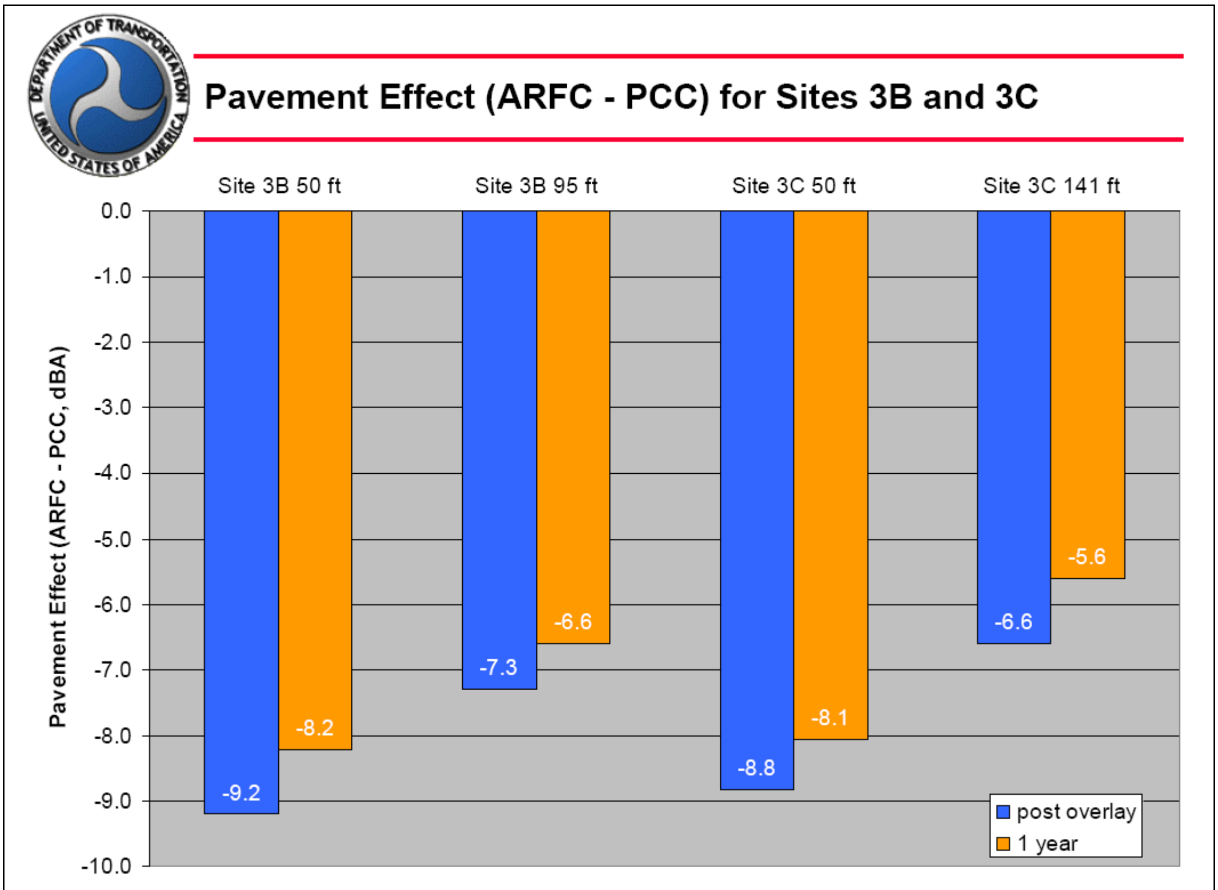


Fig. 12.4. Noise reductions at two ARFC sites measured in comparison to a tined PCC pavement. Measured values are L_{Aeq} values from the actual traffic normalized with respect to vehicle composition and speed. Two distances from the nearest highway lane were used: 50 and 95 ft (15 and 29 m) for Site 3B and 50 and 141 ft (15 and 43 m) for Site 3C. Blue bars are values measured soon after laying of the pavements, orange bars are values measured after one year of road traffic exposure. From [Rochat, 2007].

The previous figures showed a comparison with a rather exceptionally "noisy" PCC pavement. How do the asphalt rubber pavements compare with conventional asphalt pavements? Measurements of this have recently been made in Arizona [Biligiri et al, 2008]. They tested five different pavement types, of which one was an ARFC (=AR-ACFC):

- Asphalt Rubber Open Graded Friction Course (AR-ACFC), max aggr size 9.5 mm
- ADOT Standard Open Graded Friction Course (ACFC), max aggr size 9.5 mm
- Polymer Modified Open Graded Friction Course (P-ACFC), max aggr size 9.5 mm
- Permeable European Mixture (PEM), max aggr size 19 mm
- Stone Matrix Asphalt (SMA), max aggr size 12.5 mm

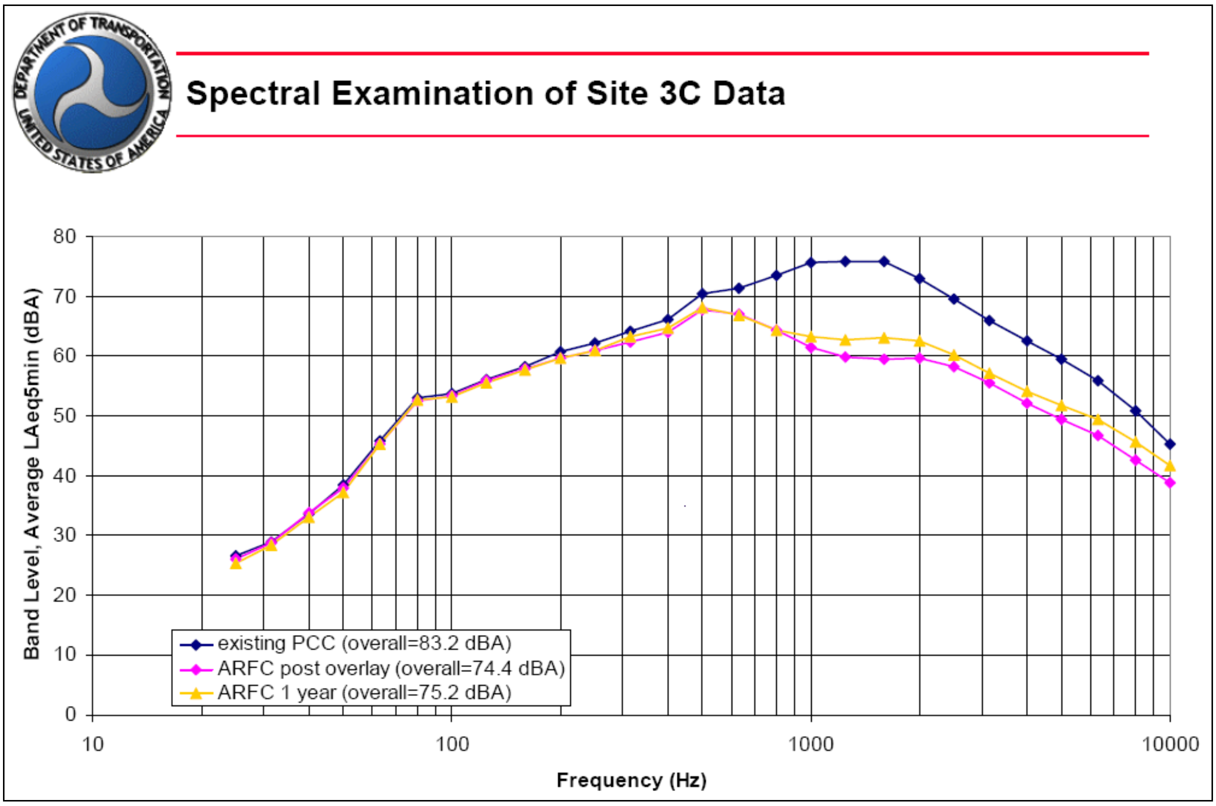


Fig. 12.5. Third-octave band frequency spectra for the 3C ARFC site measured in comparison to a tined PCC pavement. Measured values are L_{Aeq} values from the actual traffic normalized with respect to vehicle composition and speed. The distance from the nearest highway lane was 15 m. From [Rochat, 2007].

Fig. 12.6 shows results of measurements made in three different years with three variants of the CPX method at 97 km/h (60 mph). From Fig. 12.6 one can conclude that the extra noise-reducing effect of the rubber seems to be 1-3 dB depending on the equipment used and the time of measurement (this assumes that the AR-ACFC and the ACFC were similar except for the rubber, which is uncertain and difficult to achieve). The ARFC seems to be only 1-2 dB quieter than the regular SMA surface. Note that the ARFC has a max. aggregate size of 9.5 mm and the SMA has a max. aggregate size of 12.5 mm. Only this aggregate size difference should account for approximately 1 dB of noise reduction. Thus the effect of the ARFC in comparison to regular asphalt pavements used in Europe seems to be very small from this study. It is not known what the age or condition of the tested ARFC was, but it was stated that the ARFC surface experienced the least cracking and wear after 8 years of service.

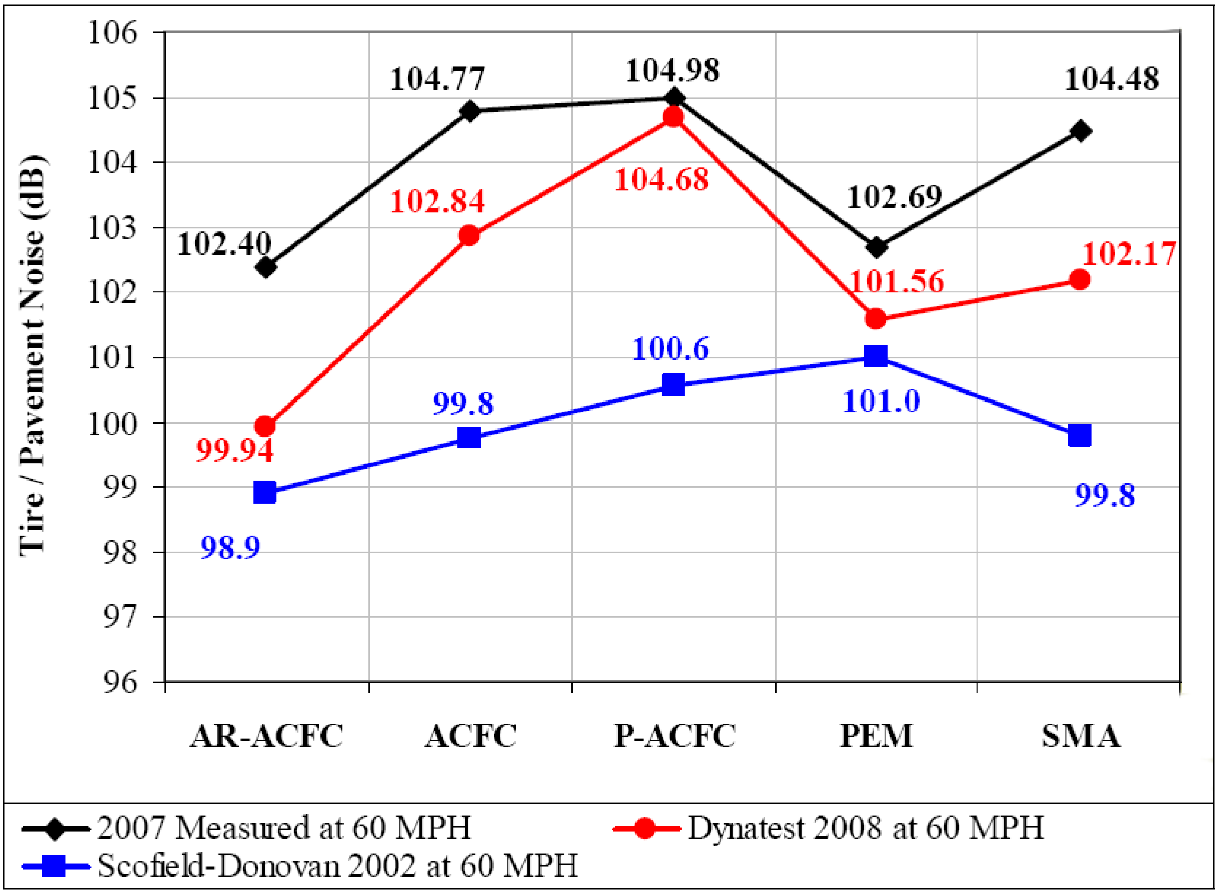


Fig. 12.6. Noise reductions of one ARFC pavement (AR-ACFC) measured in comparison to four other asphalt pavements. The ACFC is a pavement similar to AR-ACFC but without rubber. P-ACFC is also similar, but has a regular polymer modified binder. The SMA surface would be similar to many European asphalt surfaces, such as SMA 0/11. Measurements were made with three different types of CPX equipment, although the blue curve had a microphone in front of the test tyre. From [Biligiri et al, 2008].

How do the ARFC compare to the LNRS in Europe? Fig. 12.7 presents a comparison made in the so-called NITE project, in which CPX-OBSI equipment from California was brought to Europe and measurements were made on both continents in the same year with similar equipment and the same crew [Donavan, 2005]. It appears that the ARFC (which is probably a new one) is almost 2 dB quieter than its Californian counterpart and only about 1 dB noisier than the best European ones. However, it should be noted that the temperatures during measurements might have given a consistent bias towards higher noise levels in Europe, although that effect (if any) should be at most 1 dB. This author speculates that there is a bias of approx. 2 dB in favour of the US pavements in Fig. 12.7, since when comparing European with US DGAC and SMA, there seems to be such a difference.

From these findings it appears that the noise-reducing properties of asphalt rubber surfaces are large when compared to the conventional surfaces used on Arizona freeways; i.e tined PCC, and that noise reduction is almost as large as for the best pavements in Europe (Fig. 12.7). A conflicting conclusion is that other results (Fig. 12.6 and Table 12.1) suggest that the ARFC is not a particularily quiet pavement when compared to regular asphalt pavements. That figure also suggests that a conventional ACFC (open-graded asphalt concrete) is not quieter than SMA, even though it has a smaller aggregate. This is extremely confusing. More measurements are needed to clarify this and they should be part of a systematic comparison with both PCC and other asphalt pavements.

Asphalt rubber has over the years become a noise-reducing option in Arizona. However; the FHWA has been hesitant to allow it to replace other noise-reducing options such as noise barriers, and currently Arizona is an exemption in a trial project to determine the feasibility to use asphalt rubber as a longterm viable solution for noise reduction. For example, the DoT has to show that the noise reduction is durable.

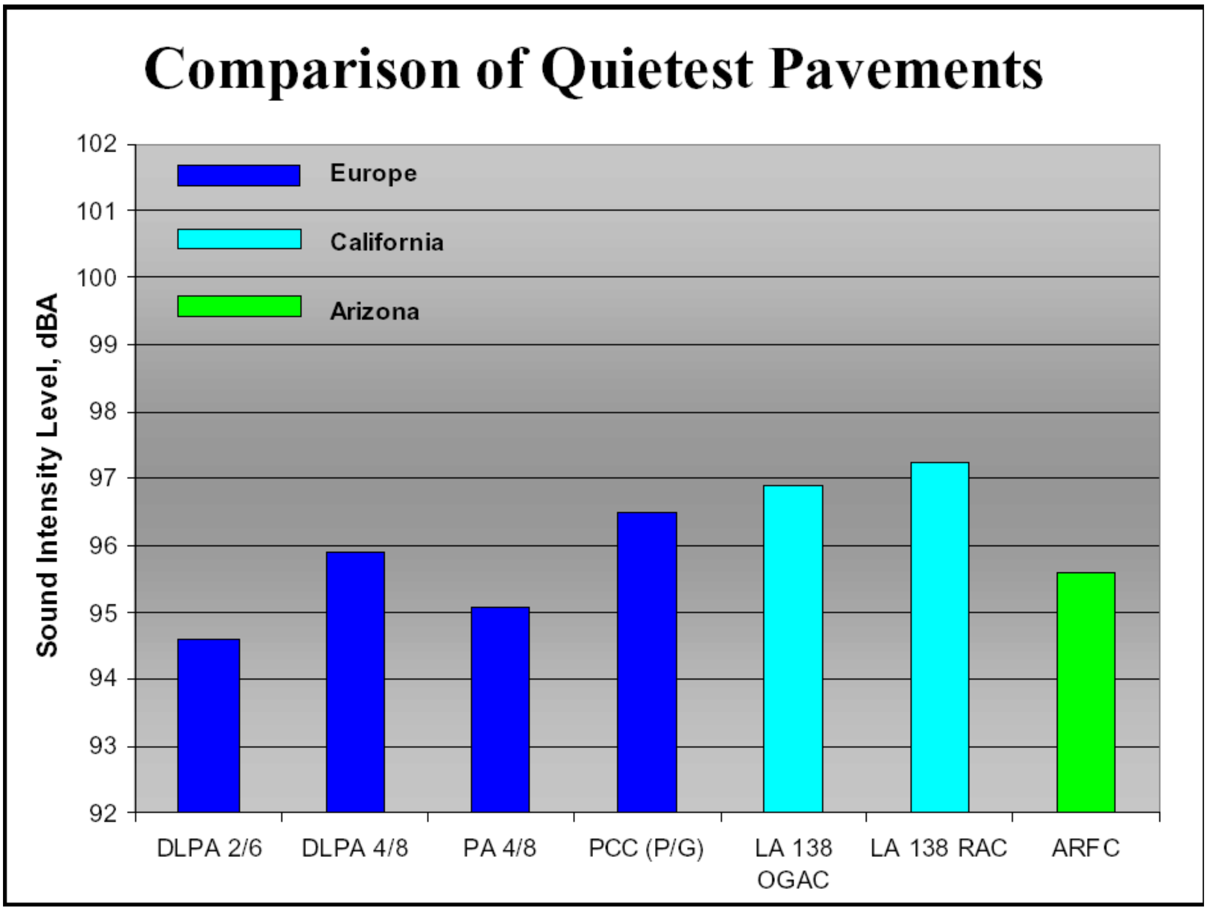


Fig. 12.7. Comparison of OBSI noise levels (sound intensity, but the method is quite similar to the CPX method used in Euriope) measured with similar equipment and same crew in USA and in Europe. The pavements listed are a sample of the quietest in each continent. DLPA is double-layer porous asphalt, OGAC is open-graded asphalt concrete and RAC is the Californian variant of asphalt rubber. The blue PCC bar represents the German porous cement concrete. From [Donavan, 2005].

12.2.6 Causes of noise-reducing properties

Provided there is indeed a substantial noise reduction of ARFC, what could it be due to? Is the inclusion of rubber the reason, is sound absorption (porosity in the mix) a major reason, or are there other reasons? The following is the current view of the author.

These are the main features which may contribute to low noise properties:

The ARFC has a significant amount of air voids. Although most of the voids are not interconnected, they are probably sufficient to create some sound absorption, especially when surface is new.

The macrotexture is favourable. Maximum aggregate size is fairly small. The surface texture has a "negative" profile; i.e. the main roughness is directed downwards as troughs and valleys. This means that the surface on which tyres roll is relatively flat and causes a minimum of vibration excitation due to texture impact on the tyre tread.

The thick binder with its rubber makes the chippings somewhat flexible as they sit in the mix. Especially during rolling (with a steel roller) the chippings can align themselves in the direction which gives the lowest local forces on them, which is the same as the alignment which gives the least vibration excitation to the tyres.

The much lower stiffness than normal which is created by the excess amount of binder and its rubber content makes the impact between tyre tread and surface texture softer (compare a rubber hammer knocking on stone and a rubber hammer knocking on rubber).

The embedment of chippings in the relatively thick binder film may also give a kind of "cushion" effect. The isolated small but many air voids in the mix may also act as an extra "cushion" making the surface softer.

High temperatures, such as are normal in Arizona, are known to reduce tyre/road noise. It may be that such effects are especially large on asphalt rubber due to the lower stiffness of the road surface (apart from that tyre rubber gets softer at higher temperatures).

The relative softness of the surface should cause a higher than normal dynamic deflection of the tyre/road interface under the load of tyres. This will then make the tyre/road contact at the leading and trailing edges somewhat smoother and not so abrupt, which would reduce vibration excitation.

In addition to the above speculations, it has been proposed that viscoelastic properties, especially the hysteretic losses in the asphalt rubber mix (when it is assumed to be deflecting under load or vibration-excited), may be responsible for the noise reduction [Sotil et al, 2006]. It has been proposed that the Dynamic Complex Modulus (E*) test would be a potential indicator for an asphalt mixture's tyre/road noise characteristics [Biligiri, 2008]. If this is the case asphalt rubber surfaces should also have high rolling resistance, which would not be desirable.

It could thus be that the advantages of asphalt rubber are becoming more important in very warm climates, since the asphalt rubber is likely to become quite soft at high temperatures which may make the surface texture more resilient to the impact of the tyre tread on the surface, and the increased flexibility at high temperatures may also make the alignment of the aggregate in relation to the tyre tread more optimal for low texture impact on the tyre treads. Thus, asphalt rubber should perhaps be best suited for states and countries such as Arizona, Texas, Hong Kong, the warmer parts of southern Europe and south-east Asia.

12.2.7 Discussion

If nothing else, the above shows that there are a number of mechanisms which potentially could contribute to noise reduction in comparison to a conventional asphalt mix. For the open-graded variant there is little doubt that there is at least some sound absorption which contributes to noise reduction; albeit not at all as important as for porous asphalt. The role of the rubber is small or just moderate, but many small contributions may account for a few dB extra noise reduction when rubber is added. As is discussed in Section 7.5, however, the rubber should be even higher than in the Arizona pavements to give an optimum noise effect. One would ideally increase it to (say) 6 % of the total mix by weight; i.e. three times the Arizona types. This may of course compromise durability, and definitely increase costs, but it may be worth it.

In summary one can say that the asphalt rubber, at least the open-graded variant, as compared to single-layer porous asphalt (PAC) with low voids content (15-20 %) may in the best case give about the same noise reduction; 3-5 dB relative to DAC 0/11, SMA 0/11 or similar. It would then also be comparable to well-designed thin layers (but not to the best thin layers). In the worst case, the ARFC is only 1-2 dB quieter than an SMA with 12.5 mm max aggregate (which would be rather similar to a DAC 0/11). This may not look very favourable at first. However, there are some advantages with the asphalt rubber that must not be considered:

- It would probably be somewhat less expensive than porous asphalt; not because of the material cost per weight unit, but since it achieves the same noise reduction with about half the thickness.

- Durability is proven to be high, thus lifetime should be longer than for PAC. This is also an economical advantage.

- Ravelling does not seem to be a serious problem.

- Application is not as critical as for PCC, since ARFC seems to work well also in curves and at intersections, and as overlay on cement concrete.

- Its noise reduction depends less on porosity; thus any clogging will not have such detrimental effects as for PAC. This could be a longterm advantage in low-speed cases or where studded tyres are used in wintertime. In any case it will not need any cleaning.

Finally, it should be noted that when asphalt rubber pavements are compared with noisy pavement types such as tined PCC, some dB of noise reduction may be attributed just to the "noisiness" of the PCC. For example when comparing an average tined PCC with a good asphalt concrete surface in new condition with 10 mm aggregate, at least the first 3-4 dB, maybe 5-6 dB, of noise reduction can be attributed to the "noisiness" of the PCC. That is to say that if one would overlay the PCC with conventional asphalt with an aggregate size of 10 mm a noise reduction of some 5 dB would be recorded immediately. For an optimised asphalt pavement (without rubber) one would easily get at least 7 dB of noise reduction. Thus, the net "rubber effect" alone is far from the high noise reductions measured in Arizona; albeit it is still valuable; especially since this surface also contributes to solving the problem of tyre recycling and disposal.

12.3 Research in California

If Arizona has focused on its asphalt rubber pavements, California has been studying several options. The most important project is probably the one that established a set of test sections on the semi-desert, straight and level highway LA138 located 130 km north of Los Angeles. See Fig.12.8. This author calls it "the LA138 project".

Fig. 12.8. The eastern end of the LA138 test section.

The LA138 project utilizes five asphaltic test pavements, all of them having a maximum aggregate size of half an inch which is 12.5 mm. See Fig. 12.9. They are:

DGAC	Dense-graded asphalt, 9 % air voids.
$OGAC_{thick}$	Open-graded asphalt concrete, 12 % air voids, 75 mm thick.
$OGAC_{thin}$	Open-graded asphalt concrete, 15 % air voids, 30 mm thick.
RAC typeO	Rubberized asphalt, open-graded, 12 % air voids, 30 mm thick
BWC	Bonded wearing course, 7 % air voids, 30 mm thick.

The rubberized asphalt (RAC) is the Californian variant of the asphalt rubber in Arizona. However, note that it has an air voids content which is lower than that of ARFC and its thickness is also greater. One may consider it as a hybrid of the AR and the ARFC in Arizona.

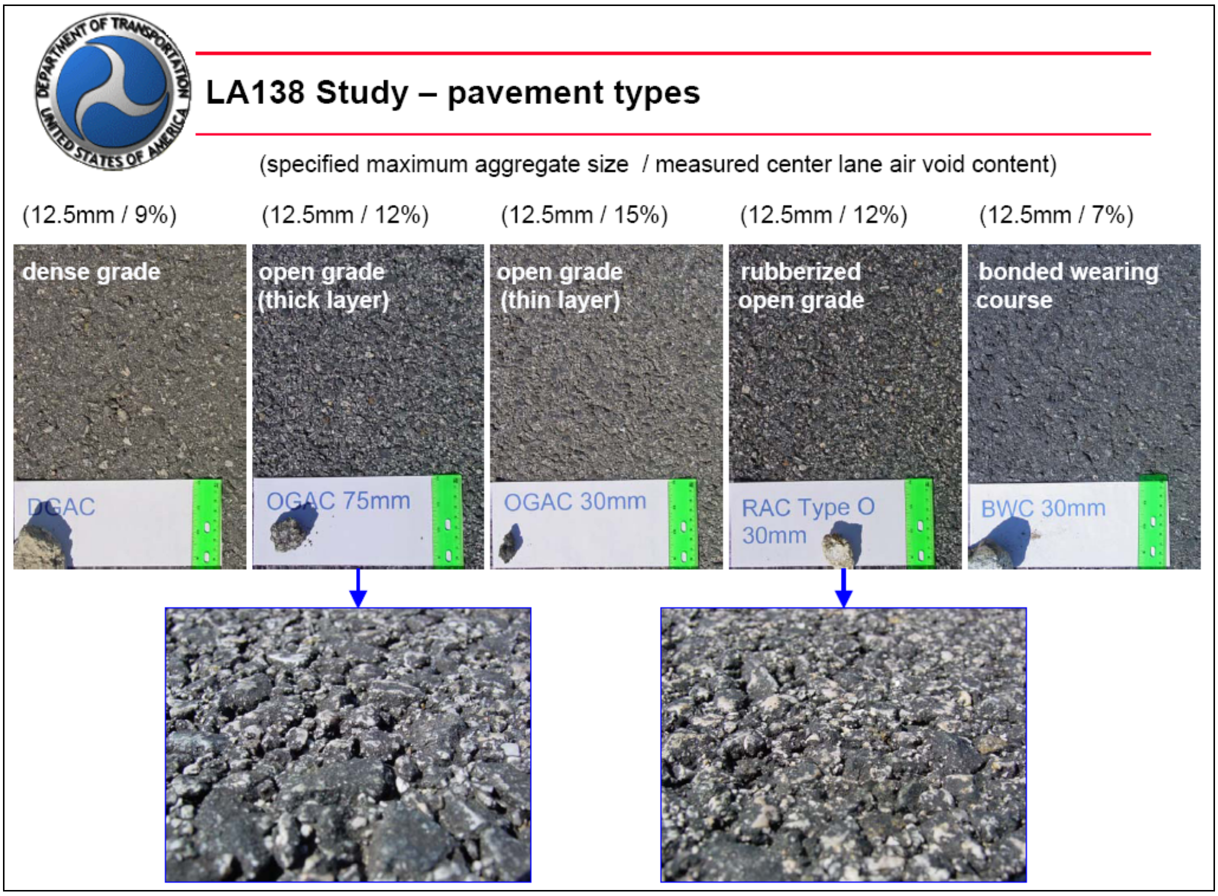


Fig. 12.9. The five test sections in the LA138 project. From [Rochat, 2007].

Measurements were made at various times over a 5 year period with both the OBSI and the SPB (somewhat modified) methods. Only the SPB results are reported here. Fig. 12.10 shows the SPB results as a function of time. The values on the ordinate axis are the difference against the DGAC pavement which was considered as a reference. It appears that the thicker of the OGAC is the quietest and that the RAC is sond quietest; further that the noise differences to DGAC are rather stable over the studied time period. Note that none of the pavements is porous as the highest air voids is 15 %, which in Europe would be considered as "semi-porous" and not considered as a drainage pavement. Consequently, the highest noise reduction is "only" 4 dB; and this is probably achieved thanks to the thick semiporous layer of the thicker of the OGAC:s.

It is especially interesting to compare the RAC with the thin OGAC, since they are essentially different only with respect to the rubberized binder. It appears that the extra noise reduction due to the rubber seems to be about 0.5 dB. Note that the RAC is probably not as efficient as the ARFC in Arizona since it has a coarser aggregate and lower air voids. The author does not know the rubber and binder contents.

Fig. 12.11 shows the same data but where the noise levels for different vehicle categories have been seprated into cars ("auto") and heavy trucks (HT). It is interesting to note that the RAC is most efficient for reducing noise of cars; in fact equally as good as the thicker OGAC, but it is less efficient for heavy trucks. The reason might be that it is too thin to provide sound absorption at the lower frequencies of the trucks; something it shares with the thin OGAC.

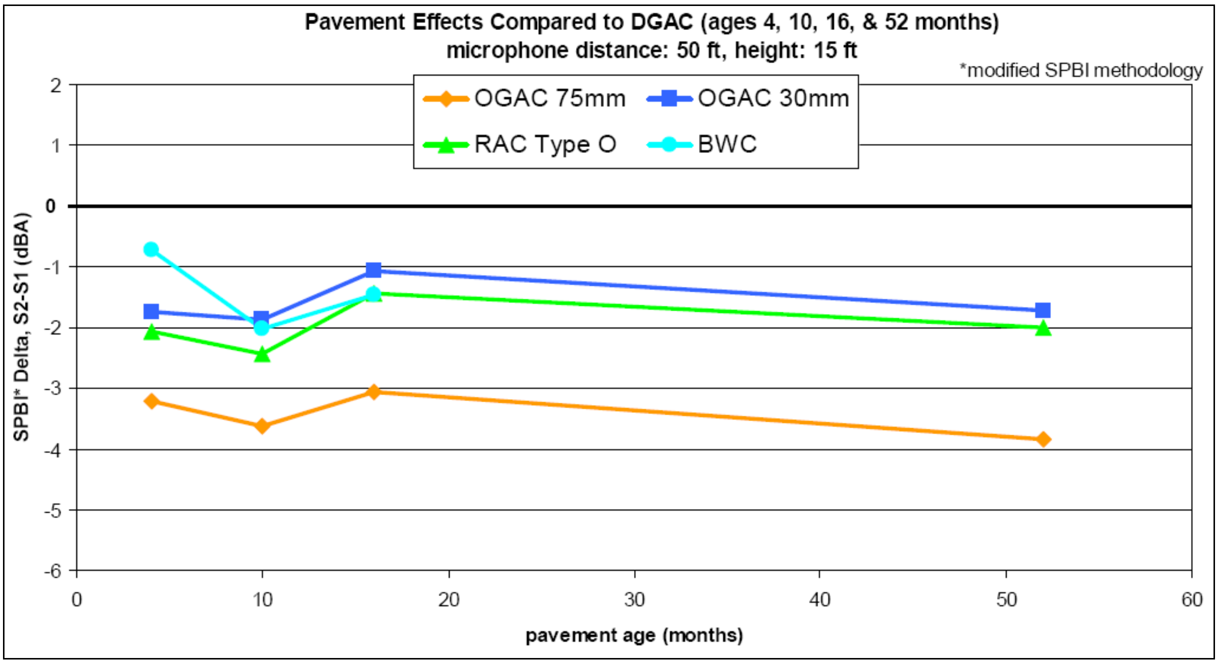


Fig. 12.10. The noise reduction relative to DGAC of the test sections in the LA138 project, measured with the SPB method at four different pavement ages. The value is a composite SPBI; i.e. it takes both light and heavy vehicles into account. From [Rochat, 2007].

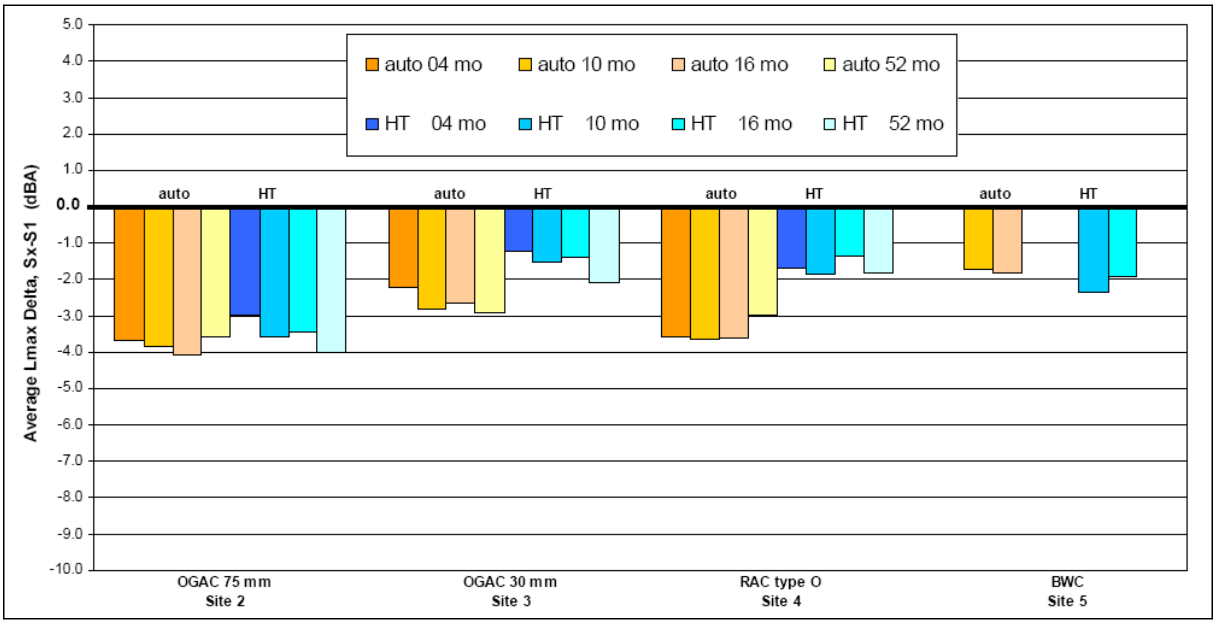


Fig. 12.11. The noise reduction relative to DGAC of the test sections in the LA138 project, measured with the SPB method at four different pavement ages. The values have been separated for light ("auto") and heavy vehicles ("HT"). From [Rochat, 2007].

Judging from Fig. 12.11, OGAC 30 mm versus RAC, the "rubber effect" would be approx. 1 dB for light vehicles and 0 dB for heavy vehicles. This would be interesting to compare with results measured at other places in other projects. For example, it is in line with the

Swedish results reported in Table 7.3 where the asphalt rubber pavements provided only about half the tyre/road noise reduction when using tyres representing trucks than when using tyres representing cars.

Probably most of the noise measurements related to pavements in the past 15 years in California have been made by the consulting company Illingworth & Rodkin. For example, they have established a noise property database of Californian pavements; see as an example [Rymer & Donavan, 2005]. Fig. 12.12 shows this in a diagram, and Table 12.1 shows the data in a table. Note that all the measurememts have been made with the OBSI method, using a Goodyear Aquatred tyre as the (only) test tyre. Later measurements have established a good correlation between measurements with this tyre and the SRTT tyre.

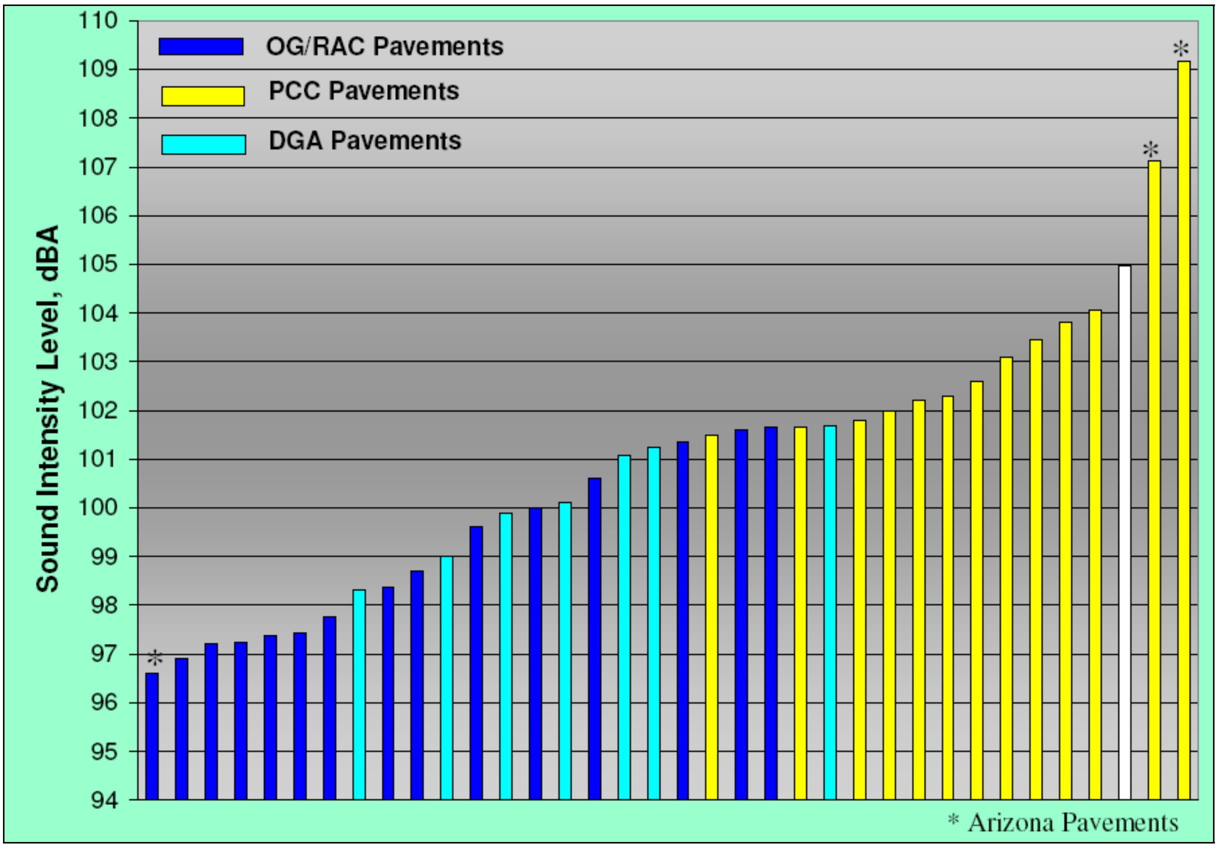


Fig. 12.12. The California Dept. of Transportation (Caltrans) State-Wide Data Base. Results of OBSI noise measurements on 36 pavements in California, including three Arizona pavements. From [Rymer & Donavan, 2005]. See further Table 12.1.

Note that the ARFC in Arizona (leftmost in the diagram) is 11-12 dB quieter than the tined PCC pavements in Arizona on the far right. This indicates that the tined PCC in Arizona are very "noisy" pavements, against which ARFC is often compared. More ARFC pavements from Arizona are included in Table 12.1. Note that the four ARFC in Table 12.1 range from 96.6 to 101.4 dB and that an Arizona SMA pavement has a noise level of 99.6 dB. The noisiest ARFC is stated to be in poor condition. This probably explains the confusion noted in the previous section about Arizona, namely that there are both quiet ARFC (new and in good condition) and those which are noisy and in poor condition; even noisier than SMA.

Table 12.1. The California Dept. of Transportation (Caltrans) State-Wide Data Base. Results of OBSI noise measurements on 41 pavements in California, including 10 Arizona pavements. From [Rymer & Donavan, 2005]. Partly the same OBSI data as in Fig. 12.12. The right column includes predicted noise levels for pass-by measurements at 15 m from the roadway (predicted from the OBSI measurements by subtracting 30 dB and rounding to the nearest integer).

AC or PCC	State - County - Route - Material - Description	Pavement/Tire Sound Intensity (Avg dBA)	Noise Level at 50 Feet ** (Sound Pressure Level) (dBA)
	AZ Marc 10 ARFC	96.6	67
	CA Sac Test Track DGAC	96.7	67
	CA SM 280 OGAC SB Shoulder	96.8	67
	CA LA 138 OGAC 75 mm	96.9	67
	CA SM 280 RAC(Type O)	97.2	67
	CA LA 138 RAC(Type O)	97.2	67
	AZ Marc 202 ARFC Best Condition	97.4	67
	CA LA 138 OGAC 30mm	97.4	67
	CA Fre 5 RAC(Type O) High Binder	97.8	68
	CA LA 138 DGAC	98.3	68
	CA SBd 40 RAC(Type O) High Binder	98.4	68
	AZ Marc 10 P-ACFC	98.7	69
	CA LA 138 DGAC Existing	99.0	69
	AZ Marc 10 SMA Stone Matrix Asphalt	99.6	70
	CA LA 138 BWC New	99.9	70
	AZ Marc 10 ARFC	100.0	70
	CA SBd 40 DGAC Exist	100.1	70
	AZ Marc 10 Permeable European Mix. OG	100.6	71
	CA LA 138 DGAC Reference Section	101.1	71
	CA SM 280 PCC Ground	101.2	71
	AZ Marc 202 ARFC Poor Condition	101.4	71
	CA Ker 58 PCC New Burlap Longitudinal	101.5	71
	CA Yub 70 OGAC Aged	101.6	72
	CA Yol 80 OGAC	101.7	72
	CA SCl 85 PCC New Longitudinal Tine	101.7	72
	CA Sol 80 DGAC	101.7	72
	CA Ker 58 PCC New Broom Longitudinal	101.8	72
	AZ Marc 202 PCCP Longitudinal Tine	102.0	72
	CA Sac 5 PCC Aged Longitudinal Tine	102.2	72
	CA SM 280 PCC Texture Grind (var. 8mm/0.1km)	102.3	72
	CA Sha 5 PCC NB Bridge Deck Longitudinal Grind	102.3	72
	CA SM 280 PCC Grind (var. 19mm/0.1km)	102.6	73
	CA LA 14 PCC Fair Condition Longitudinal Tine	103.1	73
	CA Ker 58 PCC New Longitudinal Tine	103.5	73
	CA SM 280 PCC Aged Longitudinal Tine	103.8	74
	CA Sol 80 PCC Aged Longitudinal Tine	104.1	74
	CA SM 84 Chip Seal New	105.0	75
	AZ Marc 202 PCCP New Tranverse Tine	107.1	77
	CA Sha 5 PCC SB Bridge Deck Trans. Astroturf (Aged)	108.1	78
	AZ Marc 202 PCCP New Random Tranverse Tine	109.2	79
	CA Sha 5 PCC NB Bridge Deck Trans. Astroturf (New)	112.4	82

From Table 12.1 it appears that the OGAC pavements (corresponding to European porous asphalt but with very low porosity) are in the quitest group and that the Californian RAC (open type) is almost as quiet. However, the best DGAC pavements are also "quiet", as they are only 2-3 dB noisier than the best ARFC. This supports the speculation of this author that the comparison between European and US pavements in Fig. 12.7 is biased by a couple of dB in favour of the US pavements.

In another project in California, which was a part of Caltrans Quiet Pavement Research Program (QPR), the noise properties of various pavements, including some quieter ones, have been studied in detail. For example, they used principal components analysis to determine which of the surface characteristics parameters that are most important [Ongel et al, 2008]. In this study they measured the noise levels of different mix types and the mix characteristics affecting noise levels. Tire/pavement noise was measured using the on-board sound intensity (OBSI) method. Data was collected on four different types of pavement mixes: conventional open graded asphalt concrete (OGAC), rubberized asphalt concrete that are open graded (RAC-O), rubberized asphalt concrete that are gap graded (RAC-G), and dense graded asphalt concrete mixes (DGAC). The measured parameters included air voids content, aggregate gradation, pavement roughness, age, and surface condition. In the lab they measured sound absorption on bore cores. A total of 80 field pavement sections all over California were included in the study, all of which were less than 8 years old at the time of the measurements.

The noise measurements are summarized in Fig. 12.13 [Ongel et al, 2008]. The pavements are gathered in four groups, each of which is also divided into age categories (in years). This author does not know what "Phase ID" means. The bars extend to cover the minimum and maximum noise level within each category; the points probably show the mean value.

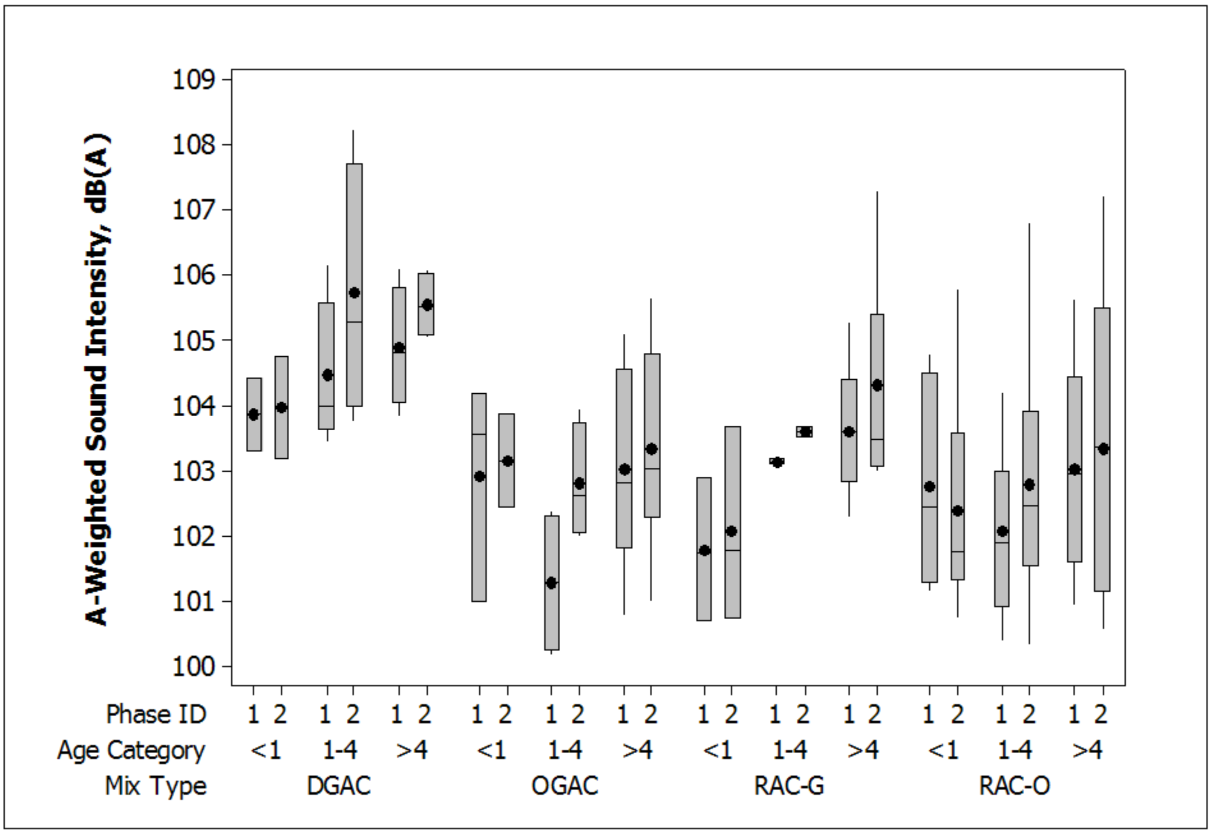


Fig. 12.13. Results of OBSI noise measurements on 80 pavements in California. From [Ongel et al, 2008].

From the principal components regression a model describing the relations was established:

OBSI = 100.87 - 1.28 x Flow properties + 0.79 x Surface roughness - 0.43 x Crack resistance + 0.002 x MPD (R^2= 61 %)

Where:

- OBSI = The sound intensity level in dB (A-weighted)
- Flow properties = A composite measure, incl e.g. air voids content and type of pavement
- Surface roughness = A composite measure, incl ravelling, IRI and age
- Crack resistance = A composite measure, incl pavement age and transverse cracking
- MPD = Mean profile depth (ISO 13473-1); i.e. macrotexture

For example, this means that if MPD increases by 1 mm, the noise level increases by 2 dB.

Further conclusions are:

- OGAC is quieter than DGAC (~2-3dB)
- RAC-G mixes are the quietest among the mixes that are < 1 year old

12.4 Research in Washington

Many other states than Arizona and California have made trials with asphalt rubber pavements. Here, only some brief results from the State of Washington are mentioned; mainly because they give an insight into asphalt rubber performance in a winter climate.

Washington Dept. of Transportation (WSDOT) makes efforts to produce pavements that reduce tyre/road noise. As part of this, two experimental sections of open-graded friction course were built using asphalt rubber in one of them and SBS modified binder in the other one. A section of conventional hot mix asphalt (HMA) served as the control section for the two experimental sections [Anderson et al, 2008].

Sound intensity measurements were conducted using the OBSI method immediately after construction and monthly since the end of construction. OBSI readings immediately after construction indicated that the open-graded asphalt rubber (ARFC) and SBS modified sections were 3.7 to 2.0 dB, respectively, quieter than the HMA control section. The most recent readings, taken in December 2007, show the asphalt rubber section to be 3.3 dB quieter than the HMA control section and the SBS modified to be 2.4 dBA quieter [Anderson et al, 2008].

Pavement wear/rutting and roughness data indicated that there had been virtually no increase in the measured rutting and only a slight increase in the roughness for both of the open-graded sections and the control section. The experimental evaluation will continue for a minimum of five years [Anderson et al, 2008].

12.5 Research on quieter cement concrete pavements

As written already in the introduction, US motorways, with some exceptions, generally are paved with PCC pavements and these generally have some surfacectreatment to incresae macrotexture. In most cases such treatment consists of tining in the transversal direction of the lane; although some states (such as California and Colorado) use tining in the longitudinal direction. If the tines are not made with a random spacing but with regular spacing, tyre/road noise will be dominated by tones ("whistles") which are extra annoying. Fig. 12.2 shows such a tined PCC surface in worn condition, under a just laid ARFC. These "noisy" treatments have been abandoned long ago in Europe, replaced with quieter ones or even with asphalt pavements, but they are still used in USA; albeit slowly replaced by better methods.

Since the 1970's several studies have sought surface treatments which are quieter. These quieter treatments have been applied only to a limited extent, so the problem is still substantial. Among the quieter surface treatments which are becoming common is the so-called diamond grinding; in which the surface is ground by small diamond sawblades to create a narrow and fine longitudinally grooved surface. Such a ground surface is seen in Fig. 12.14.

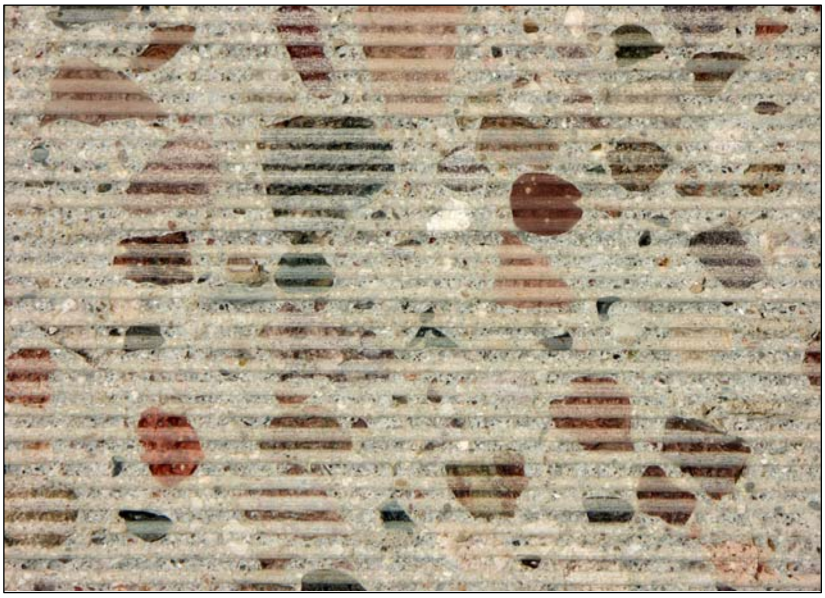


Fig. 12.14. Diamond ground cement concrete surface. Driving direction is across this page. Interstate 10 south of Phoenix, Arizona.

In later years the attempts to find quieter surface treatments have increased and resulted in some large projects. Possibly the most essential is work at the National Concrete Pavement Technology Center (CP Tech Center) at Iowa State University. This Center has amassed the largest database so far of concrete pavement surface characteristics, including measurements of noise, texture, and friction. Nearly 1,500 test sections throughout North America and Europe have been evaluated to date. They also have a Concrete Pavement Surface Characteristics Program (CPSCP), within which the CP Tech Center has developed an understanding of the fundamental surface properties that affect noise [Rasmussen et al, 2008]. Based on this they have issued a number of recommendations for construction of quieter concrete pavements.

The data collection of nearly 1,500 test sections have made it possible to make a distribution diagram of all measured noise levels, and to distinguish between the major principles of surface treatment. Fig. 12.15 shows the result of this [Rasmussen et al, 2008].

The results show that each surface treatment can result in a large range of noise levels; partly of course because the condition (wear) of the surfaces varies substantially. From the diagram it can be concluded that the noisiest treatment is the most common one: the transverse tining. If one would exchange it to longitudinal tining one would save on the average 2 – 2.5 dB. If one would change it to drag treatments (turf or hessian drag, for example), one would save another 1.5 dB and if one would use the best treatment, diamond grinding, the total noise reduction would amount to 4.5 dB on the average. The study also showed that within each type of treatment there are possibilities to optimize the procedure. A comprehensive list of recommendations are made in [Rasmussen et al, 2008].

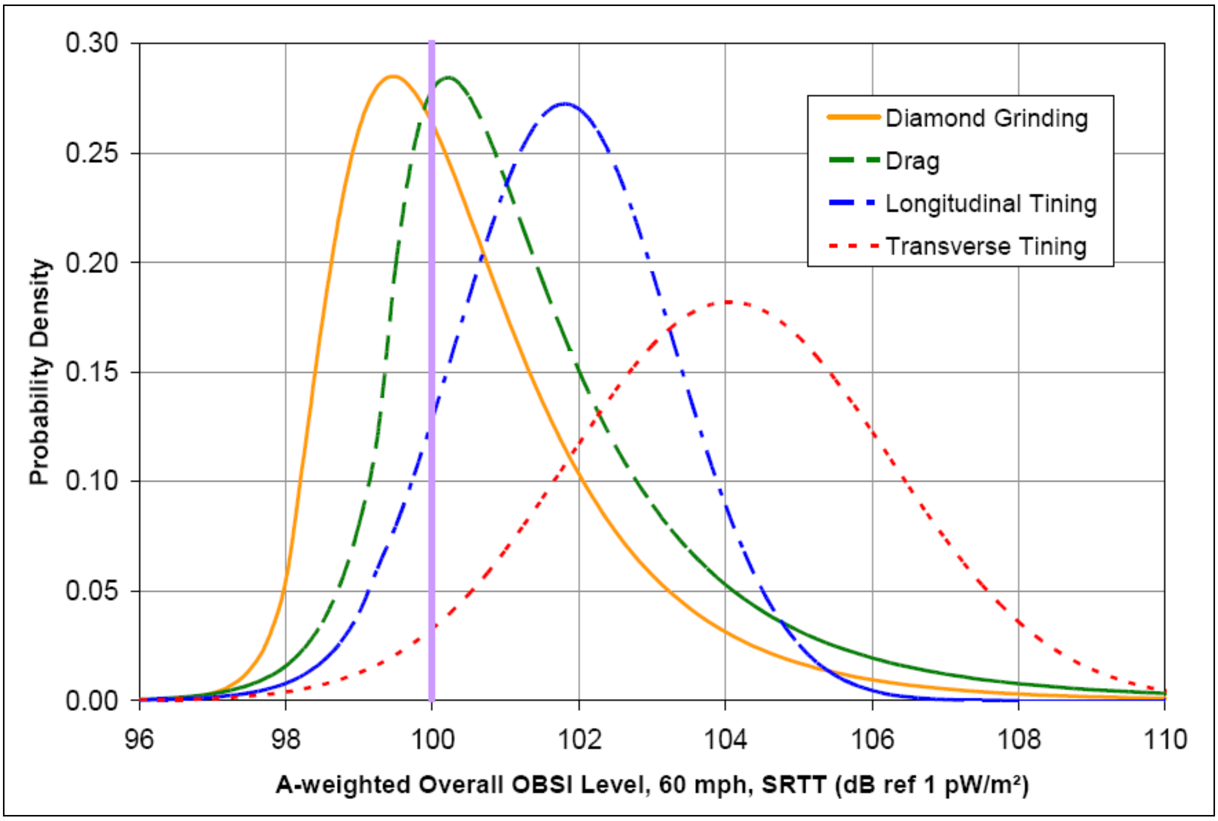


Fig. 12.15. Results of OBSI noise measurements on several hundreds of PCC pavements in USA, plotted as normalized distributions for the four major conventional surface treatments. From [Rasmussen et al, 2008].

13. EXPERIENCE IN JAPAN

13.1 General issues

It is the general policy in Japan that all expressways and all other major routes through urban areas shall have a porous asphalt pavement which gives a noise reduction; often as a supplement to noise barriers. Noise reduction is not the only reason; also improved wet weather friction is important.

The normal pavement type in Japan is dense asphalt concrete (DAC) with a maximum chipping size of 13 mm. This type of surface is totally dominating the road network; except that porous asphalt is taking over more and more. Low noise road surfaces in Japan are more or less equal to porous asphalt. Such surfaces have been applied since the early 1990's although experience the first years was bad. In later years, porous asphalt surfaces have become very effective and their use is rapidly increasing. Porous asphalt pavements used in Japan are of one of the following types:

1. Porous asphalt, single layer, max chipping size 13 mm, 50 mm thick, 20 % air voids. Traditional type laid according to Japanese specifications, used extensively on the expressway network and on highways where noise, skid resistance and water spray are a problem. It is the experience that such a surface gives 3-4 dB in initial noise reduction[65]. Then this reduction decreases by about 1 dB per year.

2. Porous asphalt, single layer, max chipping size 13 mm. Laid according to performance criteria (see below) and used extensively on the Tokyo metropolitan arterial street network.

3. The same as 1, but with max. chipping size 10 mm, 50 mm thick, 20 % air voids

4. The same as 2, but with max. chipping size 8 mm. This has been introduced in Tokyo as late as in 2003; thus there is little experience of it.

5. Porous asphalt, double layer. Top layer max chipping size 8 mm, 20-30 mm thick. Bottom layer max 13 mm chippings, 40-50 mm thick. Design air voids = 20 % (in practice 20-22 %)

6. Porous asphalt, double layer. Top layer max chipping size 5 mm, 15 mm thick. Bottom layer max 13 mm chippings, 35 mm thick. Design air voids = 20 % (in practice 20-22 %)

7. Variant of No. 6 (information from another source), double layer. Top layer max chipping size 5 mm, 20-30 mm thick. Bottom layer max 13 mm chippings, 40-50 mm thick. Design air voids = 20 % (in practice 20-22 %)

Note that PMB is always used. These binders are very advanced in order to resist ravelling.

Durability for the double-layer porous asphalt with 5 mm in the top is a little lower than for 8 mm, but just a little.

Some typical sites where the single-layer porous asphalt with 13 mm chippings is laid are shown in Figs. 13.1-13.4.

[65] Fig. 11.38 in the Tyre/Road Noise Reference Book predicts 3.5 dB of noise reduction.

Fig. 13.1. Typical application of porous asphalt for noise reduction on high-speed motorway in urban area. Mostly combined with noise barriers; in sensitive areas of extremely advanced type, like in this picture. Tokyo metropolitan expressway, northern section.

Fig. 13.2. Typical application of porous asphalt for noise reduction on medium-speed expressway (60 km/h) in urban area. Mostly combined with noise barriers. Note the sign at the upper left, saying "Please drive quietly". Tokyo metropolitan expressway, western section.

Fig. 13.3. Typical application of porous asphalt for noise reduction on low-speed street (40 or 50 km/h) in urban area. Never combined with noise barriers. Hibiya dori Avenue in Tokyo central business district (Ginza).

13.2 Urban street applications of porous asphalt and the Urban Heat Island effect

As illustrated in Figs. 13.3 and 13.4, and reported in Section 17.6, porous asphalt is applied increasingly on urban streets in Japan. Together with Hong Kong, this is unique in the world; in no other country are porous asphalt pavements applied on low speed roads to a significant extent. However, in some European cities and towns thin layers are used rather commonly on low-speed roads; for example in the U.K., but the extent to which porous asphalt is now applied in Japanese cities have no counterpart.

As an example, this author made a study visit 2004-10-06 on the "Ginza Street" in the central business district in Tokyo, which is part of the national highway No. 15. The street at this location has two lanes in each direction, including a lane mainly used for parking/stopping and a turning lane at certain intersections. Traffic volume (AADT) is 20 000 vehicles/day, with a heavy vehicle proportion of somewhat less than 10 %. There were two pavements there, with the joint between them at the intersection with a crossing street. Pavement No. 2[66] (13 mm max chipping size) and No. 3 (the 10 mm variant) had been laid about one year,

[66] See Section 13.1 above

respectively one month earlier. The thickness was 50 mm. Posted speed on this street is 40 km/h.

Fig. 13.4. Typical application of porous asphalt for noise reduction on low-speed street (40 km/h) in urban area. Never combined with noise barriers. Note the red spray applied at the exit/entrance to the multi-storey car park on the other side of the street. Street parallel to Ikebukuro Station in Tokyo.

The 13 mm single-layer porous asphalt was first suggested for use in Tokyo in 1987. In 1992 the Highway Office started to use it to some extent. A standard was published in 1996, although it is not mandatory to follow it. The standard is a guideline useful to achieve the desired performance.

On the expressway system, the porous asphalt is used with the twofold purpose: to improve safety (mainly wet friction and spray) and to reduce noise. It is mostly used in combination with advanced noise barriers, to provide an extra 3 dB of noise reduction.

On the metropolitan street network, the main purpose is to reduce temperature in summertime. There is a serious problem in Tokyo and other large cities called the "Urban Heat Island (UHI)" problem. It is caused by the absorption of solar radiation in blacktop pavements causing a temperature rise in them. As paved areas in Japanese city centres are substantial, this is an extra heat generator with large influences. In summertime, the time with pavement temperatures exceeding 30 ^{o}C is exceeding 60 days. For example, in 2004 more than 70 days had daytime air temperatures exceeding 30 °C. Top pavement temperatures of 60 °C are common. These high temperatures cause a lot of problems in terms of discomfort (heat), energy consumption (air conditioning) and environment in general. The heat build-up from the pavements increases the use of air conditioning, which due to the power consumption increases the temperature further, and so on. It is believed that the Urban Heat Island problem causes a significant extra contribution to the emission of CO_2.

The Urban Heat Island problem is treated comprehensively by research in Phoenix, Arizona. For example, researchers there have calculated that by increasing the albedo of an ARFC or SMA surface by applying a thin bright paint one can reduce the temperature above the pavement by 6 °C [Kalousch, 2009].

In Japan, it has been found that porous pavements reduce the maximum temperatures by about 10 °C. This is the major driving force behind the increasing use of porous asphalt in Tokyo, but it is recognized that it also has a favourable effect on the acoustic environment as well as on safety, provided the porosity is not filled with solid matter. There are essentially three ways in which porous pavements are used to reduce temperature:

- Just as they are, since they retain water and prolong the evaporation and thus cooling effect

- In addition they may be painted with a brighter colour to change their albedo

- As the optimum solution, the pores are filled with a material which absorbs water and retains its humidity a long time

- All the above options may be enhanced by watering the surface systematically or occasionally

A major cause for the temperature reduction is that the porous pavement retains water after rainfall for a much longer time than a dense pavement and thus results in water evaporation for a substantial time which consumes energy from the pavement which cools it.

This author had an opportunity to see an ongoing experiment the first time in 2004 with a painted porous surface; namely on Ginza Street in central Tokyo. On this location, part of the pavement had been painted with a "greyish" colour. The paint seemed to contain small grains of sand; probably to make sure that friction levels are not jeopardized. It was the impression of the author that this paint had a high viscosity and had been applied in such a way that it did not run into and filled the pores; but rather stayed on the flat surface. Figure 13.5 shows a close-up view of this surface. If epoxy is used as the paint it may add durability; see Fig. 13.8.

A new type of porous pavement filled with material capable of absorbing and storing water is called "Water Retention Pavement (WRP)" and is even more efficient in reducing its maximum temperature than conventional porous asphalt. Other contributing mechanisms may be the air movement through the surface porosity, lower thermal conductivity and the lower ratio between black mortar and brighter aggregate. These are the same mechanisms which, on the negative side, create an earlier formation of black ice. Fig. 13.6 shows bore cores with one core of porous asphalt untreated, one core covered with a thin layer of epoxy to brighten the surface while at the same time making it more durable against lateral forces at intersections, and a third core with WRP material in it. See Fig. 13.7 for a WRP surface.

Fig. 13.5. Porous asphalt with a "greyish" paint applied on the surface; intending to reduce the Heat Island effect. Ginza Street in central Tokyo.

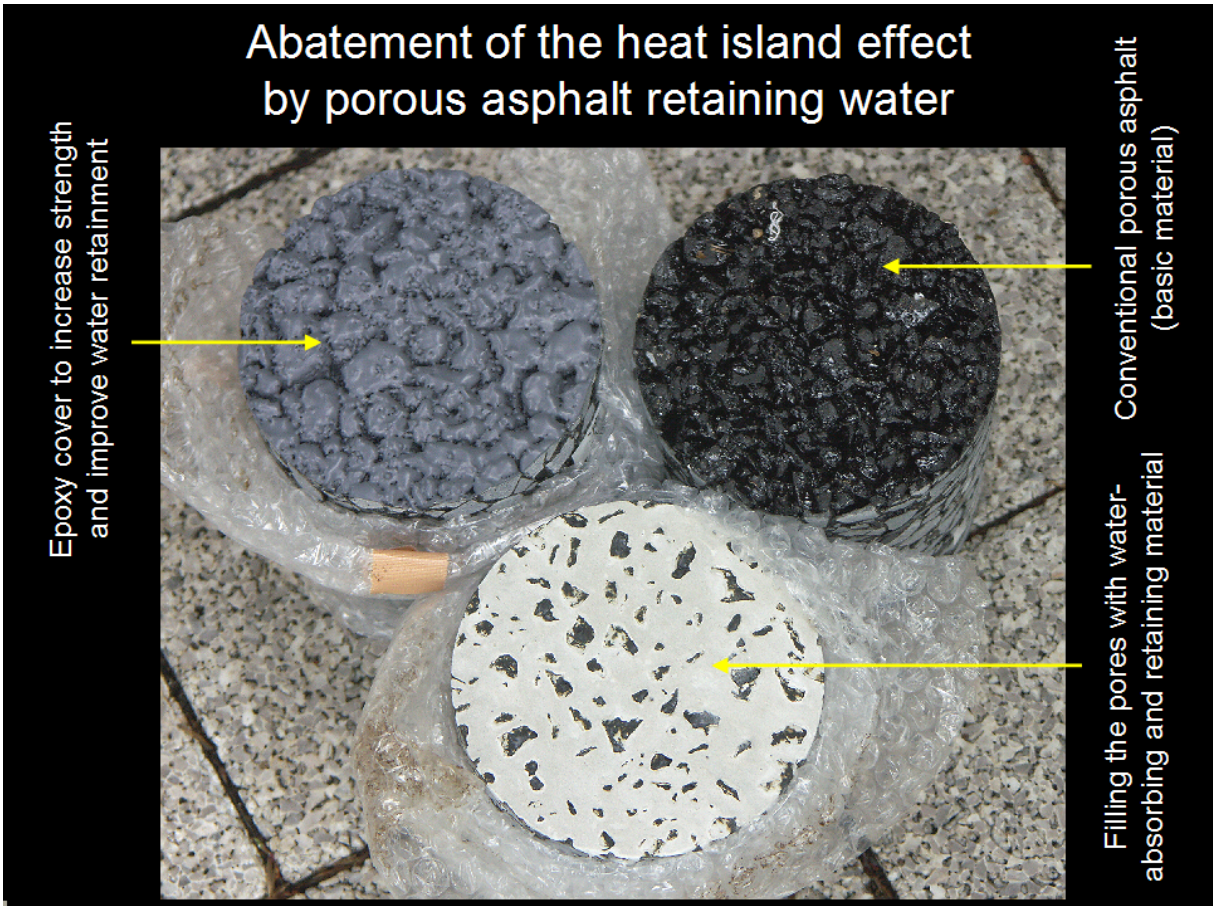


Fig. 13.6. Three types of porous asphalt with untreated sample (right), sample with epoxy applied on the surface (left) and sample filled with WRP material. Shown at HK study tour to Tokyo in May 2007.

Fig. 13.7. Trial on street in Tokyo with water-retaining material in the bottom of porous asphalt. HK study tour to Tokyo in May 2007.

Fig. 13.8. Trial on street in Tokyo with epoxy-covered porous asphalt. HK study tour to Tokyo in May 2007.

Using epoxy to increase the surface albedo is effective since it is an extremely wear-resistant material, but it also gives the surface a higher strength against the lateral tyre/road forces at intersections, at parking bays, at exits and entrances to parking areas and where there is stop-and-go traffic. Fig. 13.8 shows an example where this was applied in 2007 on a trial basis.

The Japanese trials have indicated a dramatic reduction of temperature; maximum surface temperature reductions of up to 30 ^{o}C have been reported, when they have tried the combination of a brighter surface with adding a WRP. However, it is not known how much noise reduction is affected by adding WRP.

With regard to the noise-reducing effect of the regular porous asphalt (type 1 described above) on low-speed streets in urban areas, Fig. 13.9 gives a typical example. It was reported by the Kanagawa Prefecture; i.e. the area of Yokohama and its surroundings [Ishii, 2007]. The posted speed on Road A would probably be 50 km/h and on Road B it would probably be 40 km/h. The faster deterioration of noise reduction on Road B (0.25 dB/year) versus Road A (0.1 dB/year) might be due to a combination of lower speeds and more dirt generation from adjacent activities. However, the drop in noise reduction with time is amazingly slow.

For typical drainage systems, refer to Section 16 and Fig. 16.7.

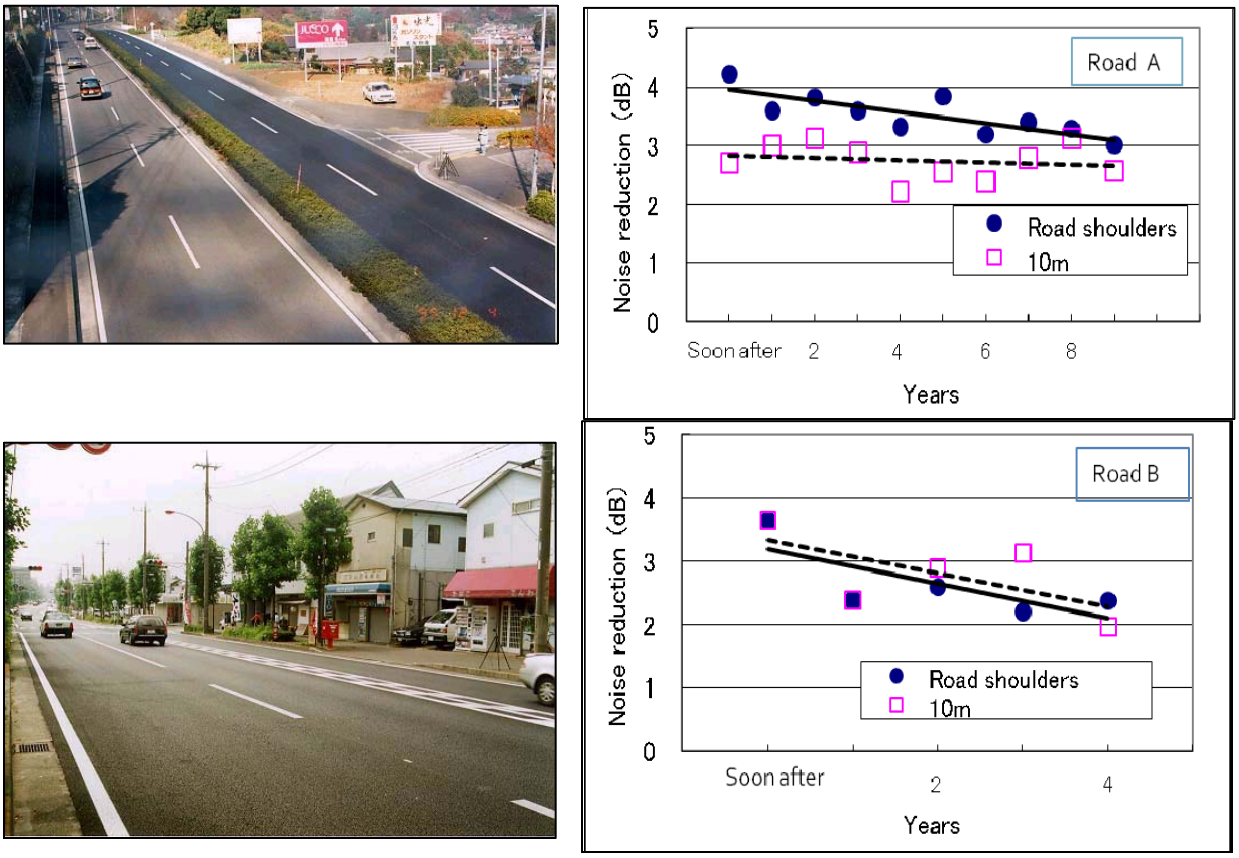


Fig. 13.9. Noise reduction of standard porous asphalt versus DAC 0/13 at city streets in two locations in Kanagawa Prefecture, as shown in the photos. Measurements of LAeq (2 hours) both at the road shoulder and 10 m from the road. From [Ishii, 2007].

The service life in urban areas is expected to be at least 10 years. The experience so far is relatively short; in 1992 only a few pavements were laid. So it is not well known how long time a pavement can be used.

Clogging occurs, but is not considered so serious that it requires repaving. In cases where there is loose soil nearby, clogging might occur after only one year, but in other cases the problem is not so aggravating. The author noticed serious clogging along the street edge on local road No. 301 running along the Imperial Palace and Imperial Garden. This street had a (probably) one year old porous pavement and due to a typhoon partly hitting Tokyo on 2004-10-09, soil from the flower bed lining the street had flowed over onto the pavement edge nearest to the flower bed. About 0.5-1.0 m of the street width from the edge had then become clogged. This was noticed the day after the typhoon and some natural cleaning might have occured later.

Cleaning by machines had been tried, but is not regularly practiced on the urban streets.

Ravelling occurs occasionally, but the ravelling problem has been largely reduced in later years following the use of more efficient modified binders. Ravelling problems are essentially limited to areas at or near intersections. For example, it may occur on street parking "lanes" where vehicles squeeze-in between other vehicles, using forced steering operations. Repairs are often just very local "fill-ins", whereas it also happens that areas are repaved over their entire width. However, as already said, the ravelling problem is by no means so serious that it disqualifies the pavement type from being extensively used. Note also that attempts are made to eliminate the problem by a thin epoxy cover (see above, but also the Section about New Zealand).

During site studies made by the author, ravelling was very rarely noticed, despite looking for it at all intersections where it was possible. It was noticed in one case that the pavement through a sharp curve was a dense one, whereas it was porous before and after the curve. It was also noticed that at some critical patches where durability problems could be expected, the pavement was dense (sometimes a semi-flexible one), but this was probably made already during the construction case and not as repairs. Such locations included for example exits from parking lots, parking houses or yards. Thus, the Highway Office seems to have undertaken deliberate precautions to avoid ravelling.

The study visits described above were generally made in sunny and nice weather. However, the author had the opportunity to study the porous asphalt pavements during a weekend in Tokyo during which a typhoon hit the city. This was made essentially but not exclusively via taxi rides; i.e. from within a car. Several photographs were taken to illustrate the effects noticed. Four of the many streets studied were Hakusan Dori, Meijiro Dori, Hibiya Dori and local road No. 301 running along the Imperial Palace and Garden (street name unknown).

The following observations were made (this refers to a condition described as "normal, moderate rain" that had been ongoing for several hours that should ensure that a stationary condition had been reached long before the observations):

When travelling around on major Tokyo streets in rainy weather, it is obvious that very substantial parts of the street network are paved with porous asphalt. It is easy to distinguish between dense and porous surfaces in rainy weather; since the porous pavements look rather dry, with no standing water, whereas the dense pavements are covered with water and thus look shiny. See an example in Fig. 13.10. This is different to the situation in Hong Kong, where the author has noted that many of the porous surfaces become so saturated with water that they do not look dry any more, but shiny. This suggests that the Japanese have a more effective drainage system.

Fig. 13.10. Typical view through a taxi windscreen when travelling on Tokyo streets in heavy rain (and it has rained a long time already). Porous asphalt near and dense asphalt further way.

At some places, repairs could be observed. This is based on slightly different colours of repaired patches versus the original surface, possibly due to more effective drainage the newer the repairment is. At the few places where the repair had been made with dense asphalt, such spots were easy to detect in rainy weather.

At a few places where extra stresses could be expected, such as exits from parking garages and bus stops, it was noticed that the dense section laid there seemed to be a "semi-flexible" pavement (similar to the Nordic "densifalt"). Most likely such places were constructed precautionally and originally, rather than being repaired sections.

The statement above about freedom from standing water on porous pavements must be modified with the note that there were small patches here and there, where one could see some standing water. It was difficult to see whether these patches or spots were in fact places where a damaged porous pavement had been replaced with dense asphalt. Most likely this would be the case; at least partly.

There were a few street sections (but a small proportion in relation to the total) where it was not totally clear whether the pavement was dense or porous. The surfaces in such cases showed a small amount of standing water, but not at all as much as on the ordinary dense pavements. It is possible that such cases were rather old porous pavements which had become partly clogged.

Finally, it could be mentioned that it was estimated that the extra cost for porous asphalt in relation to the normal dense asphalt is estimated at about 20 %.

13.3 Producing porous asphalt by means of on-site recycling

Japanese road engineers have developed a process in which they can in one continuous operation mill off existing worn-out dense asphalt, separate the materials in it, mix it with some supplementary new material and pave it as a porous asphalt [Hosokawa et al, 2006]. They call it Hot In-Place Transforming (HIT). The train of machines that perform these operations is shown in Fig. 13.11. Typical grading curves of the old dense asphalt and the new porous asphalt are shown in Fig. 13.12.

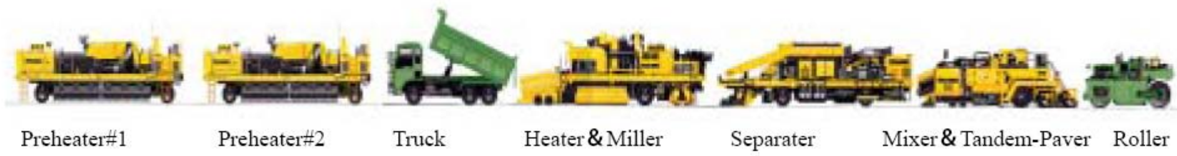


Figure 1: Train of hot in-place transforming machines

Fig. 13.11. The train of machines that perform the HIT operations. From [Hosokawa et al, 2006].

This process is useful for production of low-noise road surfaces in an inexpensive way and in a way which is environmentally friendly. For example, it has been calculated that greenhouse gas emissions are reduced substantially when the HIT is used compared to the conventional mill & fill procedure [Hosokawa et al, 2006]. See Fig. 13.13.

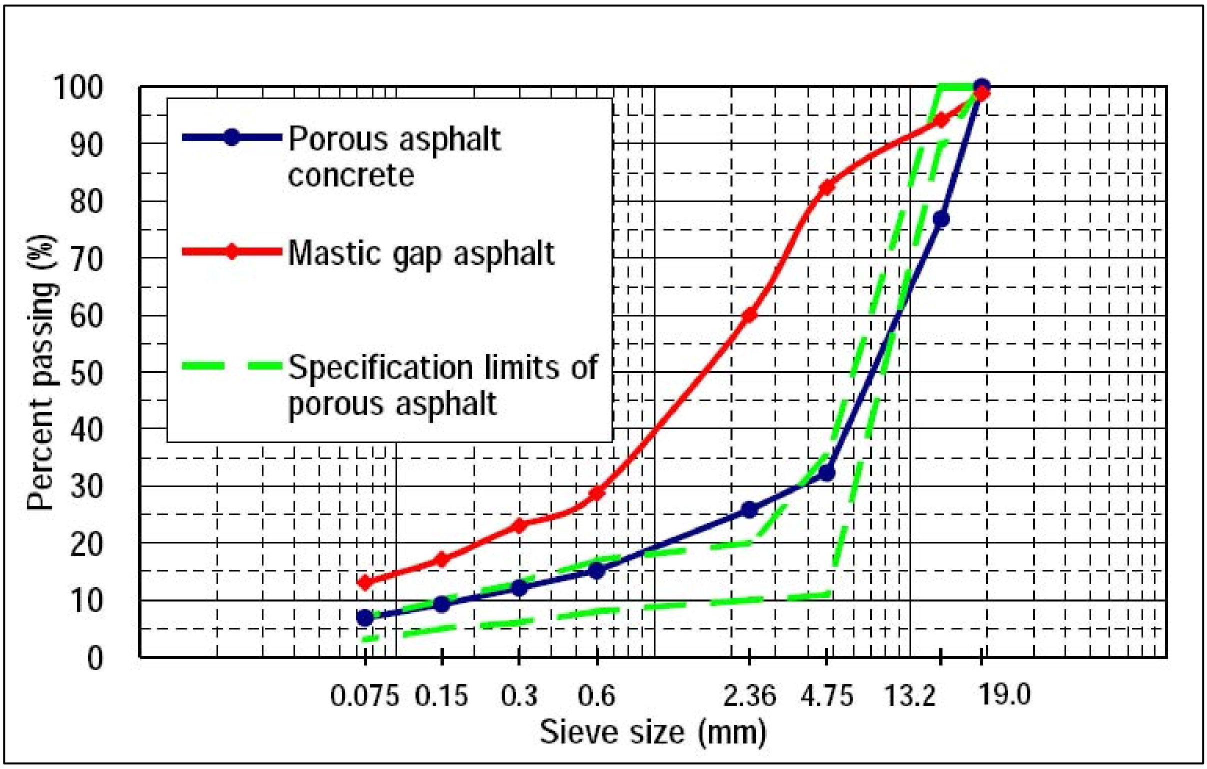


Fig. 13.12. Aggregate grading of recycled surfacing (blue) compared to the original surface grading (red) and Japanese specifications for porous asphalt. From [Hosokawa et al, 2006].

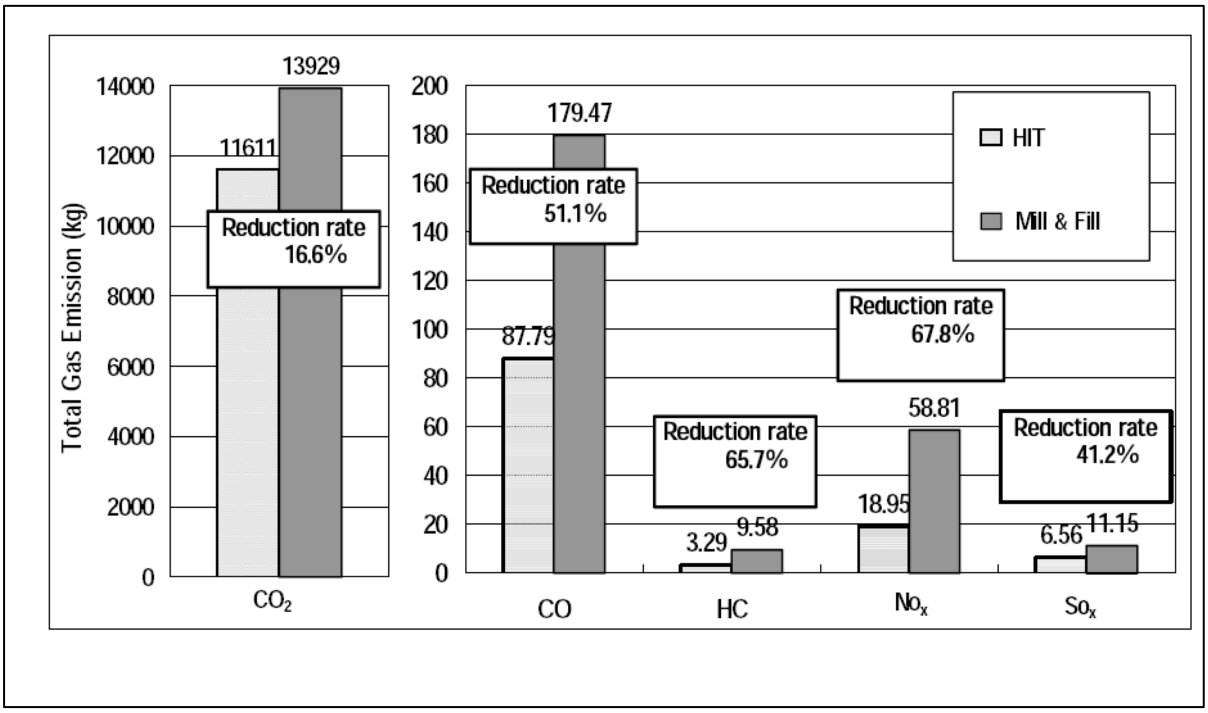


Fig. 13.13. Greenhouse gas emissions reduction for HIT vs conventional mill & fill. From [Hosokawa et al, 2006].

13.4 Poroelastic road surfaces

The Japanese work on poroelastic road surfaces (PERS) under the direction of Dr S. Meiarashi, until 2005 has been reported in a 10–page-review in [Sandberg et al, 2005]. This is not repeated here. However, a summary of what has happened with regard to PERS after 2005 follows here.

After having tested a large number of 1 m^2 large PERS variants with various adhesives to the basecourse on the PWRI test track, using a truck running back and forth day and night, three types of PERS surfaces were selected for a test on the highway immediately outside PWRI in Tsukuba City. The samples had been modified in relation to earlier materials in order to increase wet skid resistance. These were glued with double-sided adhesive tapes which had performed well in the test track testing.

The test sections were constructed in November 2006 as three 5 m long sections of one lane width, milled down 30 mm in the existing DAC 0/13. Fig. 13.14 shows the test sections from the start of the test section with the first 5 m being Yokohama, then 5 m Sumitomo and finally 5 m of Tokai material. The noise reduction when vehicles drove over the sections was clearly audible, probably around 6 dB. Noise measurements were not feasible on such short sections.

Fig. 13.14. The test section with PERS on the Route 408 highway outside PWRI (it is usually intensive traffic here but the photo was shot when the traffic had stopped at a traffic light). The plate section contains three different materials, each about 5 m long.

The PERS test sections functioned alright for a few months, but in the winter of 2007 the Yokohama and Sumitomo variants and part of the Tokai material had to be removed due to poor adhesion to the basecourse. The rest of the Tokai material remained until late 2007 or early 2008 but in the summer of 2008 also that section was removed, again due to adhesion failure. Thus, one may conclude that the double-sided adhesive tapes did not provide sufficient adhesion. However, the skid resistance measurements indicated good performance, of course tested only for the very short time until the materials were removed.

Simultaneously with this experiment by PWRI, Yokohama made an own field experiment. They put a special PERS material manufactured by themselves on a 100 m long one-lane test section in Zama City, west of Tokyo. This material is a mix of sand and rubber granules (up to 4 mm), air voids approx. 20 %, thickness 30 mm. The sand content as enough large to make it difficult to press down a coin edge 1 mm into the surface by hand. The site has a downhill slope of approx 3 %, which means that the cars commonly roll down at idling. Posted speed is 40 km/h but actual speeds were up to 70 km/h when traffic allowed it.

Fig. 13.15. The 100 m long test section with PERS on a major street in Zama City, west of Tokyo. The PERS section, made by Yokohama, is the somewhat darker part of the left lane. Photo shot in Dec. 2006 when the surface probably was two weeks old.

The PERS in Zama City was perceived as extremely quiet, but only for light traffic. When cars drove (usually coasted) from the old asphalt to the PERS, it sounded as if all noise disappeared, but when trucks did the same (often applying engine brake), there was just a little quieter sound. When the author visited the surface half a year later (May 2007) there was no sign of impaired performance. Noise measurement results are not known.

Fig. 13.16. Close-up photo of the PERS test surface in Zama City, made by Yokohama. The coin is appr 22 mm in diameter. Photo shot in Dec. 2006 when the surface probably was two weeks old.

13.5 Japanese noise testing and procurement procedures

In Japan, a performance-based system for procurement of low-noise road surfaces has been in use for several years. The first versions of the system were tested as early as in 1998-99. The performance is based on prescribed tyre/road noise levels; in some cases also the price and method of construction.

Tyre/road noise levels are measured by means of special vans ("Road Acoustic Checker") equipped with a special tyre as a fifth wheel; with a method resembling the CPX method. See Fig. 13.17. The tyre is a normal Bridgestone tyre for which the normal tread has been buffed-off and a new tread has been fitted with a very special tread pattern. The tread pattern consists of large "suction cups" on one side of the tyre and large "crossbar lugs" on the other side. In this way, both the vibrational impact mechanism and the air-pumping mechanism are excited in a maximum way. See Fig. 13.18.

Currently, there are five such vans in operation in Japan. These are gathered one time per year at a test track facility at the Public Works Research Institute (PWRI) in Tsukuba City where there are four permanent "reference" surfaces. The test vehicles are run over these surfaces at the test speed of 50 km/h. The surfaces are a DAC 0/13, a PAC 13 (20 % voids), a DPAC 5+13 (23 % voids) and a poroelastic surface. These four surfaces, each 80 m long, are protected from the influence of weather by a tent which covers the entire test area except when used for testing. See Fig. 13.19. The noise difference between the test vehicles so measured must not exceed a certain value.

Fig. 13.17. The Japanese "Road Acoustic Checker" at the annual calibration event in Tsukuba in May 2005. The test tyre and microphone sit under the rear body of the van.

Fig. 13.18. The special Japanese test tyre used in the "Road Acoustic Checker".

The classification of surfaces with this tyre does not correlate so well with the SPB method, since on smooth surfaces both mechanisms are excited to a very high degree. However, within the porous asphalt surface group, the main subject of the system, tested relations show a reasonable correlation CPX-SPB.

Tyre/road noise levels are measured twice; the first time soon after the completion of the road surface construction project and the second time after one year of traffic exposure. The noise level should not exceed 89 dB soon after the completion of the road surface, and should not exceed 90 dB one year later. An extra dB is allowed for projects in which an aggregate of poorer quality has been accepted.

Fig. 13.19. The Japanese "Road Acoustic Checker" driving through the four (2x2) reference surfaces at the annual calibration event in Tsukuba in May 2005. The reference surfaces are normally covered by the retractable tent in order to protect them against weathering.

This vehicle also has a unique system contained in an enclosed unit (with a clearance to the ground) emitting sound towards the pavement from a loudspeaker at one end of the unit, reflecting it back within the enclosure against a stiff plate and finally measuring the sound reflected on the pavement twice (ideally) with a microphone within the other end of the unit. This should measure a sound-absorbing effect, but the author does not know if it ever is used and how it is used.

A special version of the procurement system allows for surfaces which are quieter than the normal requirement. This is to encourage development towards quieter surfaces than those that meet the limits cited above. In this case, the bidder (the road contractor) specifies/promises a lower noise level for his surface than the limit above and then the measured noise level after construction must not exceed this level. One year after completion of the surface, an increase of one dB is allowed.

With this system, the experience is that noise levels increase approximately at a constant rate of one dB per year (a little lower for the system which allows for quieter surfaces than the limit); thus it is justified to measure only at the ages of zero and one year. Most contracts have been based on porous asphalt with maximum 8 or 10 mm chippings for single-layer pavements and 5 or 8 mm chippings for double-layer pavements.

Starting with three procurement contracts according to this system in the fiscal year 1999, the number of contracts in 2003 had increased to about 130; a number which is still steadily increasing (the numbers for later years were not available to the author). By the end of 2003, a total of 278 contracts had been awarded. The required noise levels were met for all contracts except one in the system based on the fixed limits, while about 10 % of the projects in which quieter surfaces are encouraged did not meet the promised noise levels.

As far as this author has understood it, the requirements for the metropolitan surfaces in Tokyo are a little different. They shall meet two performance criteria:

- An A-weighted noise level of 89 dB must not be exceeded when the pavement is new. The test speed is 50 km/h. After one year the noise level may be maximum 90 dB. This is measured with the vehicles described above.

- The other performance criterion is water permeability as measured with a water outflow meter. The measure is the number of ml of water flowing out during 15 s. The author does not know the required value.

In 2004 there were in Japan only about 30 contractors who were able to lay porous asphalt for Tokyo city streets, which is only a relatively small part of the contractors operating in Japan.

14. EXPERIENCE IN HONG KONG

This report is written for the EPD in Hong Kong. Therefore, it may seem irrelevant to include the experience in the "host country". However, for the overall assessment of LNRS, it is of great interest also to consider the substantial experience collected in Hong Kong. Therefore, hereunder follows a brief summary of findings in the first report within this project: "Review and evaluation of the low-noise road surfacing programme for low-speed roads in Hong Kong". The purpose was to review the results of trials of low noise road surface (LNRS) materials being carried out at about 30 road sections in Hong Kong on noise reduction and durability aspects and to propose the possible way forward on trials of LNRS materials in Hong Kong.

In Hong Kong, trials to use low-noise road surfaces (LNRS) started in 1987 and a programme for resurfacing high-speed roads with such material has been in force since the early 1990's. The type of LNRS used is single-layer porous asphalt, in later years with a polymer modified binder. Essentially, these surfaces have been laid over old brushed cement concrete surfaces. These low noise surfaces have performed well on high-speed roads. However, it is possible to improve them in such applications, since the noise reduction which can be credited to the porosity is not as high as have been obtained internationally, when considering that the surfaces they replace mostly are relatively "noisy" brushed cement concrete. The reasons for this is that the PMFC used are not of optimum construction in accordance with international experience. Nowadays the use of LNRS on high-speed roads in noise-exposed areas is common practice, given certain traffic and road conditions.

In 2002 a new programme started aiming at trying such surfaces also on medium- and low-speed roads and streets in urban areas. In 2006, the Environmental Protection Department (EPD) of Hong Kong published a "Comprehensive Plan to Tackle Road Traffic Noise in Hong Kong". An important part of this plan is an increased and widened use of LNRS on low-speed roads and streets; i.e. mainly on streets and roads with posted speed 50 km/h. The evaluation of the LNRS trial programme at this time suggests that it has been both successful and not successful; indicating that the risks of failures have been well balanced against the opportunities of progress.

In the evaluated part of the LNRS trial programme so far, the only type of LNRS tried is the polymer-modified friction course (PMFC), which in Europe would be called (polymer-modified) single-layer porous asphalt. Lifetime of such a PMFC is considered to be 2-4 years in these low-speed conditions, depending on the traffic and topographical conditions, which is about half that of a conventional surface.

The trials on low-speed roads have been essentially successful since they have indicated that LNRS may reduce noise emission by about 2 dB(A) in comparison to the conventional paving materials used in Hong Kong and seen as an average over two years, without any major problems with technical durability. In some cases one may even achieve about 4 dB(A) of noise reduction; see Fig. 14.1. The loss of noise reduction with time has been only about 0.3 dB(A) over the two-year studied period. The potential noise reduction was found to be about 1.8 dB higher for low proportions of heavy vehicles than for high proportions, and about 1.4 dB higher at speeds in the range 50-55 km/h than at speeds in the 20-25 km/h range. An initial study (1995-97) indicated that the noise reduction deteriorates during the first 9 months and then is rather stable until at least 24 months, which is expected. The present study fails to confirm this, which is very strange.

However, it is not sure that the noise reduction is caused by the porous nature of the low-noise surface (PMFC); it could also be an effect of the macrotexture which is favourable from an acoustical point of view. One might well obtain almost the same or even the same noise reduction by using a well-designed SMA, or thin surfacing. These would then have a much better durability, economy and range of application than the PMFC in low-speed applications.

When assessing the noise reduction, one shall keep in mind that under the tested conditions the proportion of heavy vehicles has been high (typically 10-40 %) and that heavy vehicles in Hong Kong include a large proportion with high power unit noise. It is only recently that Hong Kong has introduced the same stringent noise emission limits for vehicles as have been in force in Europe since 1996.

The data in Fig. 14.2 compares the two studies. It appears that the present study achieved higher time-averaged noise reductions, but for some strange reason there is no tendency for a rapid loss of noise reduction with time during the first few months, which is so typical of porous asphalt surfaces. From the visual observations made by the author it is absolutely obvious that clogging occurs very rapidly; see below. Therefore, the lack of higher noise reduction during the first months is very strange, and no explanation for this can be offered.

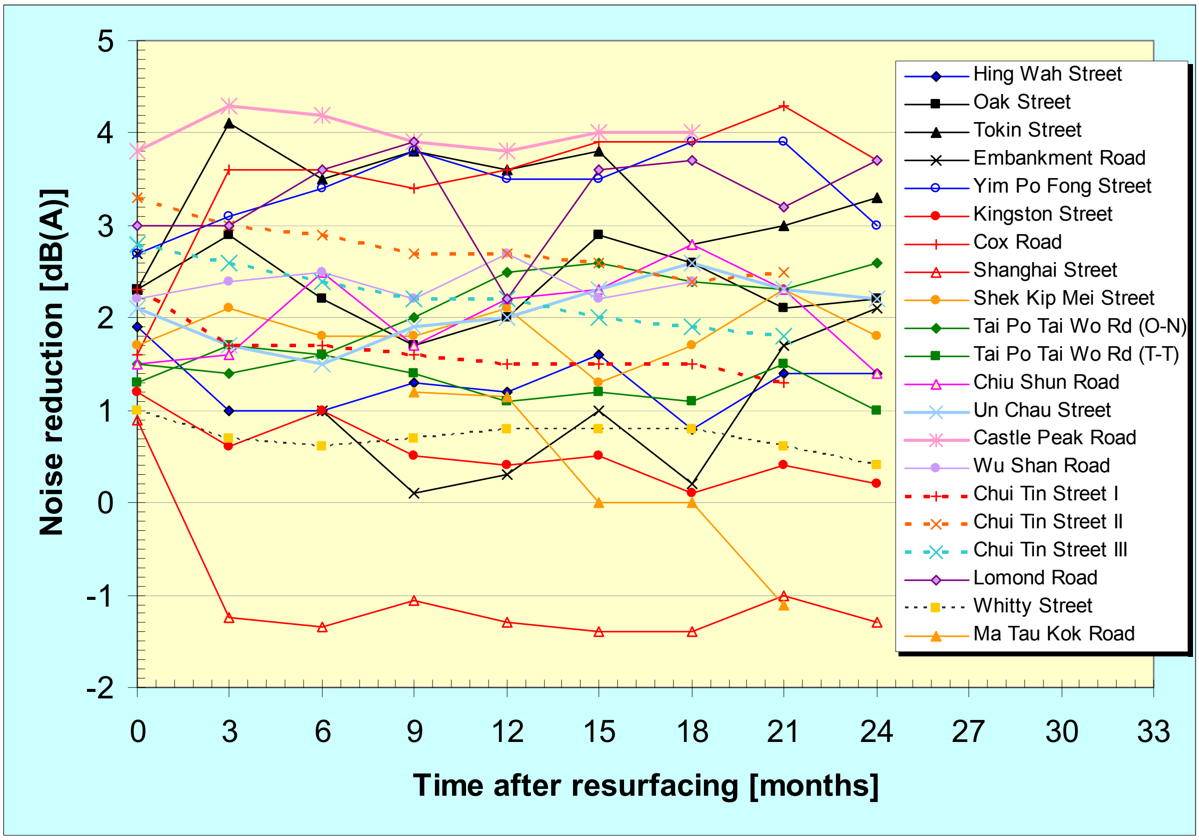


Fig. 14.1. Change with time of the noise reduction for all 21 surfaces measured. Note the lowest curve (Shanghai Street) probably is subject to an erroneous initial measurement.

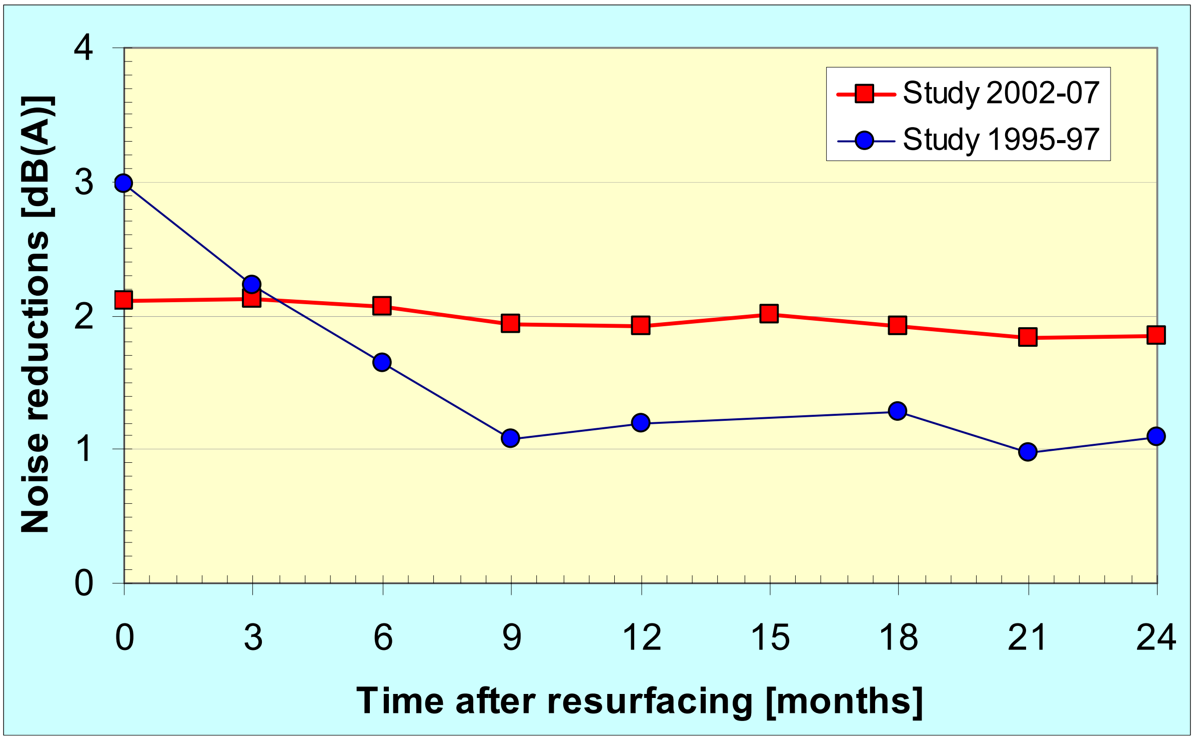


Fig. 14.2. Change with time of the noise reduction, as an average per time period for all 21 surfaces in the present study (2002-07) compared to a corresponding analysis in the earlier study (1995-97).

As mentioned, the average of the noise reduction values measured so far is 2.0 dB. This is an average over all the 21 test sections and over all 24 months during which noise monitoring has occurred. The existing old surfaces which were replaced were not defined, but since the analyses include 21 test sections, one may say that the average noise reduction is representative of what one would get for a "typical" mix of conventional Hong Kong wearing courses.

Visual observations by the author, combined with very limited information from Hong Kong observers, suggest that the general durability of the PMFC surfaces has been acceptable over the studied period. Some localized damages have been observed, but apart from parking areas and bus stop bays, these have not been serious enough to justify abandoning the trials.

The visual observations, however, clearly show that clogging of the porous surfaces occur very soon after laying. After only 6-9 months, in most cases, the areas close to the kerbs are totally clogged, and also in wheel tracks and in the middle of the lanes clogging is so severe that water drainage is seriously deteriorated. This is by no means surprising since the drainage at the roadside is very poor. In principle, with the present design of the kerbs and gulleys, most of the water will be trapped in a kind of basin in which water and dirt will collect. Before water reaches some drain, it has to run for such a long time and so slowly that any dirt in it would most likely have been deposited in the porous structure of the wearing course.

Bearing in mind that the change in noise reduction with time is a mere 0.3 dB per two years, while the visual observations make it obvious that clogging is severe already after half a year in many places, it is likely that the noise reduction obtained is only marginally, if anything at all, increased by the porous nature of the surfaces (exceptions occur at sites with medium speeds). The main reason for the reduction in noise (for most but not all surfaces) might be the exchange of relatively "noisy" and worn conventional Hong Kong wearing courses to an asphalt concrete surface in new condition with a macrotexture and megatexture which is much better optimized for low tyre/road noise than the existing old surfaces.

Ambient air temperature during the measurements affect the results marginally; over a 20 ^{o}C temperature range, the effect seems to be approx 0.5 dB of lower noise with the higher temperatures. This may systematically affect noise monitoring results, but if temperatures vary in a random manner, such effects will cancel out for long-term averages.

In the EcoPark in Tuen Mun a couple of experimental surfaces containing a substantial amount of crumb rubber have been laid on the road through the area, in accordance with recommendations made by the author at a meeting in October 2006. They are based on the asphalt rubber friction course (ARFC) of the so-called gap-graded kind used in Arizona. However, the results so far of the experiment are disappointing with a noise reduction of less than 1 dB.

15. EXPERIENCE IN OTHER NON-EUROPEAN COUNTRIES

15.1 Australia

Several studies have been performed in Australia regarding low noise road surfaces. One of the latest and most interesting is a substantial investigation of the road traffic noise attributes of five types of pavement surface currently in service in the subtropical-to-tropical state of Queensland [Samuels and Hall, 2006]. The investigation was configured to examine the acoustic performance of a set of pavements and how these performances varied over time. To do this, a considerable set of roadside noise data, measured according to the statistical passby technique (SPB), was collected at 29 sites in 2002, 2003 and 2005. These data were collected at 21 sites in South East Queensland and at 8 sites in North Queensland in the Townsville environs. Analyses of the data produced values of a parameter known as the Statistical Passby Index (SPBI) which was applied to quantifying the acoustic performance of the pavement surfaces and to exploring how they varied over time.

The main results are presented in Fig. 15.1. Note that each point denotes the average value of a number of surfaces of the same type. Some of the pavements (DGAC) exhibited very stable acoustical performance over the 2002 to 2005 period while the acoustical performance of others varied somewhat [Samuels and Hall, 2006]; over the studied 3-year period these canges seemed to be 0.3-0.5 dB/year. Note that the OGAC surfaces were not quieter than the SMA:s. This is probably because the maximum aggregate size was relatively large (19 mm) and air voids would be only 14-19 % according to Queensland specifications for OGA.

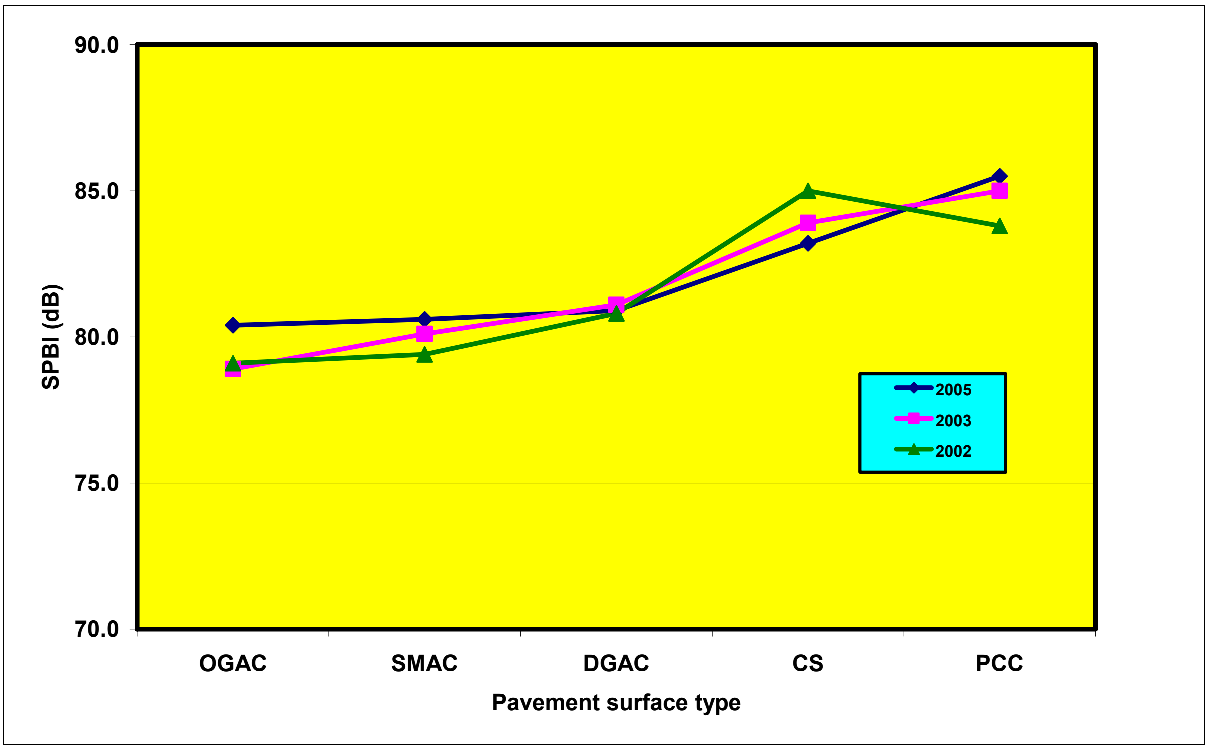


Fig. 15.1. Average SPBIs from the 2002, 2003 and 2005 investigations in Queensland. From [Samuels and Hall, 2006]. OGAC = Open-graded asphalt concrete, SMAC = Stone mastic asphalt concrete, DGAC = Dense-graded asphalt concrete, CS = Chip seal (surface dressing) 10 mm, PCC = Portland Cement Concrete. Nominal speed was 80 km/h.

15.2 New Zealand

In New Zealand there is a Long-Term Pavement Performance Programme that aims at the development of deterioration models. Earlier work, completed between 2005 and 2007, resulted in prediction models mostly for thin, flexible chipsealed pavements. Recently, the development of models for dense-graded and porous asphalt surfaces (OGPA) was reported.

The research was successful in developing pavement deterioration models for crack initiation of dense-graded asphalt surfaces, and ravelling initiation for OGPA surfaces, and has confirmed the validity of a rutting model that was developed earlier. For both the crack and ravelling initiation models, continuous probabilistic models were developed that predict the probability of the defect to occur. These models use data that is readily available on network level databases, and can therefore be applied on asset management applications.

The models were tested on the New Zealand network data and had a significant success rate (up to 75 percent) in predicting the behaviour of the surfaces. Based on this finding, it is recommended that the models are adopted within the New Zealand so-called dTIMS system. Further work required includes refining the models on the basis of individual sections' long-term pavement performance data. See further [Henning, 2009].

Porous asphalt lacks the strength needed at intersections and where there is stop-and-go traffic. However, there is hope for a much stronger porous surface type within a few years than the present types, suitable also for intersections and where tyre forces are high, namely using an epoxy-modified binder, with approximately 75 % bitumen and 25 % epoxy.

Experiments have been conducted in New Zealand with this principle recently, which have so far been successful (one ongoing field test and some lab tests). Laboratory investigations were undertaken into the cohesive properties of OGPA manufactured using epoxy modified bitumen and an associated accelerated loading test was carried out at Transit New Zealand's Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF) to demonstrate the technology [Herrington et al, 2007].

Binder oxidation is the principal factor governing the ultimate life of porous asphalt. Because of the very open nature of the material, oxidation and binder embrittlement is more rapid than in dense mixes. Oxidative hardening ultimately leads to failure of the mix through loss of material from the surface (ravelling or fretting) under traffic shearing stresses. The result is a rough uneven riding surface. The short average lifetime in New Zealand of 10 to 11 years for porous asphalts (in many cases only seven to eight years), compared with that of dense mixes (about 16 years), adversely affects their benefit-cost ratios and thus inhibits the more widespread use of this safe and environmentally friendly surfacing [Herrington et al, 2007].

Results from the Cantabro test (a test of mixture cohesion relating to the resistance of OGPA to surface abrasion losses) indicated that the early life cohesive properties of cured epoxy OGPA should be comparable to that of standard OGPA at 25°C and markedly superior at 10°C. The modulus of the cured epoxy mixture was much higher than that of the standard OGPA but this is probably of little benefit given that failure through rutting and deformation is uncommon for properly designed OGPA.

The superior oxidation resistance of the epoxy material was clearly evident in Cantabro tests conducted at both 25°C and 10°C. The CAPTIF trial demonstrated that full-scale manufacture and surfacing construction with epoxy OGPA could be easily undertaken without any significant modification to plant or the necessary operating procedures. Trafficking of the test sections resulted in early signs of surface abrasion in the control section but not in the epoxy.

Experiments with new surfaces will continue in December 2007, involving full-scale field testing of OGPA, both with 20 and 30 % air voids. The author is in close contact with the NZ researchers to follow the progress.

16. DRAINAGE SYSTEMS

Clogging of porous asphalt is one of the major problems associated with this type of surface. On high-speed roads, clogging is not very serious since the traffic automatically cleans the surface when there is rainy weather due to the high pressure of the water at the leading and trailing edges of vehicle tyres when water is pushed away from the tyre/road contact and sucked up at the rear of the contact area. On low-speed roads, such cleaning does not accur since the water pressure is much lower due to the lower speeds. Furthermore, on low-speed roads there is often more dirt generated from the roadside. In order to make porous surfaces efficient other than when new, it is necessary to avoid clogging. The way to avoid clogging is to have excellent drainage from the entire wearing course both over its area and vertically through its depth. Drainage can only be and remain effective if dirt can be:

(1) as effectively as possible prevented from reaching the friction course
(2) transported away from the friction course as soon as possible

There are a number of measures than can be undertaken to reduce the problem:

- Whenever porous asphalt is used, give the surface a 1 % higher cross-slope than is normal; i.e. usually 3.5 % instead of the normal 2.5 %. This will increase water/dirt runoff speed. In case of wide road shoulders, it is recommended to increase crossfall even more
- Never block the runoff of water/dirt from a porous surface along its lower edge (except for approx one or two dm), make sure the full depth of the wearing course has unobstructed access to the roadside or an underground drainage system (if any)
- In an urban street where there is a walkway for pedestrians lined with kerbstones, put a drainage channel along the kerb into which water and dirt from the porous asphalt easily can run without obstruction at the edge, as mentioned above. Consider the solutions in Japan and Denmark, but make sure that the slots are somewhat wider than in the Danish case
- In order to prevent water and dirt generated by businesses along the street from running out into the porous asphalt, put an extra drainage channel along the walkway outer edge. Optimize the slot width and shape in order to prevent ladies heels to get stuck in the slots, yet providing good drainage

In cases where there are plant areas or loose soil close to the road with a risk of dirt/soil running out onto the road in case of rain storms, use a similar drainage channel to separate the porous asphalt from the roadside.

The above would be valid also for thin layers of the porous and semi-porous type, as well as for asphalt rubber of the open-graded type.

Some examples how such drainage is managed in some low-speed porous asphalt projects in Europe and Japan are shown in the following Figs. 16.1-16.6.

<u>Fig. 16.1.</u> Kerbside drainage provided in the double-layer porous asphalt experiment in Copenhagen, Denmark, mentioned earlier in this report. Condition after one year of operation.

<u>Fig. 16.2.</u> Kerbside drainage provided in the double-layer porous asphalt experiment in Copenhagen, mentioned earlier in this report. Condition after 6 years of operation. Most of the slots have become clogged; the author cleaned the third one from the left. Conclusion: The slots are too thin. The special kerbstone is called Keradrain and is made in Italy.

Fig. 16.3. Kerbside drainage, including a gulley, along a major street in Tsukuba City, Japan. Condition after two years of operation.

Fig. 16.4. Kerbside drainage at the same location as in Fig. 16.3, but this time at the corner of an intersection. Note that the kerbstone is constructed like a shallow valley in order to prevent dirt from flowing over the grating.

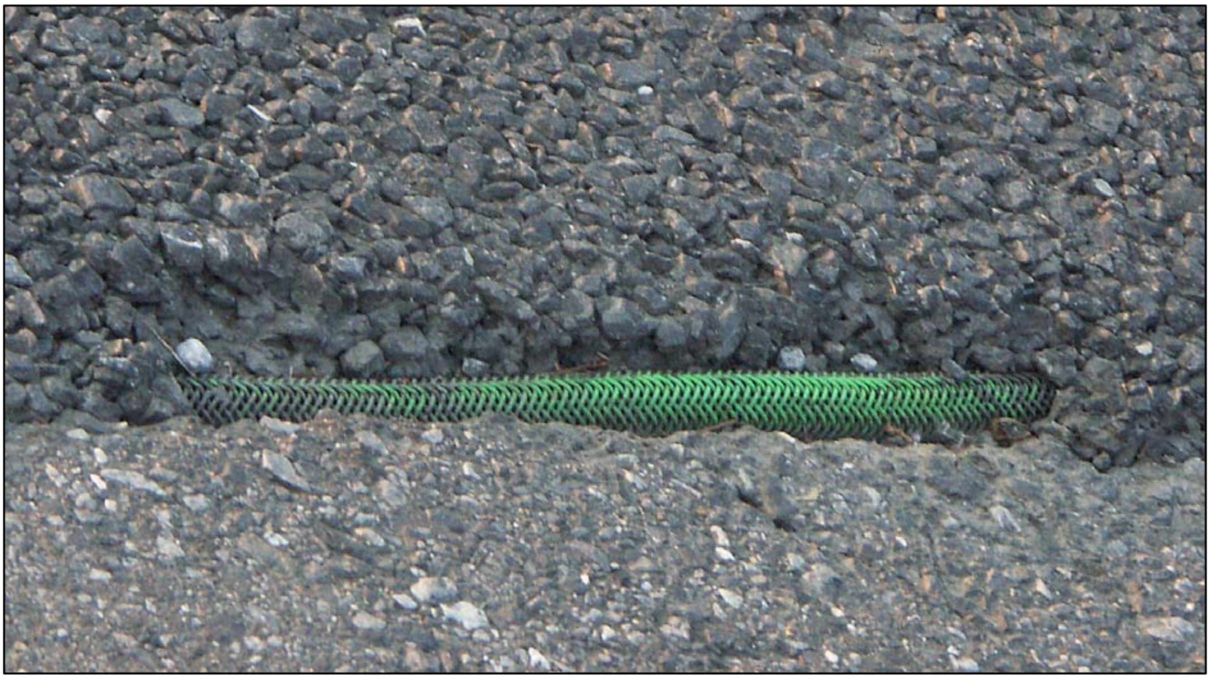


Fig. 16.5. Special plastic drainage pipe provided along a joint between porous asphalt and dense asphalt. Tsukuba City in Japan (the asphalt was removed at this point to show the pipe).

Fig. 16.6. Kerbside drainage along a street in Utrecht, the Netherlands. The inset shows an enlarged picture of the grating.

Along porous thin layers or porous asphalt (the latter is not common) in the U.K., most often applied in urban areas, it is common to provide some more advanced drainage systems than the regular gulleys if there are kerbstones along the road.

At the gulleys there are "weepholes", small holes, in the grating frame in order that sub-surface water can get way there, or if the surface becomes saturated water flows over the top into the grating. On flat roads they use a combined kerb channel detail (commonly known as a 'beany block' after the inventor)[67]. In this case the holes go down below the surface by about 30 mm to drain the porous subsurface directly towards the side. On major motorways the road side open concrete channel section is set down below the surface to drain the interface [Walsh, 2008].

See further Section 11.2.5 and Fig. 11.12 for a very advanced system.

The porous asphalt surfaces in Japanese cities, where there are kerbstones as a rule, are provided with drainage as follows. Drainage of water away from the roadway is accomplished by the use of nylon/plastic pipes (13 mm inner diameter) of the type shown in Fig. 16.5, or similar. These are put along the pavement kerbstones and ending at water drains. Water drains (gulleys) are seen in Figs. 13.3, 13.7 and 13.9. These pipes are put just under the top level of the dense asphaltic basecourse, sitting in an extra drainage asphalt "ditch", see crossection in Fig. 16.7. The temperature of the porous mix laid on top of the plastic pipes (about 140 ^{o}C) is not a problem for the pipes (one might fear that the pipes might melt or deform but this is not the case).

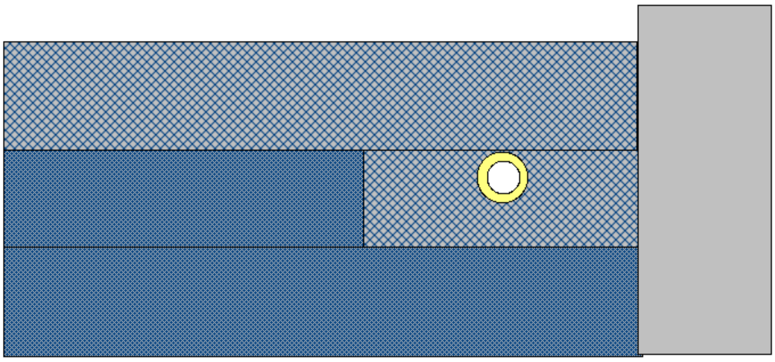


Fig. 16.7. Schematic drawing of a cross-section of the right side of a road with drainage pipe embedded in drainage asphalt (medium blue). On the right side is a kerbstone (light blue). Under the drainage asphalt, part of the basecourse is depicted (darker blue).

[67] This can be seen at: http://www.marshalls.co.uk/select/speciality.php?specialist=Water+Management

17. ROAD SURFACE POLICIES IN THE DIFFERENT COUNTRIES

17.1 Sweden - the land of "noisy" SMA surfaces

Stone mastic asphalt, SMA, was introduced in Germany over 30 years ago and designates the original idea of achieving an open-graded coarse aggregate skeleton filled with rich mastic. Today, SMA is well-established in many countries where it is regarded as high quality wearing course material, primary, due to its ability to withstand rutting as well as to ensure high skid resistance. SMA has also shown superior wear resistance against studded tyres, a serious deterioration mechanism in countries such as Sweden. The first years when SMA surfaces were used, it was rather common that they became inhomogene, having frequent patches with excessive binder and filler, resulting in almost bleeding parts. By and by these problems have become more rare and today all major contractors produce high-quality SMA surfaces. An example of an exception appeared in 2007 when a 10 km section travelled daily by this author was paved with a very inhomogeneous and patchy SMA. That work should have resulted in some penalty for the contractor. These experiences demonstrate that paving SMA needs experienced contractors working with great care.

So far it has been the durability of the road surface against the wear of studded tyres in wintertime that has been the determining factor in the Swedish road surface policy. This has meant that the SMA surface with maximum 16 mm aggregate size generally is the preferred surface type on all high-volume roads and streets, sometimes challenged by dense asphalt concrete (DAC). Where speeds are lower (70 or 50 km/h) sometimes the 16 mm variant is replaced with 11 mm, and in some cases where speeds are low and the volume is not too high, even 8 mm maximum aggregate size is used. On roads with posted speeds 50-90 km/h and especially in urban or suburban areas, also DAC with 16 or 11 mm chippings are used. On 50 km/h streets, probably the DAC dominates. Due to the lucky combination of availability of durable and high-PSV aggregates in Sweden and development of more durable and homogene versions of SMA and DAC surfaces, much of the studded tyre wear has been reasonably well counteracted. A few motorway sections, most notably the latest new one, have cement concrete surfaces; nowadays they are always constructed with the EACC technique.

On low-volume rural highways and on local roads outside urban areas, it is common to use chip seals (surface dressings); mostly with either 16 or 11 mm maximum chippings. When new, these are considered as very noisy, but the texture in the wheel tracks is gradually worn or pressed down and noise is accordingly reduced. Often, such chip seals (max. 16 mm aggregate) are laid directly on a gravel road, then called "oil gravel", but the appearance and texture is similar to the chip seal laid on a paved road.

Porous asphalt surfaces were tried already in the 1970's, followed in the 1980's with new test sections with varying success. The (too) high expectations were rarely met. In a few cases the limited experience of road contractors resulted in poor durability and invariably the clogging quickly reduced the advantages of the porous surfaces, giving them a somewhat undeserved bad reputation, amplified by similar experiences in Norway and Finland. Only recently, has there been a revival of porous asphalt surfaces; starting with the successful trial made in the SILVIA project on motorway E18, with both a single- and a double-layer porous asphalt. This was followed up in 2005 with a similar double-layer porous asphalt surface (max 11 mm aggregate in the top layer) being laid on a section of motorway E4 through the Stockholm suburb of Botkyrka. See Chapter 7.3 about this experiment. There are also some other projects around Sweden in which porous asphalt has been laid on high- or medium speed roads in the most recent years.

The politicians and administrations in the major cities have become very interested in a wider application of porous asphalt surfaces due to their low-noise characteristics. As an outstanding example, a drastic environment-improving programme was announced in May 2008 for Hornsgatan (street) in central Stockholm, which is one of the most polluting streets in the country; with respect to noise but also with respect to exhaust gases and emission of particulates. This street has symbolized the inability of some city administrations to meet the requirements for emission of particulates set up by the European Commission. It was announced that about 4 million Euros over a three year period are assigned for improvements on and along this street and that this will include a low noise road surface, by which is probably meant a porous asphalt surface. The posted speed limit will be variable between 50 and 30 km/h and there are plenty of intersections and street lights so it will be interesting to see if the city can find a low-noise road surface durable enough for this environment. Maybe one candidate could be the QCITY surface described in 6.5. One of the measures to reduce emission of particulates will be to spray the street periodically with CMA. The author thinks that it will be interesting to see how this combination of porous asphalt and CMA works; the idea with the CMA is to bind the dust and if this finds its way down into the porous asphalt rather than blowing away it may increase clogging. It shall be mentioned, though, that this seems to be “just” a political initiative rather than plans firmly anchored within the city’s road administration; thus it is uncertain whether the plans will ever be realized. If nothing else, it illustrates the political will and interest in this noise-reducing measure.

See further Chapter 17.8 regarding a new innovative Swedish low-noise road surface policy, which deserves a special chapter.

17.2 Denmark – beginning to focus on thin layers

Although geographically a neighbour of Sweden, Danish regulations forbid the use of studded tyres. This makes the road surface policy more similar to the ones in continental Europe. The most common road surface on high-volume roads and streets is DAC 0/11, and this is commonly used as a reference surface in Danish road traffic noise research. Sometimes they use on open-graded variant of this with a voids content of 15-20 %, which is a kind of "semi-porous" asphalt. DAC 0/8 are also used commonly, but then mostly in urban areas.

There is a commitment to consider LNRS in noise-sensitive areas as a means of reducing the exposure; i.e. when noise exposure levels exceed the given limits (usually 55 dB). Special annual funds are available for noise abatement measures, including the use of surfaces giving lower traffic noise emission.

To select the right surfaces, the Danish road authorities, in conjunction with industry and consultants, have recently developed and are trying to implement on a trial level a noise classification system for road surfaces. This resembles a little the SILVIA classification system, but it is somewhat simpler.

The system is based on the Close Proximity Method (CPX) and encompasses the following components [Kragh, 2007-2]:

- A guide to the use of asphalt surfacings in traffic noise abatement.
- A system for the documentation and declaration in classes of the noise reduction of the asphalt surfacing.
- Three classes A, B & C, where class A surfacings exhibit the highest noise reducing effect and class B & C exhibit lower noise reducing effects as compared to regular dense graded asphalt surfacings.
- Reference values of the noise emission as determined by the CPX method.
- Description of the CPX method including the definition of method variables and requirements on supplementary calibration of the measuring device.
- Paradigm for use in contracting and preparation of tender documents. The paradigm contains an introduction, special specifications for noise reducing surfacings (SRS), example of a noise declaration document, and example of Bill of Quantities.

The system is a first attempt in Denmark for contracting noise reducing asphalt surfacings. It still has some limitations and several subjects need to be addressed in the future development of the system. Especially, there is a need for better knowledge on the accuracy offered by the CPX method, and for the development of appropriate acceptance criteria to be used in contracting [Kragh, 2007-2]. The low-noise road surfaces (in Hong Kong called LNRS) tested according to the Danish system are called "SRS".

The reference values included in the 1st generation system refer to the CPX method and are defined as the national CPX_{DK} index. The CPX values correspond to the noise emission assumed in the Danish part of the Nord2000 traffic noise prediction model, representing approximately 8 year old asphalt surfacings of dense graded asphalt concrete or SMA, both with 11 mm nominal aggregate size. The reference levels are:

CPX_{DK} reference at 50 km/h: 94.0 dB(A)
CPX_{DK} reference at 80 km/h: 102.0 dB(A)

These reference values have been rounded up in order to make the values more robust. No reference has been defined for the traffic speed 110 km/h, due to the limited data available for this speed. When a producer wants to claim a certain noise reducing property of one of his asphalt surfacings, he will need to declare a noise class appropriate for the product. For the preparation of the necessary documentation, the producer must test his product on a trial section, where proper noise measurements by the CPX method can be performed. The result obtained is then compared to the appropriate reference value (see above) and the actual noise reduction is computed as the difference “x” [Kragh, 2007-2].

When declaring the noise reducing properties of an asphalt surfacing (by comparison to the proper reference used in Denmark), one of the following noise classes A – C should be used:

Class A: Very good noise reduction	(reduction 7.0 dB or more)
Class B: Good noise reduction	(reduction 5.0-6.9 dB)
Class C: Noise reduction	(reduction 3.0-4.9 dB)

The declaration shall indicate the noise class and traffic speed. Surfacings with limited noise reduction properties below 3.0 dB(A) will not be classified as a noise reducing surfacing. At present the producers offer surfacings in class B and C. The higher class A has been introduced as a driver for future development and improvement of the noise reduction properties. An example of a "noise declaration form" is shown in Fig. 17.2 [Kragh, 2007-2].

To ensure that the choice of CPX equipment does not influence the results, before any equipment can be used for CPX measurement, the CPX trailer must have carried out a supplementary calibration protocol (field calibration) described in the 1st generation system. If any differences between results obtained by different CPX trailers are encountered, such differences are compensated for by a correction constant attributed to each piece of equipment. The field calibration is carried out by annual measurements on selected reference sections. Currently, in Denmark, there are two CPX trailers in operation; one is of the M+P construction and the other is of the DGMR construction. The latter is shown in Fig. 17.1.

Supervision of the field calibration and evaluation of the results is the responsibility of the Danish SRS Committee, which prescribes the actual correction constants attributed to each CPX trailer. The SRS Committee will also prescribe those reference sections, where field calibration shall be made [Kragh, 2007-2].

Fig. 17.1 One of the two CPX trailers available in Denmark (2007). The construction is made by the Dutch consultant company DGMR. Note that the trailer is open; there is no enclosure.

The Danish have made a lot of studies related to thin asphalt layers (reported elsewhere in this report) and it is expected that several of the products approved as SRS will be of this main type. An example of measurements performed as a background for the classification system is shown in Fig. 17.3, from [Kragh, 2007-1]. The three low-noise classes A, B, C are indicated.

SRS NOISE-DECLARATION

X (80)
X (50)

Producer:____

Product: ____________________ **Type:**________________

Recipe No.: ______________________________________

NOISE MEASUREMENT:	**CPX-measurement at 50 km/h**	**CPX- measurement at 80 km/h**
Declaration section Name/number: Chainage: Side of road: Constrution date:		
Job Mix Formula Identification/date:		
QC test results Production & constr. Lab. ID. No:		
CPX-measurement Execution. date: Measuring firm: Measuring report-ID: Measured section:		
CPX-results. CPX_{DK} Measured value: *DK reference:* Noise reduction:	dB(A) 94.0	dB(A) 102.0
Remarks:		

JOB MIX FORMULA DETAILS:

Bitumen type:	☐ 40/60 – 160/220	☐ 250-330 – 330/430	☐ Other (describe)
Aggregate Coarse part:	☐ Quarried	☐ Crushed Gravel	☐ Other (describe)
Marshall-Voids:	____ (1 decimal)	☐ Geometric	☐ Volumetric (air/water)
Gradation. % passing:	0.063 mm: ____	2 mm: ____	5.6 mm: ____
	8 mm: ____	11 mm: ____	

Certified by: **Name:**______________________________ **Date:**_______

Noise Class	A	B	C
Noise reduction (dB_A)	> 7	5 - 7	3 - 5
	Very good noise reduction	Good noise reduction	Noise reduction

Complies with SRS-requirements for declaration of noise reducing surfacings in Denmark

Fig. 17.2 The noise declaration form suggested to be used in the Danish classification system for low-noise road surfaces ("SRS"). From [Kragh, 2007-2].

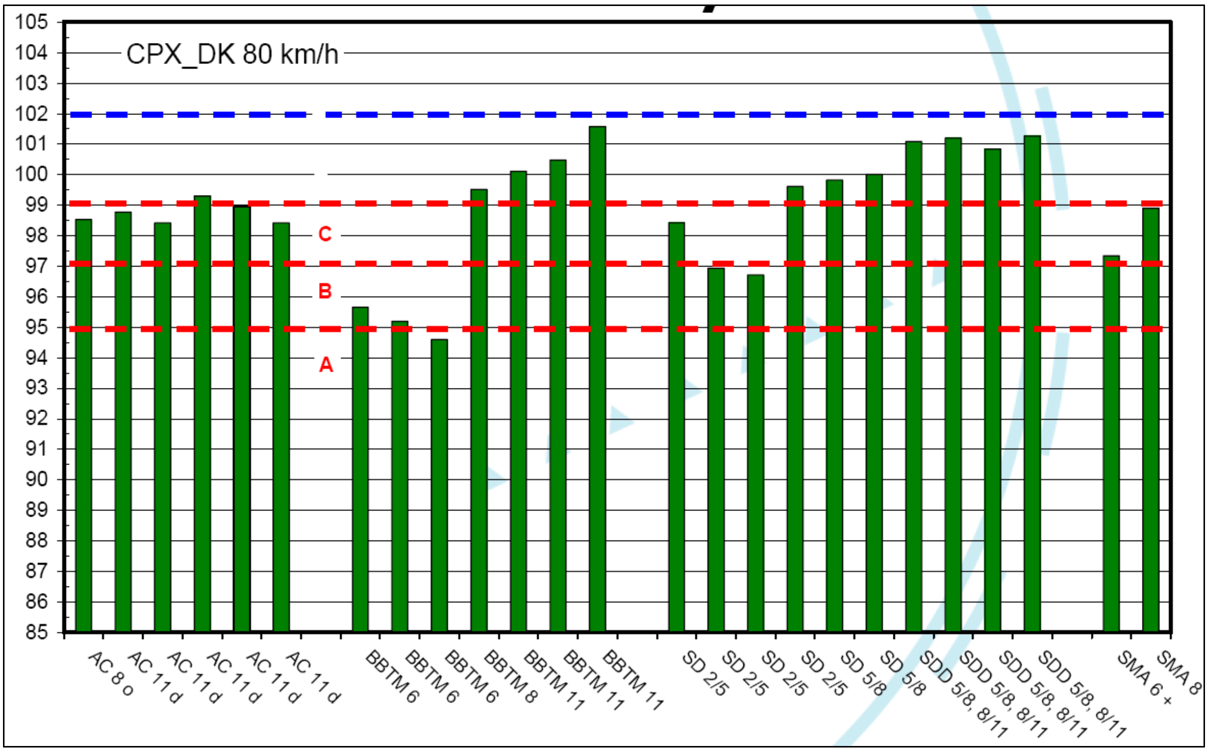


Fig. 17.3 Example of data measured at 80 km/h by the Danish Road Institute as a background for the noise classification system. AC = Asphalt Concrete, BBTM = Thin layers.

17.3 The Netherlands – low noise surfaces almost everywhere

17.3.1 Surfaces used on the high-speed road network

Most of the high-speed road network is paved with asphalt concrete surfaces, with some high-volume roads using cement concrete. The asphalt surfaces were earlier generally of the dense asphalt concrete (DAC) type with 16 mm max. aggregate size.

Already in the mid-1990's it was decided by the national road authority to use (single-layer) porous asphalt concrete (called "ZOAB") with a maximum chipping size of 16 mm, a thickness of minimum 40 mm and an air voids target of 20 % to replace existing surfaces on the entire state road network whenever repaving was needed. This means that the state road network successively has got a larger proportion of porous asphalt; the present proportion being more than 70 %. The target is to reach 100 % in 2010. The main reason for the decision was the increased traffic safety expected for the porous asphalt (less splash and spray and better wet road friction) but decreased noise emission by some 3 dB at high speeds[68] was a side effect which was appreciated. Some of these porous surfaces have now served for approximately 10 years, albeit they then show substantial ravelling and are clogged. The maintenance costs are high; one third of the national road maintenance budget is now being spent on maintaining porous asphalt roads [Hofman, 2008].

During the past few years, a rapidly increasing area of double-layer porous asphalt concrete (DPAC, TLPA) has been used on the state road network; mainly with 8 mm aggregate size in

[68] But only 1 dB at 50 km/h

the top layer and 16 mm in the bottom layer, as it has been found that this surface offers much better acoustic performance than the "standard" porous surface while still having an acceptable durability. The most recently known status (2007) is that more than 100 km of roads are using this material.

Despite the large chippings (up to 16 mm) used on the state road network, the texture of Dutch roads is generally smooth by European standards. On local highways and in urban areas, max. aggregate sizes of 5, 8 or 11 mm are used. Rough-textured chip seals are not used.

A procurement system is being developed according to which low-noise road surfaces are required to be used on any particular road and the road contractor must promised to supply a product with a certain noise level according to the C_{road} procedure (see below), connected with both penalties and bonuses depending on how well the surface performs over its lifetime.

17.3.2 Surfaces used on the low-speed urban road network

Most of the urban roads and streets use asphalt concrete or SMA as paving material. The exceptions are block surfaces which are used predominantly in old towns and historical parts of old cities. Possibly, the Netherlands might use more block surfaces than any other country which means that a fairly large proportion of the urban network is paved with block surfaces. The blocks are often a kind of tiles with a rectangular shape which are set in some attractive pattern. These surfaces are often uneven and create a distinct, rumbling tyre/road noise, but the traffic is mostly restricted to low volumes on such streets so the overall noise annoyance from this is limited.

Some years ago, double-layer porous asphalt surfaces were tried in cities, but these trials failed, due to fast clogging and ravelling. The double-layer surfaces are nowadays laid only on high-speed roads. Instead, the cities have turned their interest to the thin layers as the low noise solution on low-speed roads. The thin layers are not as vulnerable to the horizontal forces in the tyre/road interface which are so frequent in urban situations due to stop-and-go traffic, intersections and sharp curves.

The DWW (now RWS) has recently issued advice for road authorities that they are now allowed to use thin layers at up to 80 km/h when noise reduction is needed.

In order to encourage the use of quieter road surfaces in urban areas, an economic bonus was given by the Dutch authorities to communal and regional road administrations which applied low-noise surfaces. For 2001 and the next three years there was available about € 50 million (in total) for the quiet roads compensation scheme. It originated from a budget to compensate for the environmental damage caused by high economic growth, especially by the high growth of road traffic. More than 15 million € were paid in two years in such bonuses and according to unconfirmed information in mid-2002 local authorities had already formally asked for € 40 million.

What the Dutch government did was to provide a compensation for the extra costs of low noise pavements compared to the costs of a conventional asphalt pavement. This includes normal maintenance for 15 years and a new top layer after 7-8 years. The contribution was fixed and depended on the kind of road surface: one or two porous layers, open- or semi-open or any other noise-reducing elements. The prime target was to stimulate the local authorities to gain experience. The second target was to stimulate research by the road builders and to put together a lot of information about the behaviour of these kinds of roads.

The surfaces had to be tested according to the C_{road} procedure and provide a certain noise reduction in new condition in order to eligible for the bonus. What happened afterwards was not considered in this system, why it was suspected that some of these surfaces showing "almost incredibly" high noise reductions (up to about 7 dB) were optimized for high initial noise reduction only. Even if this bonus system is now abandoned, it was considered to be a success and had indeed the effect of opening the eyes of the street authorities for the advantages of using thin layers.

As an example of a city policy under development, Groningen studies various aspects of low-noise road surfaces, in a 10-year project started in 2000. After it has finished a final decision will be made on when and where to put what product. The major costs of this project are for periodic noise measurements which are financed from a so-called ZOAB fund. More and more cities and provinces in the Netherlands adapt a similar type of funding to stimulate the wide application of low-noise road surfaces. This has led to a temporary policy to apply low-noise road surfaces where there is a noise problem and to replace conventional road surfaces by low-noise versions, except when it is not possible because of constructional reasons [Van Keulen, 2008].

17.3.3 Dutch standard procedure for classification of noise properties of road surfaces – The Δroad or C_{road} procedure

The Dutch are using a unique system to assign a noise reduction value to each type of road surface (labelling), which may be used for specification of a certain (maximum) noise level in a certain road project. The procedure is called the Δroad procedure, and sometimes C_{road} in English, and the value assigned is in Dutch called C_{wegdek}. To obtain the C_{wegdek} for a type of surface, a test section is chosen on which SPB measurements are made. The values obtained are compared to corresponding values which have been obtained on a number of Dutch reference road sections (DAC 0/16) and the difference in noise level becomes the C_{wegdek}. On 1 April 2008, the list (see below) contained 44 road surfaces (including the reference).

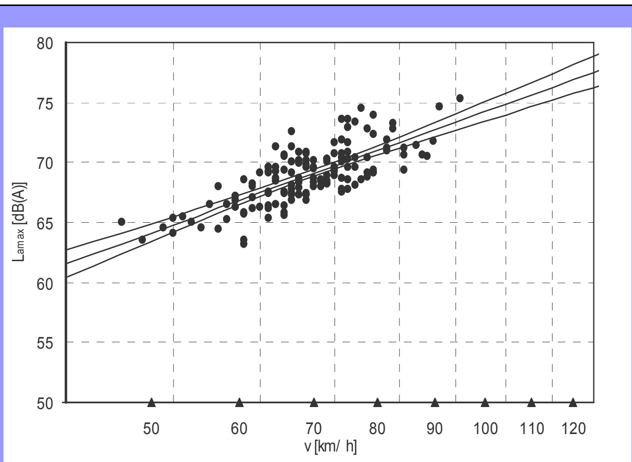
The measurements in this system are conducted with the SPB method (ISO 11819-1). Some details are listed here:

- At least 100 passengers cars and 50 trucks must be measured
- Corrections are made for differences in temperature between the measurements
- At least five test sections of the tested product must be tested, and average calculated
- The measured A-weighted maximum noise levels are plotted against the logarithm of vehicle speed in a regression diagram
- The linear regression line (noise level vs log of speed) is determined, including an accuracy measure, which is the 95 % confidence interval at speed intervals of 10 km/h

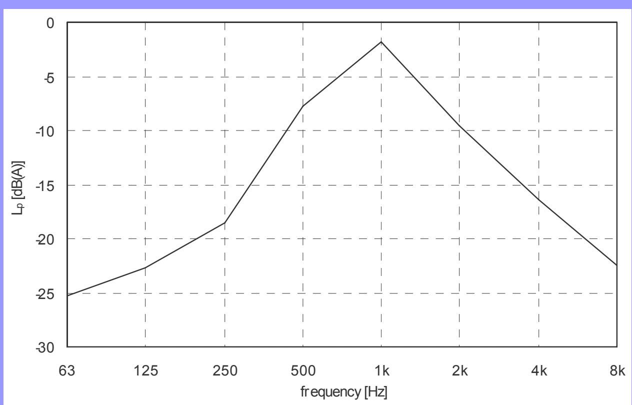
The SPB results are valid when the 95 % confidence interval (CI) at a certain speed is no more than 0.3 dB. The results are reported; for example, as follows (see also Fig. 17.4):

1. Technical and administrative information about the measurements, etc
2. The noise level vs speed regression line; e.g. $L_{SPB}(v) = 71.6+33.4*\log10(v/80)$ where v is the vehicle speed. This is reported for each vehicle class (light, medium and heavy vehicles; although the two latter are added into "heavies").
3. The valid speed range for the measurement (in this example): 60-70 km/h
4. Octave band frequency spectrum, e.g. as (63;-25,3), (125;-22,7); (250;-18,6); (500;-7,8); (1k;-1,8); (2k;-9,5); (4k;-16,5)

The method is described (in Dutch) on the following website:
http://www.stillerverkeer.nl/index.php?section=rmv&subject=Cwegdek
The results are published in an Excel spreadsheet (again in Dutch) together with individual road surface reports in pdf format on the following website:
http://www.stillerverkeer.nl/index.php?section=rmv&subject=Cwegdek&page=actuelelijst
The spreadsheet version of 1 April 2008 is downloadable from:
http://www.stillerverkeer.nl/rmv/Cwegdek/Wegdekcorrectiefactoren010408.xls
The most current spreadsheet is available at: http://www.stillerverkeer.nl/stillewegdekken/



v [km/h]	$L_{A,max}$ [dB(A)]	95% CI [dB(A)]
40	61,6	1,1
50	64,8	0,7
60	**67,5**	**0,3**
70	**69,7**	**0,3**
80	71,6	0,5
90	73,4	0,7
100	74,9	0,9



f [Hz]	Lp [dB(A)]
63	**-25,3**
125	**-22,7**
250	**-18,6**
500	**-7,8**
1k	**-1,8**
2k	**-9,5**
4k	**-16,5**

Fig. 17.4 Example of how data for a measurement according to the C_{road} system are presented: Regression diagram (noise vs speed) and octave band frequency spectrum; in both diagrams and tables. Note that such a report must be made for each vehicle class (light and heavy vehicles). The figure is based on [Padmos, 2007].

17.4 *The United Kingdom – low noise surface approval scheme*

17.4.1 General policy

In the U.K., a compensation for noise nuisance from roads may be paid if a new road is built or is changed significantly, according to Part I of the Land Compensation Act 1973[69]. A series of five booklets explains the Land Compensation Code in simple terms, covering the following topics[70]:

Booklet 1: Compulsory purchase procedure
Booklet 2: Compensation to business owners and occupiers
Booklet 3: Compensation to agricultural owners and occupiers
Booklet 4: Compensation to residential owners and occupiers
Booklet 5: Mitigation works

As a recent example, more than 2000 compensation claims, each averaging about £3,000, have been paid by the Highways Agency to people who say their lives have been blighted by the Bingley relief road north of Bradford in West Yorkshire opened in 2003. Claims can be made until 2010. The payments total about £6 million, which is about 13 % of the overall road construction cost[71]. A virtual photographic tour along this road can be made[72]. However, it is sometimes reported that more money is spent on noise compensation to residents along a new motorway than what is spent on actually building the road [Baxter, 2000]. Furthermore, residents' outcry sometimes result in resurfacing with a quieter surface just a few months after original construction [Baxter, 2000]. These reports have been confirmed to the author by [Kinsey, 2000].

In 2000, the U.K. Government published a Ten Year Transport Plan which, in brief terms, said:

- 60 % of trunk road network – including all concrete roads - shall be paved with low-noise road surfaces
- The target to achieve this is March 2011
- Existing non-concrete roads shall be resurfaced with quieter surfacing when maintenance is justified

The author recently wrote to the Highways Agency asking about the present status of the Ten Year Transport Plan. The answer was that in the intervening period, it has become apparent to the Agency that replacing concrete surfaces ahead of their maintenance need is very expensive both in the short and longer term, and hence they now only replace all existing surfaces, including concrete, when required to for structural reasons. It was not possible yet to provide anything definitive on how this will impact upon the 60 % target in 2011. The position at the end of March 2006, was that approximately 30 % of the strategic road network had been resurfaced with low-noise materials [Lowery, 2007].

---

[69] http://www.highways.gov.uk/roads/2568.aspx
[70] http://www.highways.gov.uk/knowledge/790.aspx
[71] http://archive.thetelegraphandargus.co.uk/2007/2/22/193253.html
[72] http://bealach-na-ba.fotopic.net/c516396.html

The Highways Agency Noise Specialist Lowery is currently working on an update of the DMRB[73] roads design manual, planning to publish the revision in August 2008. Noise sections were last updated in 1993. The revised DMRB will cover issues that have developed since 1993, for example the use of low noise road surfaces [Anon, 2008].

It is interesting to note in the DMRB, that SMA surfaces are not generally preferred as wearing courses (citations are from [DMRB Vol 7, 1999]): "*stone mastic asphalt to a generic specification shall not be used as a wearing course on trunk roads including motorways in England, but it may be used as a basecourse*". However, "*to take advantage of the superior properties of SMA as a wearing course, proprietary versions designed for particular aggregate sources have been developed as thin wearing course systems to ensure surface texture is maintained. These require BBA HAPAS Certification*", as described below.

Work is also underway to revise the CRTN – the Calculation of Road Traffic Noise guidance [Anon, 2008].

Traditionally, the most common road surface in the U.K. has been the hot rolled asphalt (HRA) in which chips are added on the surface, either pre-coated with binder or not. In chipped HRA wearing courses, the nominal single size coarse aggregate is 14 mm. On motorways, cement concrete has been used. However, due to noise concerns, the policy is changing in favour of using SMA and thin layers. With regard to using low-noise porous surfaces, the U.K. policy has been very conservative. Presently, the policy is as follows:

- Porous asphalt is not allowed on high-speed roads (speed limit 70 mph, 113 km/h).
- Porous asphalt is allowed on roads with lower speed limits, but actually used to a very small extent.
- There are some experimental sections of porous asphalt.
- The maximum chipping size in porous asphalt used to be 16-20 mm.
- Thin layers are often preferred to porous asphalt as a "low-noise" surface (provided they are approved according to the HAPAS procedure, see below)

The Highways Agency controls the high-speed roads, and supports some work by TRL Ltd on this, but controls very few low- or medium-speed roads. Therefore, the Highways Agency would not spend money researching surfaces for low-speed roads. The local councils who control all other roads than those of the Highways Agency (which can include some high speed roads) tend to follow the Highways Agency in surfacing policy as they do not do any research themselves.

London has 13,600 km of streets. The Mayor of London is responsible for 580 km of London's important roads - the Transport for London Road Network (TLRN). These are mostly Red Routes. The TLRN accounts for about 5 % of London's roads but carries 33 % of London's traffic. London's 33 local authorities manage the other roads, apart from motorways, which are the responsibility of the Highways Agency[74]. The most common surface throughout London still seems to be 14 or 20 mm HRA. Despite the earlier negative views on SMA as a wearing course, SMA surfaces (which are quieter than HRA) have now begun to be used extensively in London, see more about this and the use of thin surfacings in Chapter 10.

[73] Design Manual for Roads and Bridges; see http://www.standardsforhighways.co.uk/dmrb/index.htm
[74] This information is taken from http://www.london.gov.uk/mayor/transport/streets.jsp

17.4.2 HAPAS - The low noise thin surfacing approval scheme

In the U.K., a system has been developed that is in practice a new type approval procedure. It is called HAPAS (for Highway Authorities Products Approval Scheme) and is operated by the British Board of Agrément (BBA). It was set up by the Highways Agency, CSS (County Surveyors' Society) and the BBA in 1995, with the objective of developing national approval arrangements for innovative products, materials and systems for use in highways and related areas. This removed the need for individual authorities to carry out their own assessments and tests. The BBA's approval process for HAPAS involves laboratory and witness testing, site inspection and evaluation of the source of production of the material under assessment. Existing test or performance information is also investigated. Data generated from these key elements is then considered by the BBA's HAPAS Project Managers/Assessors in the context of the requirements set out in the Guideline. If the data is acceptable, the HAPAS Certificate is drafted [HAPAS, 2008].

With regard to road surfacings, HAPAS currently covers the following types:

- High friction surfacings[75]
- Thin surfacings
- Permanent Cold-Lay Surfacing Materials
- Coloured Surface Treatments for Highways

Such surfaces are usually proprietary (i.e., the exclusive rights to use them belong to a certain company). Of the types mentioned above, the only one in which noise properties are an issue is thin surfacings. The others listed may have some noise-reducing properties too, but they are not tested within this system.

The approval procedure is a 6-stage process; see Table 17.1, which applies to several surface characteristics, such as safety and durability properties. At the time of writing, among surfacings of special interest for low noise, 19 high friction surfacings[76] have been approved as well as 28 thin surfacings.

For thin surfacings, the surface characteristics considered includes an optional noise test using the SPB method, although no noise limits are set. From the SPB measurement results (data for light and heavy vehicles separately, not the SPB index), a "Road Surface Influence (RSI)" factor is determined. Road Surface Influence (RSI_H), high speed and (RSI_m), medium speed are defined in the Guidelines Document. They are a measure of the difference in noise that could be expected if compared against a theoretical HRA surface with 2 mm texture depth (usually achieved on HRA with added chips 14 or 20 mm max. size). A negative result indicates a reduction in noise level.

[75] High friction surfacings are in general surface types designed as a surface dressing using small chippings of high durability and very high friction properties, usually laid where friction may be extra critical, such as at light-controlled intersections, in sharp curves or where there is a severe grade.
[76] These are normally not designed to provide low noise, and not even tested for it, but in practice they would often give low-noise characteristics

Table 17.1. The U.K. Highways Agency 6-stage BBA-HAPAS procedure for evaluating new materials

Stage number	Action
1 Assessment of Applicant's data	Assess and evaluate existing information on the material
2 Assessment of production control	Assessment of quality control procedures of the Applicant or Installer, e.g. ISO 9000 certificate
3 Laboratory Testing	Test the mechanical properties to allow theoretical predictions to be made of their performance
4 System Installation Trial	Evaluation of construction and performance of materials over two years on at least five road sites
5 System Performance Trial	Provided the previous stage was not successful, a full-scale trial over two years may be made, including visual observation and texture depth measurement (some optional tests may be required too, like noise)
6 Certification	A certificate will be issued in the BBA Roads and Bridges series that verifies the system's compliance with the requirements. The validity of the Certificate is reviewed by BBA every five years. At least two annual visits by BBA to each production location and/or Certificate Holder's office shall be made

In principle, only approved products may be used without restrictions on trunk roads and motorways in the U.K. Since no noise limits are set, the noise test currently only gives "consumer information" that may be considered an advantage or disadvantage when procurement is made. However, some agencies have set their own limits. For example, for certain noise exposure situations, the Highways Agency has specified guidelines for determining the types of materials that may be used based upon their HAPAS noise levels.

Finally, it might be interesting to note that in the HAPAS system a "low noise surfacing" is one that is 2.5 dB(A) quieter than the reference type. As written above, the latter is in reality an HRA with 14 or 20 mm chipping size. This is a relatively "noisy" surface, which means that many conventional DAC and SMA surfaces would also be considered as "low noise surfacings" under the HAPAS system.

As an example, one can mention the so-called UL-M 20/10 surface which has a 10 mm max aggregate size in a layer which may be as thin as 20 mm. This proprietary surface has according to its certificate an RSI_H of -5.6 dB and an RSI_m of -5.2 dB, measured at a surface age of 4-5 months. A variant of this with 6 mm max aggregate size gave a noise reduction of 7.0 dB at medium speeds when it replaced an old HRA surface [BBA-ULM, 2005]. Read more about the UL-M in Chapter 10.

For noise purposes, currently only two speed ranges are considered in HAPAS; medium (70-90 km/h) and high (100-130 km/h). However, when it comes to thin surfacings ("thin layers"), these are in other countries than the U.K. very often considered as useful on low-speed roads.

17.5 USA – low noise surfaces not yet recognized for abatement

The Federal Highway Administration (FHWA) policy related to tyre/pavement noise, contained on page 31 of "Highway Traffic Noise Analysis and Abatement: Policy and Guidance" reads as follows [FHWA, 1995]:

> "Pavement is sometimes mentioned as a factor in traffic noise. While it is true that noise levels do vary with changes in pavements and tires, it is not clear that these variations are substantial when compared to the noise from exhausts and engines, especially when there are a large number of trucks on the highway. Additional research is needed to determine to what extent different types of pavements and tires contribute to traffic noise.
>
> It is very difficult to forecast pavement surface condition into the future. Unless definite knowledge is available on the pavement type and condition and its noise generating characteristics, no adjustments should be made for pavement type in the prediction of highway traffic noise levels. Studies have shown open-graded asphalt pavement can initially produce a benefit of 2-4 dBA reduction in noise levels. However, within a short time period (approximately 6-12 months), any noise reduction benefit is lost when the voids fill up and the aggregate becomes polished. The use of specific pavement types or surface textures must not be considered as a noise abatement measure."

The FHWA policy restricts making adjustments for pavement type in the prediction of highway traffic noise levels and using specific pavement types or surface textures as noise abatement measures [FHWA, 2005]. Instead the US noise abatement policy largely relies on the use of earth berms or noise barriers (called "noise walls" in the USA). Until the noise benefits of low-noise road surfaces have been quantified and longevity determined, one cannot use specific pavement types or surface textures as noise abatement measures and one cannot make adjustments for pavement type in the prediction of highway traffic noise levels. This noise policy will not change until benefits and longevity have been determined.

This does not mean that it is *forbidden* to use quieter pavements; but the benefits of them cannot officially be taken into account and they will not be funded by federal money. On the other hand, local governments are allowed to self fund the extra costs of quieter pavements.

As a result of input from the general public, as well as results from studies conducted during the 1990's, Arizona Dept. of Transportation (ADOT) has asked the FHWA for an exemption to the above policy, i.e. for approval to implement a Quiet Pavement Pilot Program (QPPP), specifically to use asphalt rubber friction courses on selected freeway segments in the Phoenix area to reduce noise. FHWA and the ADOT then jointly developed the first QPPP to allow ADOT to use quieter pavements as one of their noise abatement options. The FHWA approved ADOT's QPPP in June 2003.

A QPPP is a voluntary program currently open to any U.S. State[77]. Two requirements must be met:

- Evaluating the changes in the pavement's noise abatement properties over time
- Making a commitment to maintain in perpetuity any noise reduction attributed to the pavement.

[77] See the official FHWA memo for more information:
http://www.fhwa.dot.gov/environment/noise/qpppmem.htm

Based on similar public concerns and tyre/pavement noise studies, the California Department of Transportation has indicated a desire to develop a proposal for a QPPP in California. It is strongly stressed that "Pavement safety and durability should never be jeopardized to obtain noise reduction" [FHWA, 2005].

The QPPP:s allow the use of an adjustment to the predicted sound levels to account for noise benefits of quieter pavement, but requires the commitment to maintain noise reduction in adjacent communities, if necessary, by means of repaving or other mitigation. They are intended to demonstrate the effectiveness of quiet pavement strategies and to evaluate any changes in their noise mitigation properties over time. Current knowledge on changes over time is extremely limited. Thus, the programs will collect data and information for at least a 5-10 year period, starting from 2003 in the Arizona case, after which the FHWA will determine if policy changes to a State DOT(s) noise program are warranted [FHWA, 2005].

In summary, current FHWA policy does not allow the use of pavement type or surface texture as a noise abatement measure. If policy change is to occur, results of the QPPP and/or additional research must demonstrate the safety and durability of each "quiet pavement," as well as its noise reduction capability. The safety and noise reduction of the pavement must last in perpetuity. In the short term, any policy change will be State specific, i.e., the change will only apply to a given State DOT(s) for a specified pavement type and/or texture. If warranted, changes in national policy may be considered in the future. The FHWA will disseminate information regarding Quiet Pavement Pilot Programs and Tire/Pavement Noise Research as they are developed and as deemed appropriate [FHWA, 2005].

In addition to the information above, it is interesting to note that the NCHRP in October 2007 issued a call for proposals (RFP) for a new project named "Methodologies for Evaluating Pavement Strategies and Barriers for Noise Mitigation" and with the objectives to develop methodologies for evaluating the feasibility, reasonableness, effectiveness, and longevity of acoustic and economic features of pavement strategies and barriers used for noise mitigation [NCHRP, 2007]. It may perhaps be seen as a follow-up of a workshop on "Cost Benefit Analysis of Transportation Noise Control Technology" organized in February 2007 by the National Academy of Engineering in Boston, USA, at which event the author was invited. The intention with the project seems to be to get appropriate tools for evaluating which of noise barriers or quieter pavements that are the most favourable noise control measures in cases where these are exchangeable. This together with the QPPP:s may also be the starting point of a partly new policy in the US.

The major pavement types in the USA are Portland Cement Concrete (PCC) and dense-graded asphalt (DGAC), the latter of which one major variant is called Hot Mix Asphalt (HMA). The PCC is used on high-volume roads, such as interstate highways and motorways and on freeways (multi-lane motorways) in large urban areas, but also on many high-volume city streets. This is not without exceptions; there are several motorways with DGAC pavement too. The DGAC or HMA are primarily used on roads with lower volumes and on city streets which are not paved with PCC. In terms of lane length, the asphalt pavements dominate, but if traffic volume were considered, probably the PCC would dominate.

The PCC pavements are generally too smooth-textured to be safe in wet weather in the untreated version; and therefore they are almost always treated with some texture-increasing method. The most common one is transverse tining. Some states use longitudinal tining, such as California and Colorado, in order to reduce noise, but this tining is considered by some people to create non-negligible lateral forces on vehicles with narrow tyres. For example, to reduce this effect, in Colorado the specification for longitudinal tining is 1/8” deep tines with ¾” spacing. Since the transverse tining often creates severe noise disturbances, it has become rather common to use diamond grinding to provide an even and relatively quiet surface. In too many cases, despite knowledge about this problem and its solutions since the 1970's, the transversely tined PCC have been constructed with poor or no randomization of the spacing of the tines, in which cases noise complaints have been frequent.

In Arizona, open-graded or gap-graded asphalt rubber surfaces are common, if not dominating, on the freeway system in the greater Phoenix area. Several states have made or are making own studies of the efficiency of such pavements. SMA surfaces and porous asphalt are uncommon in USA. For some reason trials with such surfaces have failed many times in USA, whereas it is now common practice in many European countries, Japan, Hong Kong and Australia to use such surfaces.

17.6 Japan – porous asphalt widely used also in cities

In Japan there are three types of road administrations:

- Ministry of Land, Infrastructure and Transport (NILIM) for national roads except expressways
- Expressway companies (companies responsible of the expressways)
- Local governments (prefectures, municipalities) for local roads

The largest local road administrator is the Tokyo Prefecture. Other large ones are for example Kanagawa (southwest of Tokyo), Chiba (southeast of Tokyo), and Osaka. In Tokyo, there is also a company managing the expressway system in the greater Tokyo area by the name Tokyo Metropolitan Expressway System (MEX).

The traditional surface type in Japan is the dense-graded asphalt concrete with 13 mm maximum aggregate size. With the exception of porous asphalt, this type is totally dominating both on highways and local roads.

In order to meet the Japanese Environmental Quality Standards (which are binding) and the Requested Limits (not binding but desirable), noise barriers are used to a very large extent. However, once the potential for using low-noise road surfaces was realized, the road authorities started to use such surfaces. Except for some research studies, the type which has been used is porous asphalt. The most common maximum aggregate size is 13 mm but also 10 mm is becoming popular.

Now it is the policy that all expressways and all other major routes through urban areas shall have a porous asphalt pavement which gives a noise reduction. Very often using either noise barriers or porous asphalt does not provide sufficient noise reduction, and therefore porous asphalt is frequently used as a supplement to noise barriers. The noise reduction is not the only reason; also improved wet weather friction is said to be an important issue. In the last few years, porous asphalt has been frequently laid also on major streets in urban areas and on through-roads in smaller cities and towns. In the large cities, it is not only the noise reduction which is driving this development; but it is the possibility of porous asphalt, with its water-retaining capacity which prolongs the time after rainfall when evaporation occurs, to reduce the heat island effect which has been the major driving factor.

The Tokyo Metropolitan Expressway System (MEX) is a high-capacity urban motorway system in Tokyo running to a large extent on elevated roadways. Posted speeds are 50-80 km/h and the total length is 283 km (October 2004). The system was then paved to an extent a little less than 50 % with porous asphalt. However, most new pavement reconstructions are utilizing porous asphalt so the porous asphalt proportion is constantly increasing and was in 2007 substantially higher than 50 %.

Fig. 17.5 shows how the noise-reducing measures on the national road system have changed from noise barriers and buffer zones to the use of low-noise road surfaces. The total length of this road system was 8,763 km in 2005, which means that then drainage pavements (porous asphalt) were installed on approximately 40 % of the road network, while noise barriers were used on approximately 4 % of the road network and buffer zones over approximately 1 %. This shows the dominance of the porous asphalt solution.

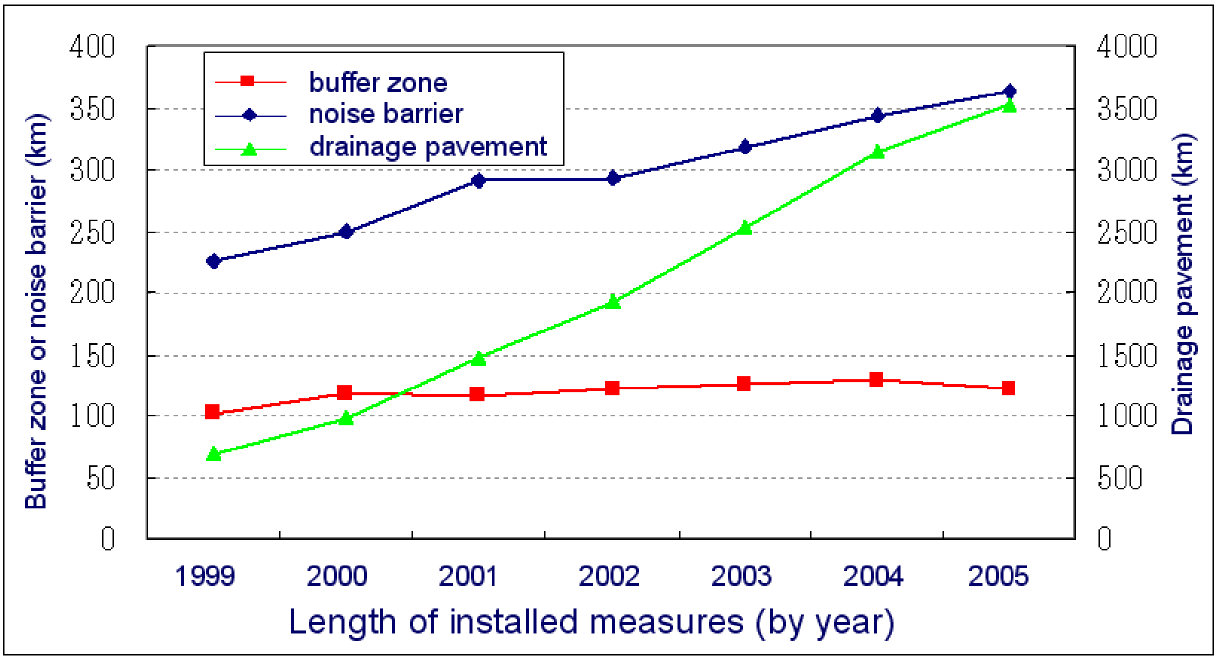


Fig. 17.5 The length of installed noise-reducing measures over the time period 1999-2005. From [Namikawa, 2007].

17.7 Other countries

17.7.1 Germany

The German Federal Highway Research Institute (BASt) is developing an assessment procedure to characterize the acoustical properties of porous road surfaces. The final objective is to specify the life-cycle of these pavements with respect to their acoustical performance based on civil engineering properties [Altreuther & Bartolomaeus, 2008].

17.7.2 Italy

The Italian motorway network is run by the company Atlantia S.p.A. (previously Autostrade S.p.A.). They have been using porous asphalt on the motorways for many years. By the end of 2007, 78 % was paved with low-noise road surfaces; the remaining parts are not feasible to pave with such surfaces due to e.g. mountainous area [Luminari, 2008]. Fig. 17.6 shows the extent of the low-noise road surfaces. In the region of Lombardy (which is around Milan in northern Italy containing a part of the Alps), as much as 92 % of the network is paved with porous asphalt [World Highways, 2007]. Thus, on the motorway network, more or less everything which is feasible to pave with low-noise road surface is already paved with it.

Low-noise road surfaces are not generally used on any low-speed roads, other than for research or trial purposes. The normal type of surfacing is dense asphalt (DAC). In old cores of cities, it is common that low-volume streets are still paved with block pavements, with blocks as large as approximately 3 x 3 dm.

Fig. 17.6. Roads paved with low-noise road surfaces on the Italian motorway network shown in green. Figure obtained from [Luminari, 2008].

17.7.3 Switzerland

The most common road surface types in Switzerland are dense asphalt (DAC) or SMA. However, porous asphalt is used increasingly. In January 2004, 131 km of Swiss motorways were paved with porous asphalt. In the canton (region) Vaud, 1/3 of motorways were paved with porous asphalt; and the target is 100 % up to an altitude of 600 m. Porous asphalt is not regularly laid on low-speed roads, but a research program with the aim to design surfacings useful for this has been conducted [Angst et al, 2008]. As a result of this, the Swiss authorities will encourage the use of LNRS in urban areas; see further Section 11.3.

17.7.4 Austria

Low noise road surfaces have been used in the Austrian "high level road system" (highways and motorways) for a couple of decades – the first porous asphalt surfaces were laid in 1984. However, in recent years the use of porous asphalt has dropped substantially due to problems with regard to winter maintenance and because of the shorter structural lifetime compared with dense asphalt [Haberl & Litzka, 2008]. The distribution of road surface types used on the Austrian high level road system in 2006 is shown in Fig. 17.7.

In Austria a procedure for measuring tyre/road noise emission is specified in the “guidelines and regulations for road construction” – RVS 11.06.64 (RVS, 1997) - and used either for acceptance testing of new pavements concerning tyre/road noise or for a technical evaluation of different road surface layers concerning their acoustic performance [Haberl & Litzka, 2008]. The measuring procedure resembles the CPX procedure of ISO 11819-2, but it uses a PIARC tyre with ribbed tread pattern for testing; something which has been criticized for being unrepresentative of real road conditions since the tyre is so special.

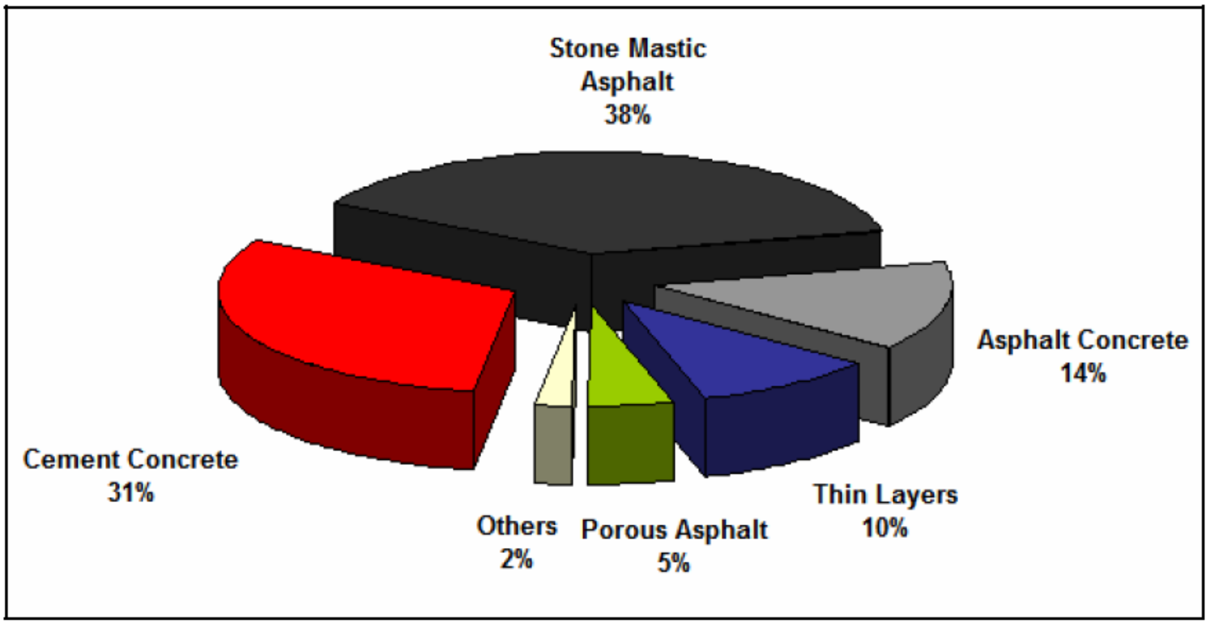
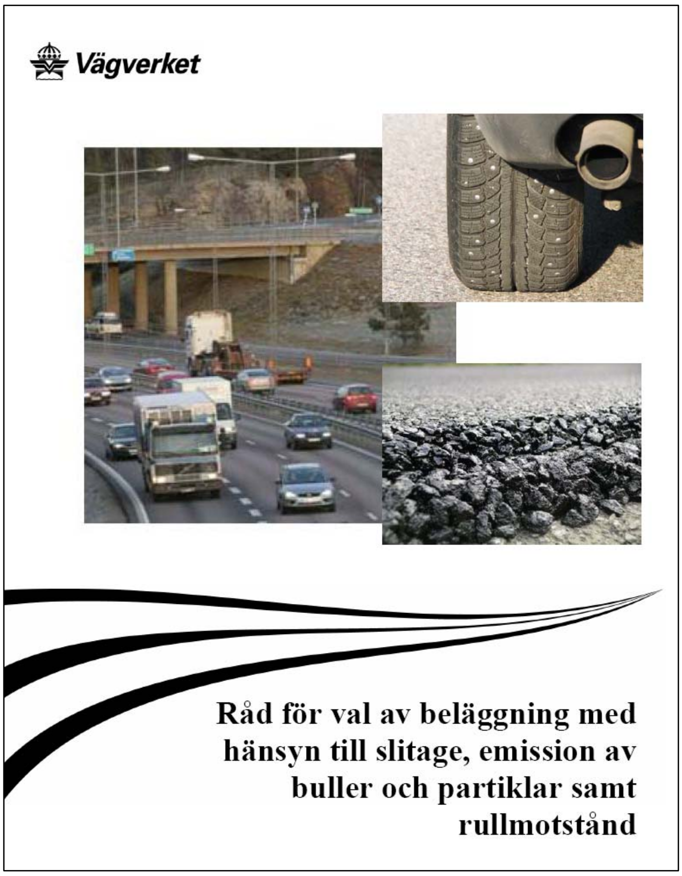


Fig. 17.7. Distribution of road surface main types on the Austrian highways and motorways network in 2006. Figure from [Haberl & Litzka, 2008].

17.8 New innovative policy in Sweden

The SMA and chip seal surface types mentioned in 17.1 are among the noisiest used in Europe, and the dominating SMA 0/16 on Swedish high-volume roads (where noise is most often a problem) is one of the noisiest types used in the industrialized world. It may be compared to the British HRA, which is now being phased out. The measurements by VTI have also shown that the SMA 0/16 is one of the most energy-consuming surfaces due to its high rolling resistance.

The awareness of this in the Swedish Road Administration (SRA), to a great extent due to the research by VTI, has recently led to a total revision of the surfacing policy. In the autumn of 2007, the SRA announced its intention and recommendation to its national and regional branches to start using a new approach in surface selection; an approach based on a cost-benefit analysis (CBA) where the most important environmental parameters are evaluated and balanced against the durability and economical parameters. As far as this author is aware, this approach is unique in the world. It warrants a description here.



The document describing the procedure has the title "Advice for choice of surfacing with regard to wear, emission of noise and particulates as well as rolling resistance" when translated from the original Swedish document [SRA, 2007]. The cover page is shown in Fig. 17.8.

Fig. 17.8 The cover page of the advisory document from the Swedish Road Administration (SRA). Preliminary version from October 2007, to be implemented as soon as possible, beginning in 2008.

The document is accompanied by an Excel file in which all calculations are made by means of macros. So far, all calculations are made as a comparison to the "normal case" of using an SMA 0/16 surface. However, by running a comparison of two different surfaces one can indirectly compare also those two surfaces.

The calculations are made in four steps, before an overall evaluation can be made, based on the three environmental parameters considered:

- Calculation of the cost and benefits related to noise emission
- Calculation of the cost and benefits related to emission of particulates
- Calculation of the cost and benefits of rolling resistance (and following fuel consumption)

Simultaneously, also calculations of the paving and maintenance costs are made, based on the expected lifetime of the particular road surface and costs according to experiences of the SRA. The lifetime is estimated from a model worked out and validated by VTI and based on simulated wear of a great number of road surfaces in a road simulator machine. Against the costs of the road surface, added costs of the three parameters listed above are compared, and the resulting cost/benefit is calculated.

But how are the costs of the three environmental parameters calculated? First, concerning noise emission, the external costs of noise exposure are calculated based on studies of depreciation of values of private houses and apartments. Such studies in Sweden have resulted in a monetary evaluation of road traffic noise following the relation shown in Fig. 17.9. Note that a newer version has been worked out in which the costs for noise influence on health are also included. Using these costs and using demographic information, one may calculate the aggregated costs around and beside the studied road section based on the number of residents and the noise exposure outside their facades. One must also know the differences in noise emission of various road surfaces. This is currently based on the data in Table 7.1 in this report as compiled by VTI.

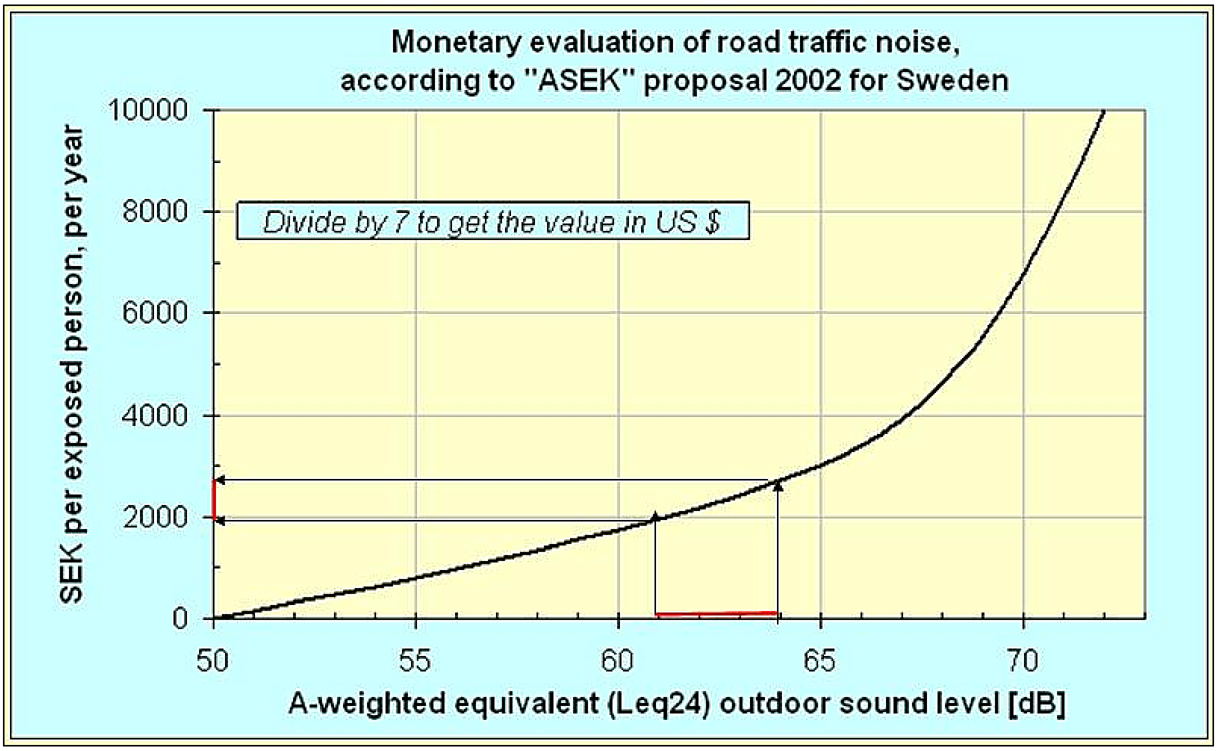


Fig. 17.9. Monetary evaluation of changes in noise exposure levels (outside façade) according to Swedish practice. In the example, a 3 dB noise reduction results in a "saving" of SEK 700 (approx HKD 800) per exposed person and year. One SEK equals about 1.15 HKD.

Needless to say, the resulting costs are very sensitive to the density of residents and their distances to the road. In a Hong Kong situation, the population density is far above common Swedish densities; thus it is likely that the external costs of noise exposure in general would be much higher in Hong Kong than in Sweden.

It is recognized that there are also other costs that could be blamed on noise exposure, such as effect on health. For example, in Denmark, it has been estimated that the costs of the health effects are about 2/3 of the costs of the depreciation of values of homes. In the SRA calculations, so far the health effects are neglected. Further, there should be costs of impaired working and learning efficiency due to both noise disturbance and poor sleep in noisy environments. As it is impossible to estimate these at the moment they are simply neglected.

With regard to emission of particulates, VTI has made a study of the effects of these on health and calculated the resulting socio-economic costs of particulates in $\mu g/m^3$ of air [Nerhagen et al, 2005].

With regard to the effects of rolling resistance, the differences in fuel consumption per vehicle is calculated from the differences in rolling resistance, and further aggregated to cost differences in energy use (fuel) for the entire traffic volume on the road section. Most of the background material, such as the relation between rolling resistance and road surface type, has been measured and processed by VTI. Not only the fuel costs are considered but there is also a term that estimates the costs of the CO_2 emissions following the differences in fuel consumption.

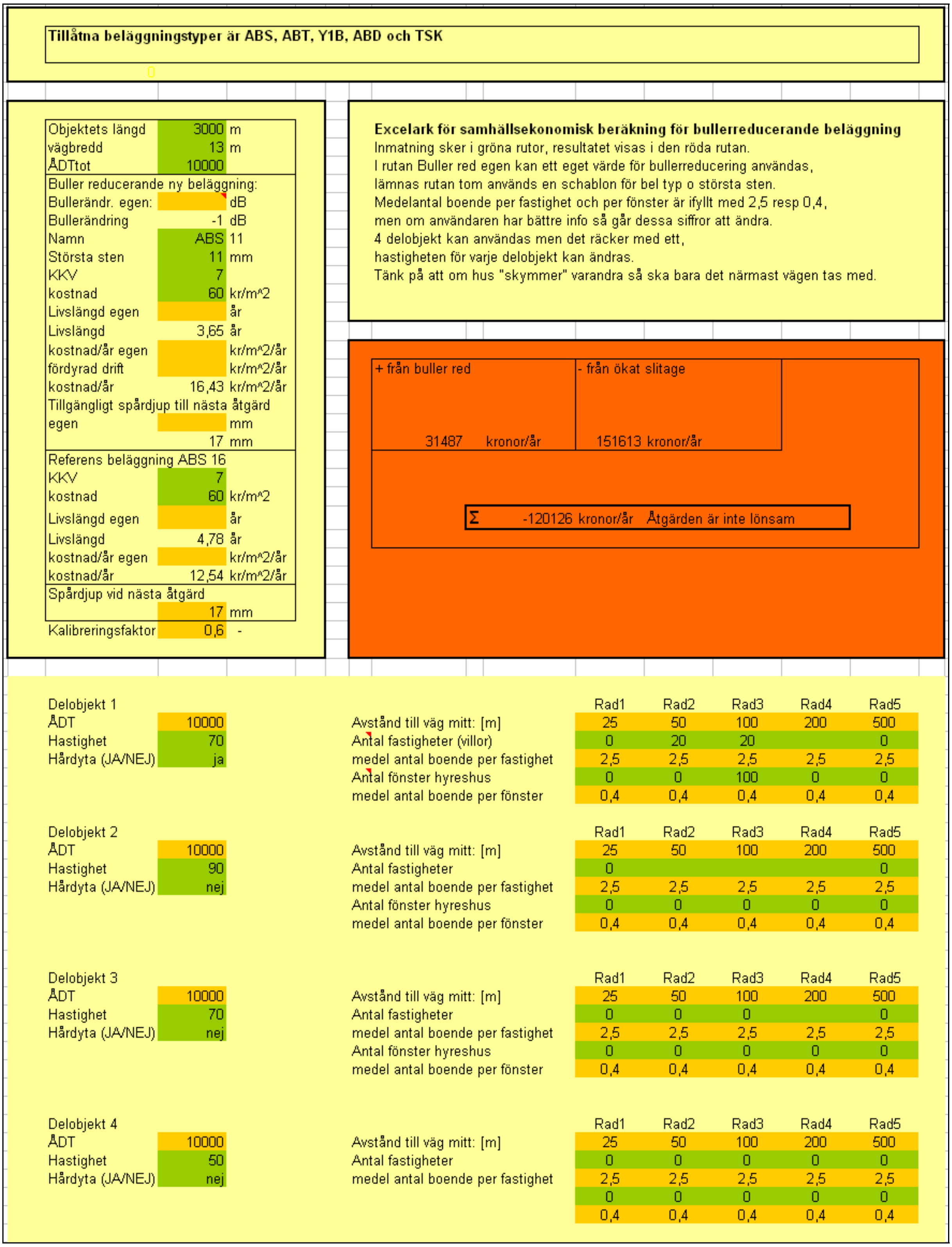
The SRA now recommends its regions to implement this procedure as a planning tool as soon as possible; if possible already from 2007.

So far, the document is only available in Swedish. However, this author has proposed that in 2008 an English description of the procedure shall be produced and the response to this has been positive (but no decision is yet taken).

Some calculated examples have been presented. In general these have shown that surfaces with smaller aggregate sizes are favourable provided traffic volume is high and the number of residents close to the road is high. The smaller aggregate increases the wear and thus road maintenance costs and costs of emission of particulates, but such costs are balanced by savings in noise exposure and fuel consumption and CO_2 emission. Many cases with high traffic volume and high population density, but only such cases, come out very favourable also for substantially more expensive low-noise surfaces such as porous asphalt.

An example of a calculation sheet ("input and result" sheet) in the Excel file used in the noise calculation in the SRA procedure is shown in Fig. 17.10.

This author thinks that the new procedure will change the road surface policy from the use of the dominating SMA 0/16 to an increased use of smaller aggregate sizes (SMA 0/11, SMA 0/8, or corresponding DAC:s) in areas along roads where population density is moderate or high. Where population density is high, there will be an increased use of more efficient LNRS such as thin layers and single- and double-layer porous asphalt.



Tillåtna beläggningstyper är ABS, ABT, Y1B, ABD och TSK

Objektets längd	3000	m
vägbredd	13	m
ÅDTtot	10000	
Buller reducerande ny beläggning:		
Bullerändr. egen:		dB
Bulleränding	-1	dB
Namn	ABS	11
Största sten	11	mm
KKV	7	
kostnad	60	kr/m^2
Livslängd egen		år
Livslängd	3,65	år
kostnad/år egen		kr/m^2/år
fördyrad drift		kr/m^2/år
kostnad/år	16,43	kr/m^2/år
Tillgängligt spårdjup till nästa åtgärd		
egen		mm
	17	mm
Referens beläggning ABS 16		
KKV	7	
kostnad	60	kr/m^2
Livslängd egen		år
Livslängd	4,78	år
kostnad/år egen		kr/m^2/år
kostnad/år	12,54	kr/m^2/år
Spårdjup vid nästa åtgärd		
	17	mm
Kalibreringsfaktor	0,6	-

Excelark för samhällsekonomisk beräkning för bullerreducerande beläggning
Inmatning sker i gröna rutor, resultatet visas i den röda rutan.
I rutan Buller red egen kan ett eget värde för bullerreducering användas,
lämnas rutan tom används en schablon för bel typ o största sten.
Medelantal boende per fastighet och per fönster är ifyllt med 2,5 resp 0,4,
men om användaren har bättre info så går dessa siffror att ändra.
4 delobjekt kan användas men det räcker med ett,
hastigheten för varje delobjekt kan ändras.
Tänk på att om hus "skymmer" varandra så ska bara det närmast vägen tas med.

+ från buller red	- från ökat slitage
31487 kronor/år	151613 kronor/år

Σ -120126 kronor/år Åtgärden är inte lönsam

Delobjekt 1	
ÅDT	10000
Hastighet	70
Hårdyta (JA/NEJ)	ja

	Rad1	Rad2	Rad3	Rad4	Rad5
Avstånd till väg mitt: [m]	25	50	100	200	500
Antal fastigheter (villor)	0	20	20		0
medel antal boende per fastighet	2,5	2,5	2,5	2,5	2,5
Antal fönster hyreshus	0	0	100	0	0
medel antal boende per fönster	0,4	0,4	0,4	0,4	0,4

Delobjekt 2	
ÅDT	10000
Hastighet	90
Hårdyta (JA/NEJ)	nej

	Rad1	Rad2	Rad3	Rad4	Rad5
Avstånd till väg mitt: [m]	25	50	100	200	500
Antal fastigheter	0				0
medel antal boende per fastighet	2,5	2,5	2,5	2,5	2,5
Antal fönster hyreshus	0	0	0	0	0
medel antal boende per fönster	0,4	0,4	0,4	0,4	0,4

Delobjekt 3	
ÅDT	10000
Hastighet	70
Hårdyta (JA/NEJ)	nej

	Rad1	Rad2	Rad3	Rad4	Rad5
Avstånd till väg mitt: [m]	25	50	100	200	500
Antal fastigheter	0	0	0		0
medel antal boende per fastighet	2,5	2,5	2,5	2,5	2,5
Antal fönster hyreshus	0	0	0	0	0
medel antal boende per fönster	0,4	0,4	0,4	0,4	0,4

Delobjekt 4	
ÅDT	10000
Hastighet	50
Hårdyta (JA/NEJ)	nej

	Rad1	Rad2	Rad3	Rad4	Rad5
Avstånd till väg mitt: [m]	25	50	100	200	500
Antal fastigheter	0	0	0	0	0
medel antal boende per fastighet	2,5	2,5	2,5	2,5	2,5
	0	0	0	0	0
	0,4	0,4	0,4	0,4	0,4

Fig. 17.10. Example of a calculation sheet ("input and result" sheet) in the Excel file of the SRA procedure. The upper left are input data (and some default values) for the road section and traffic, as well as for the surface which is compared against the normal SMA 0/16 surface. The lower half are data about houses/apartments and residents and their distance to the road, and the red area show the resulting savings in noise exposure costs compared to the increased paving and maintenance costs of the road surface.

The new policy is being implemented on a trial level in 2008. All the road regions in Sweden except the northern (less populated) ones use the new policy in one or more paving projects; especially in the Stockholm area. In general it means that the rougher-textured SMA 0/16 which would be the normal choice is replaced with SMA 0/11 or SMA 0/8.

The SRA plans to spend 200 million EUR in 2008 on repaving, of which just a small part is in areas where noise is a problem. Of this, about 4 % was subject to consideration with regard to the new policy, and of the latter about half has actually been procured according to the new policy.

A presentation of the new policy is available in [Sandberg, 2008-2].

17.9 European policy in the future?

There is no common European policy for selection of road surfaces, and there will most probably never be such a policy. The main reason is that the climatic conditions differ dramatically over the continent and road surfaces must be adapted to this.

However, there are some attempts to work out a common policy, procedure or even European standard related to acoustical classification and conformity checking of road surfaces.

It started with an initiative by the DG ENV (Directorate General for the Environment) of the European Commission, funding a project conducted in 2006 by the Belgian Road Research Centre (BRRC) in cooperation with consultant company COWI A/S in Denmark. The project was named Noise Classification of Road Pavements and the purpose was to enable DG ENV to promote the issuing and signing of a request from the Commission to CEN to prepare standards for low noise road pavements, to provide relevant conclusions and recommendations with regard to the issues of classification and standardisation, and to explain and disseminate information on net benefits to be gained from low noise road pavements.

It is intended that if a European standard will be worked out on this subject, it shall be based on the work of the project SILVIA (see Section 6.3.1 and Figs. 6.12-6.15); i.e. both SPB and CPX measurements are needed, plus some other types of measurements depending on the type of road surface.

As part of the project, a "Stakeholders workshop" was held 1 August 2006 in Brussels with participation by 35 European stakeholders (of which not many were road authorities). A report was issued after the workshop [Jespersen et al, 2006], in which the following conclusions were drawn (citation from the mentioned reference):

In summing up, David Delcampe[78] revisited the five key questions put forward in the introduction session, and concluded as follows:

1 Can low noise road surfaces significantly and beneficially reduce road traffic noise in addition to noise limitation of vehicles and tyres or other abatement measures? *Conclusion: yes.*

2 Should road surfacing be locally considered under noise action plans due by D. 2002/49/EC? *Conclusion: yes.*

3 Can public procurement authorities specify acoustic performances of road surfaces? Can they check the acoustic performances of road surfaces once laid down? *Conclusion: surprisingly many acoustic measurement methods and classification systems already exist in Europe, but they are neither harmonised nor comparable. Moreover some systems refer to commercial product and are not technologically neutral; or introduce restrictions onto the access to national markets for low noise road surfaces.*

4 Are there common standards allowing that such specifications are set and checked while ensuring healthy competition of road surfaces providers? *Conclusion: The workshop has clearly pointed to the need in Europe for harmonised standards if one wants to foster healthy competition. ISO and CEN standards already exist which may support the elaboration of the needed CEN standards and be beneficial for public procurement authorities.*

5 Should the Commission mandate the CEN with a view to develop such standards? To which main aspects should the EC pay attention in its mandate to CEN? *Conclusion tends to be positive. Ad hoc working group under CEN has already concluded that such standards are desirable and should be supported by the Commission. The workshop has also pointed to the need to strike a delicate balance between many diverging technical views and current procedures. Availability at short term of CEN standards is desirable but should not prevent further improvements in order to take advantage of technical and standardization progress and innovation. This calls for a careful design of a possible CEN mandate fostering a progressive and open approach, as well as for appropriate support from the part of the Commission.*

After this workshop, it was proposed by the French chairman of CEN/TC 227/WG 5, which is the Road Surface Characteristics working group under the European Committee for Standardization (CEN), to give the mentioned group the formal mandate to work out a standard for noise classification of road surfaces. However, when this is written such a mandate is discussed, and terms of reference are being outlined, but there is not yet any formal decision.

Instead, the DG ENV funded a project in 2006-2008 called INQUEST which is the acronym for "Information Network on QUiet European road Surface Technology". The INQUEST project is described on the Commission's "IST World Portal" as follows[79]:

[78] Mr Delcampe was the officer at the DG ENV who was responsible for this subject /The author's note
[79] Citation from http://www.ist-world.org/ProjectDetails.aspx?ProjectId=d731a1a79b3d42d4bca66291882e0a4f&SourceDatabaseId=7cff9226e582440894200b751bab883f

The project aims at coordinating communication and dissemination of past and present research pertaining to guidance on the use of low-noise technologies for road surfaces to European countries with less access and experience in applying knowledge in that field. One of the main instruments will be the dissemination of the contents of the Guidance Manual developed by SILVIA ("Sustainable Road Surfaces for Traffic Noise Control", a European-funded project completed in August 2005) by means of a series of workshops in countries that were not involved in SILVIA, with priority given to new member states. Two of the partners (the Belgian Road Research Centre and the Danish Road Institute) were leaders in SILVIA and key staff from SILVIA are also working for FEHRL. These partners will coordinate the dissemination from SILVIA with the latest findings of on-going research activity carried out a European and national level. One of the main outputs of SILVIA is a proposed acoustic classification procedure for road surfacing materials and technologies. A complementary objective of the INQUEST project is to promote European harmonisation of testing methods and equipment for this purpose. To that end, one partner will set up a European network of users of the measurement methods involved in the classification procedure in order for them to exchange experience and data and to organise equipment comparison tests. It is noted that these tests are not proposed as part of the project.

As a final activity of INQUEST a new workshop "Workshop on classification procedures & systems" was organized in April 2008 in Ljubljana, Slovenia. This workshop presented the views of the DG ENV, the possibilities to produce European standards (within CEN), and the views of the project team. A number of invitees reviewed the current practice and prospects in European countries. As a follow-up to the INQUEST project and workshop, there was a new workshop in September 2008, where a "Users Group" (“NCAG”) was set up. A second meeting was held in Januray 2009 with participation by CEN representatives. Documents are currently being produced which can initiate the work on a formal CEN basis. After that the NCAG might either work under CEN (if CEN approves it), or as a voluntary separate constellation (if CEN disapproves), to work out documents which would form a basis for some kind of or specification that finally can be turned into a European standard. This question is politically sensitive.

18. SPECIAL ISSUES

18.1 Metrics and annoyance

So far, no other weighting has been demonstrated to be superior to the A-weighting; thus A-weighting shall be the normal procedure. The time constant shall be in accordance with the respective standards or drafts for them. Frequency spectra shall be measured in the CPX method, and it is recommended to be made also in the methods based on Leq measurement. It is an advantage if frequency spectra are measured in the SPB method too but it may be considered too expensive sometimes.

In the noise monitoring programme of the low-noise resurfacing trial on low-speed roads (see the Evaluation Report) it appears that the type of sound level used for reporting noise reductions is the L_{10}. Internationally, it is the L_{eq} that is used (or L_{DEN} or L_{DN} which are L_{eq} levels but where increased weight is given to noise during night and evening hours). It was only the U.K. and some commonwealth states that used L_{10}. Nowadays, even the U.K. has switched to L_{eq}.

Therefore, it would be natural to use L_{eq} for the evaluations in the Hong Kong experimental projects instead of L_{10}. However, consider what these metrics are mainly influenced by:

The L_{10} is the level exceeded 10 % of the time (18 minutes of the 3 h monitored in the past and present programmes). This level will have the following features:

- Passages of heavy vehicles will influence the level, during most of the passage
- Passages of light vehicles will influence the level, but mostly when the vehicles are closest to the microphone
- Extremely noisy events such as people shouting, blowing in horns, illegal motorcycle driven in noisy mode, poor exhaust systems, release of air from heavy vehicles, etc (which are mostly short events) will <u>not</u> contribute with their high noise level, just with the time during which they occur
- Background noise will not at all influence results

The L_{eq} is a kind of time "average", but which puts much higher weight to noisy events than to the "average" events. This level will have the following features:

- Passages of heavy vehicles will influence the level for the entire passage, but in particular when they are closest to the microphone
- Passages of light vehicles will influence the level too, but only when the vehicles are closest to the microphone
- Extremely noisy events such as people shouting, blowing in horns, illegal motorcycle driven in noisy mode, poor exhaust systems, release of air from heavy vehicles, etc (which are mostly short events) will have a major influence on the final level
- Background noise will not at all influence results

Due to the characteristics of many of the local streets, it is likely that there are many very noisy events which will influence the L_{eq} levels but not the L_{10} levels. The road surface will not affect these very noisy events at all, and it will affect the heavy vehicle noise just marginally. Thus the L_{eq} is not a good measure of the effect of the surface. Therefore, the author prefers using the L_{10} instead of the L_{eq} for the main evaluations in this particular case where very noisy and irrelevant events may occur. However, the very best measure to evaluate the surface effect in an urban environment like this should be the L_{50} since it is not much influenced by extremely and irrelevant noisy events and neither of background noise (like a machine constantly working in the background). It would depend to a large extent on both car and truck/bus pass-bys. A recent and very relevant study found the L_{50} to be the one which was the best related to subjective annoyance in an urban area, so this is further justification for using the L_{50} [Nilsson et al, 2007]. However, since there is little extra effort, if any at all, to report the different values it is suggested to report the L_{eq}, the L_{10} and the L_{50}, but to put the highest emphasis in the assessment on the L_{50} values.

The author has made a comparison of L_{10}, L_{90} and L_{eq} noise reductions on two road sections in the low-speed resurfacing programme. The results appear in Table 5 in the Evaluation Report.

As elaborated in more detail in the Evaluation Report, the author also suggests distinguishing between the daytime and night-time noise levels. The reason is that the LNRS may have quite different effects (noise reductions) in daytime versus night-time, due to the different types of vehicles dominating the noise levels and the different driving patterns (it is probably more free-flowing traffic at night-time). A surface which seems to have little effect in daytime may well have a reasonable effect in night-time; i.e. it may improve the sleep quality of the residents along the section.

Finally, a note on the effect in urban environments of small changes in noise reductions, which is of particular importance to the Hong Kong low-speed LNRS test program: While noise reductions as small as 1 to 2 dB were previously regarded as too small to be significant, it appeared in a recent study in New Zealand that such reductions could actually be of considerable benefit to the community living adjacent to busy urban roads [Dravitzki, 2006]. Mr Dravitzki wrote "*Small changes in traffic noise level were matched with changes in behavioural disturbance, even if the change was less than 3 dB. Behavioural change in the form of closing windows, raising one's voice or altering one's scheduled activities as a consequence of traffic noise is a natural adaptive response to a negative stimulus. Results suggest that behavioural adjustment and annoyance interact in a complex way to produce a reaction to changes in the noise environment. It is apparent that behavioural disturbance is a more sensitive measure than mean annoyance, as it has a higher correlation to noise volume changes.*"

18.2 Noise prediction model

Models do not directly reduce noise. However, the use of a poor model may result in poor decisions regarding noise abatement being made and money being spent in a non-optimized way. There is no reason why Hong Kong should stick to an outdated noise prediction model.

In Hong Kong the U.K. model named CRTN is used for noise prediction. It may have served its purpose in a satisfactory manner, lacking better models, but CRTN is nowadays far from state-of-the-art. For example, the author considers the new ASJ (Japanese) model, the interim European model, the Nord2000 model, and the new European model named HARMONOISE (improved by IMAGINE), as all being potentially superior to CRTN. The author knows that even many of the British colleagues no longer prefer CRTN. The Nord2000 model is currently being implemented in the five Nordic countries (Sweden, Denmark, Norway, Finland and Iceland) and it is an up-to-date model which also calculates the maximum levels used for night-time disturbance evaluations, as well as the L_{den}.

Whichever model that is applied, Hong Kong may consider improving its possibilities to calculate noise propagation at distances high above the ground level, since none of the mentioned European models has been applied and validated in areas with such tall residential buildings as Hong Kong. The Japanese seem to work on adapting their model for use in such circumstances; for example by measurements up to 120 m heights by means of balloon-lifted microphones [Hiramatsu, 2007]. It may be that the new model coming in 2008 may include such improved characteristics.

18.3 Tyre/road rolling resistance on low-noise surfaces

Rolling resistance of tyres influences fuel consumption of the vehicles and thus both economy and the air pollution; for example the CO_2 emissions contributing to the greenhouse effect. This author has shown already long ago that the road surfaces affect rolling resistance substantially [Sandberg, 1990][Sandberg, 1997], but the road authorities have failed to respond to this challenge until recently. Usually increased texture means increased rolling resistance. The influence is around 50 %, measured as the increased rolling resistance of the worst compared to the best road surface and this may be translated to about 10 % influence on fuel consumption; which really has a dramatic effect on economy and air pollution. However, the range within which the common "interchangeable" road surfaces operate is approximately 20 % rather than 50 %, which means a fuel consumption range of approx. 4 %, but even this is a most significant effect which road authorities should not neglect.

Low-noise road surfaces may affect rolling resistance in at least three major ways:

- Different texture; for porous surfaces the texture is mostly deeper than for corresponding dense surfaces; which potentially may increase rolling resistance
- Texture-optimized surfaces (for low noise) have different texture than conventional surfaces and thus different rolling resistance; this may be an advantage for "thin layers"
- Different porosity; the porous surfaces may decrease the air resistance that the tyre faces by the air drainage effect
- Different elasticity of the surfaces may result in different compression of the material which may result in differences in rolling resistance (which has been reported to be a disadvantage of asphalt surfaces compared to cement concrete surfaces for heavy traffic).

When evaluating the monetary values of different road surfaces, taking into account traffic safety, fuel consumption and associated costs, costs of noise and costs of air pollution, it is believed by this author that the rolling resistance effects may be one of the most influential effects. Thus road authorities should urgently consider this effect.

In Sweden, a number of recent studies have attempted to shed some light on this issue. The first one was a study regarding the possible effect on rolling resistance of the "super-low-noise" poroelastic road surface (PERS). Intuitively, most people would expect that PERS would create increased rolling resistance for the tyre/road interaction. As children, most of us have observed that a hard ball rolling on a soft surface will stop rolling sooner than on a hard surface such as asphalt. However, in the experiment by VTI in 2004, rolling resistance measured on the drum facility of the Technical University of Gdansk (TUG), Poland, indicated that rolling resistance was the same on the PERS panels as on a common DAC (11 or 16 mm maximum chipping size), or even lower.

One reason may be that the viscous losses in PERS are very small: the resistance to motion at the leading edge of the tyre from the compressed rubber will be compensated by a corresponding push at the trailing edge from the expanding rubber. Another reason (and both of them may well be valid) may be that on the soft PERS surface, the tyre will not be so much deformed, which leads to lower rolling losses. The deformation needed in the tyre/road interface will be shared between the tyre and the PERS; in fact, the PERS should be more deformed than the tyre due to its high porosity.

In 2005, measurements of rolling resistance were made on six Swedish road surfaces by VTI in cooperation with TUG. The measurements were made with a special single-wheel trailer developed for this purpose at TUG, using five different tyres running at 50, 70 and 90 km/h. The results are shown in Fig. 18.1, plotted as the rolling resistance coefficient (C_R) against the texture (Mean Profile Depth, MPD, according to ISO 13473-1). The point with the coefficient 0.014 is for an SMA 0/16 surface. The two best ones, at approx. 0.012, are for a DAC 0/8 and an SMA 0/8 and are approximately 20 % lower. These two surfaces are about 5 dB(A) quieter than the SMA 0/16. The point at 0.009 probably represents an erroneous measurement. It thus seems that low-noise dense surfaces may mean a substantial saving in terms of reduced rolling resistance.

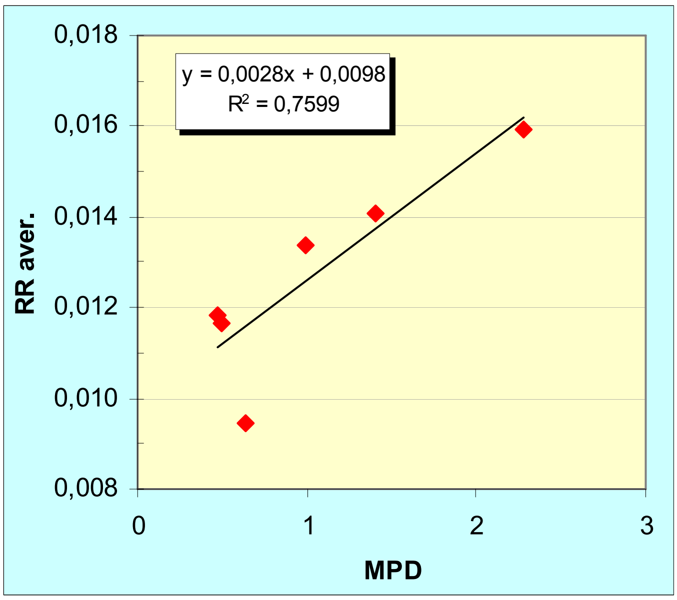


Fig. 18.1. Relation between rolling resistance coefficient C_R and Mean Profile Depth MPD as measured in a Swedish-Polish pilot study in 2005 (see further in the text).

How about porous low-noise road surfaces? The ones constructed in Sweden have not had features which would have allowed accurate rolling resistance measurements (very long straight and level surfaces). However, the one referred to above in the particulates measurement programme; i.e. the double-layer porous asphalt on E4 at Botkyrka southwest of Stockholm was measured before it was laid (when the surface was an SMA 0/16) and one year after. In this way, the poor conditions were identical in both the "before" and the "after" measurements and the rolling resistance measurements can be compared.

The results showed that the rolling resistance at 50 and 70 km/h for two tested tyres was 10 % lower on the low-noise porous surface than on the SMA in one direction and 6 % higher in the other direction. The different results are probably due to the measurement errors, with difference in wind conditions and influence of wind pull of other vehicles in the traffic. The conclusion was that the rolling resistance of the two surfaces were within 10 % of each other; probably even within 5 %.

The results reported above have led to an interest in the issue from the Swedish Road Administration (SRA). In an ongoing work, the author has suggested a preliminary relation between rolling resistance and road surface type which is likely/intended to be used by the SRA in benefit/cost calculations when selecting road surface type [Sandberg, 2007c].

18.4 Study of emission of particulates from low-noise surfaces

Particulates, alternatively referred to as particulate matter (PM), aerosols or fine particles, are tiny particles of solid or liquid suspended in the air. They range in size from less than 10 nanometres to more than 100 μm in diameter. The notation PM_{10} is used to describe particles of 10 μm or less, which are inhalable. PM_{10} in an urban environment consists mostly of particulates from the road surfaces, but also from wear and tear from brakes and tyres.

The quality of air is regulated as a limit for PM_{10} in the EU from 1 January 2005 in order to alleviate severe health effects on the population. The new legislation urges the authorities to reduce particle mass concentrations to comply with the limits.

In Sweden, there is an ordinance (2001:527) on environmental quality standards for ambient air, containing standards for nitrogen dioxide, oxides of nitrogen, sulphur dioxide, carbon monoxide, lead, benzene, particulate matter (PM_{10}) and ozone in ambient air. The standards are based on the EC directive 1996/62/EC, and its daughter directives 1999/30/EC, 2000/69/EC and 2002/03/EC [Swedish EPA, 2007].

There are also epidemiological studies indicating that high concentrations of nanometre-sized particles could pose a threat to health. These are too small to significantly influence the PM_{10} values and should be measured separately. However, it is rarely done.

Particles emitted by vehicles through exhaust gases essentially are in the nanometre range and contribute very little to the PM_{10} levels. Particles formed through the wear of asphalt contribute to PM_{10} concentrations when the road surface is dry. On moist road surfaces there is still road wear, but the particles accumulate on or in the road surface until it once again dries out. The proportion of the time when the road surface is dry has a decisive importance for the levels measured.

The limit values for Particulate Matter (PM_{10}) in ambient air are [Swedish EPA, 2007]:

- For a 24 h period (not to be exceeded more than 35 times/year): 50 µg/m^3
- For one year: 40 µg/m^3

In Sweden, it has been found that these limits are exceeded in the larger cities of Stockholm and Gothenburg. One major reason is the use of steels studs in tyres in winter time, but the limits may occasionally be exceeded even at other times than when studded tyres are used. This problem is considered as one of the worst health problems associated with roads. Studies at the laboratories of Swedish Road and Transport Research Institute (VTI) have shown that the PM_{10} emissions depend significantly on the type of road surface used; with generally less emissions the more durable the road surface aggregate is.

It is thought that a country not having the extremely durable aggregates used in Sweden, like Hong Kong, would potentially have significant PM_{10} problems even without studded tyres. In an urban environment with residential homes very close to the streets with high-volume traffic, such as is typical in Hong Kong, the particulates could potentially be a serious health problem.

Low-noise road surfaces may affect PM_{10} emissions in at least four major ways:

- Different wear rates; for example due to use of a different stone material (aggregate)
- Different proportions between sand and aggregate and different proportions between aggregate sizes
- Different drainage properties, where in low-noise road surfaces much of the particulates may be transported or get stuck in the porosity of the pavement, whereas on a conventional surface all particulates will be either blown away or running-off as dirt water on top of the surface.
- Different duration of wetness or moist. As stated earlier, when the surface is moist or wet the particulates do not whirl up in the air

Low-noise road surfaces have been/are studied in two different projects in Sweden. The first one was a project in which a poroelastic road surface was developed [Sandberg & Kalman, 2005]. It was then found in a laboratory study in 2004 that the PM_{10} emissions were much lower on the poroelastic road surface than on the conventional SMA surface; in fact, the concentrations of PM_{10} in the air for the poroelastic surface were barely measurable.

The other study is ongoing and concerns the double-layer porous asphalt laid on motorway E4 at Botkyrka southwest of Stockholm, as mentioned in another section of this report. Measuring stations have been located alongside both the low-noise surface motorway section and alongside a reference section paved with an SMA 0/16; both sections having the same traffic and as similar conditions as possible.

The results of the first measurement campaign, which took place in March-June 2006 are as follows:

- PM_{10} emissions were 30-40 % lower on the low-noise surface section than on the reference SMA section; see Fig. 18.2.
- However, when considering differences in wind conditions (normalization with respect to NOx emissions were made[80]), the PM_{10} emissions were 3-12 % **higher** on the low-noise surface section than on the reference SMA section
- Emissions were greater in March-April (season when studded tyres are used) than in May-June (season when studded tyres are forbidden)
- The 24h limit values were exceeded several times during March-April, but also a few times in May-June
- It was concluded that the differences between the two surfaces are less than 15 % and thus within the measuring errors

Data above are reported in [Johansson, 2006]. A more general description of the problem as well as a study on the emission of particulates in Stockholm before and during a congestion charging trial can be found in [SLB, 2006].

The field studies are supplemented by a laboratory experiment at VTI in Sweden in which plates of the two surfaces are mounted in a circular track which is exposed to tyres rolling around the circle during a certain time period to simulate intensive traffic. The experiments have just finished but are not yet published. It can be reported, though, that the low-noise road surface gave a significantly lower emission of PM10 than the SMA surface. However, when looking only at the nanometre-sized particulates, the relations were reversed [Gustafsson, 2007]. It is believed (but not proved) that the micrometer-sized particulates come essentially from the road surface and the nanometre-sized particulates come essentially from the tyres.

The Swedish work, along with an even more ambitious, ongoing project in Norway, is unique with regard to the subject of emission of particulates.

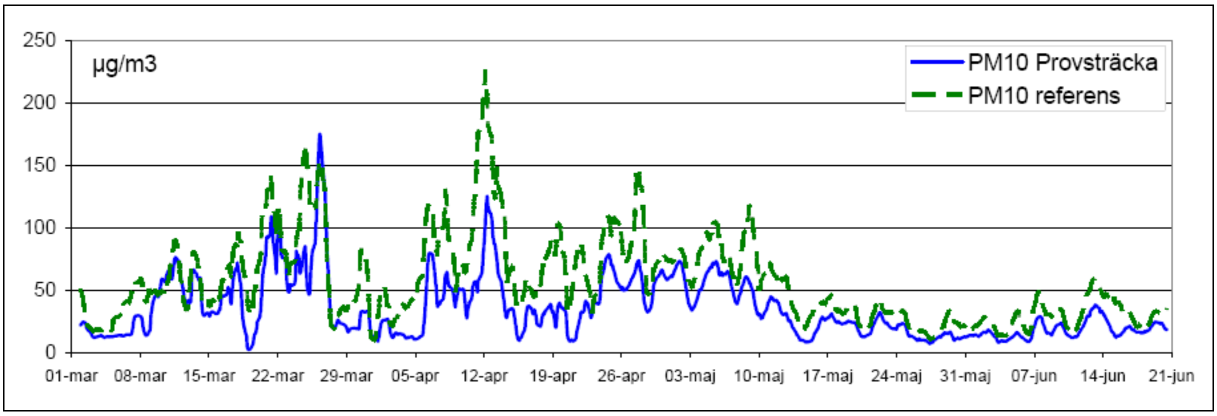


Fig. 18.2. Daily average values of PM_{10} concentrations as a function of time. The solid blue line presents the values measured alongside the low-noise porous asphalt and the broken green line alongside the SMA reference surface. Note that most of the difference between the two locations is believed to be due to wind and other differences in conditions; see text. From [Johansson, 2006].

[80] This author is not at all convinced about the justification for this normalization

18.5 Extra benefit of low-noise surfaces in reverberant sound fields

When low-noise road surfaces are applied in low-speed cases; which mostly means in city streets where there are buildings on one or both sides of the street, multiple reflections will occur. Fig. 18.3 shows results of calculations made with a BEM model to see how much extra noise reduction a low-noise road surface might provide when the sound travels multiple times over the surface such as in a street canyon [Watts & Morgan, 2005].

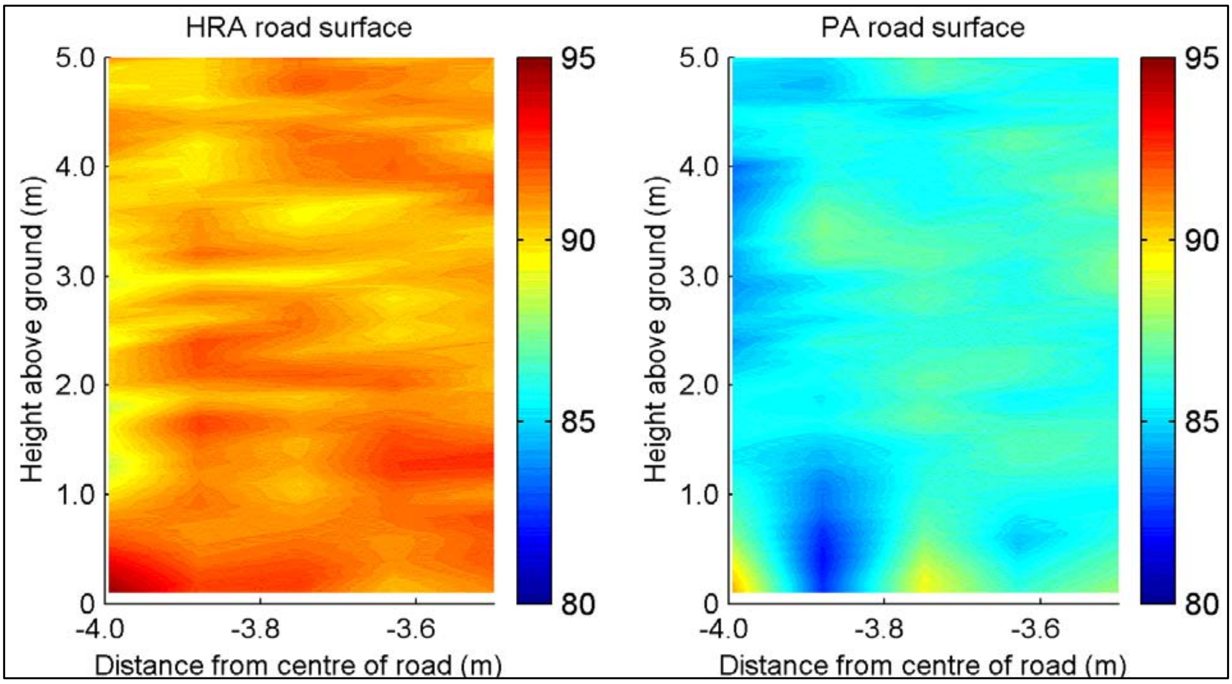


Fig. 18.3. Simulation by BEM modelling of sound reflections in a street canyon and its effect on sound level. From [Watts & Morgan, 2005]. See text for explanations.

The figure shall be interpreted in this way: The horizontal scale shows the distance from the centre of the road, where at -4 and +4 m there is a perfectly reflecting wall of a building. The vertical scale is the height above ground along the façade. The vertical bars filled with colours show what the colours mean in terms of sound level. The left case is when the road surface is a hot-rolled asphalt (HRA - which is dense) and the left case shows when the road surface is a porous asphalt (PA).

The difference in noise level HRA-PA when there is only one façade is 3.9 dB(A). As can be seen in the figure, near the façade the HRA case is approx. 90 dB(A) while the PA case is approx. 85 dB(A). This means that the reduction when there are two parallel façades is more than 1 dB(A) higher than when there is only one façade. In comparison to a free field it would be even a little bit more effective; this author estimates the benefit to 2 dB(A) then. The British authors also simulated the addition of covers on top of the façades, i.e. a tunnel structure, and found that then the benefits of porous asphalt increased substantially to 9.7 dB(A); i.e. approx 6 dB(A) more than in the open one-façade case.

Based on the simulations reported in [Watts & Morgan, 2005], the extra benefits of a low noise road surface which gives a noise reduction of 3 dB(A) in the free field, are estimated by this author as given in Table 18.1. It is yet to be confirmed, but logically the extra benefit would be higher if the sound absorption of the porous asphalt would be higher than in the simulated 3 dB(A) case.

The results indicate that porous asphalt is more effective in reducing noise levels where the conditions are more reverberant.

Table 18.1. The extra benefits in three different reverberant sound fields of a sound absorbing porous asphalt which gives a noise reduction of 3 dB(A) in a free field case, as estimated by this author based on [Watts & Morgan, 2005].

Case	Noise reduction of porous asphalt
Free field	3 dB(A) = ref
Facade on one side	4 dB(A) = 1 dB(A) extra
Facades on both sides (street canyon 8 m wide)	5 dB(A) = 2 dB(A) extra
As above, but partial cover (tunnel)	10 dB(A) = 7 dB(A) extra

18.6 Noise reduction of porous surfaces after rainfall

After a rainfall, the traffic noise level on dense surface very quickly returns to the pre-rainfall (dry) level. This does not happen for a porous surface. A documentation of such effects was recently presented and is cited here[81]:

"*Noise levels (from light cars only) were measured to determine deviations in noise levels at different periods after rain had fallen. Measurements were planned four hours after rainfall, then two days (fifty hours) after, then seven days after. Unfortunately, at the time of the measurements, rain fell every two to four days, so it was impossible to measure at seven days (dry) after rain. Two attempts were made, resulting in two lots of measurements being made after two rainy periods, each taken fifty hours after the relevant rainfall. These measurements were compared with a reading made four hours after rain had fallen.*

Figure 5.1[82] *shows that the OGPA's performance is significantly affected by rain, with the noise levels measured 4 hours after rain being 1.3–2.1 dBA higher than those measured 50 hours after rain. The material with the higher proportion of voids (the Flexiphalt) appears to drain more quickly than the 20% voids material (the TNZ P/11). The Flexiphalt '50 hours after rain' values are 1.5 dBA and 2.1 dBA quieter than the reading made 4 hours after rain, compared to the readings from the 20% voids material, which were 1.3 and 1.9 dBA quieter.*"

[81] The citation is from [Dravitzki & Kvatch, 2007]
[82] In this report it is Fig. 18.4

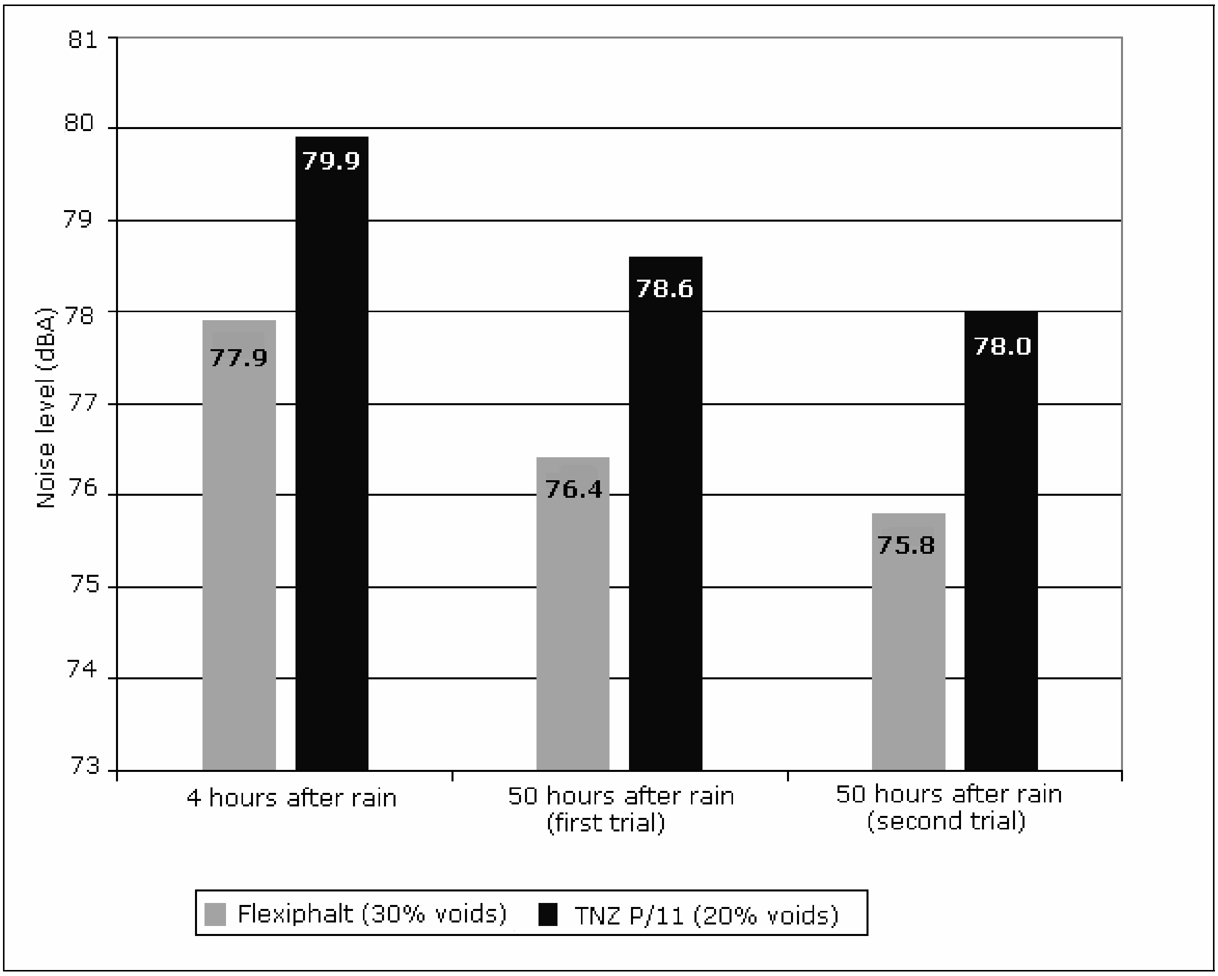


Fig. 18.4. Effect on noise level of slowly drying porous asphalt after rainfall. From [Dravitzki & Kvatch, 2007]. See text for explanations.

This has serious implications to PMFC effects in two ways:

- Water remaining in the porous structure a long time after a rainfall will significantly limit the noise-reducing effect over a longer time; in particular in rainy locations or periods. If, for example, it is common that there is a short rainfall once per day in a particular climate or season, it is likely that a PMFC will be quite inefficient.

- Measurements taken a few hours after a ceasing rainfall will not show the noise-reducing potential of a (dry) PMFC; it will substantially underestimate it. It is not sufficient to wait until the surface looks dry. Consequently, it is important to have a clear picture of the rainfall time history before a noise measurement is made. This author thinks that measurements will be unaffected by rainfall only after about 24 hours after a rainfall has stopped.

18.7 Expansion joints on bridges and flyovers

A special noise and vibration problem is the effect of expansion joints between sections on bridges and elevated roads. These expansion joints, with movement ranges of up to ± 300 mm depending on season and temperature, are needed in order to allow the thermal expansion and compression caused by temperature changes without causing damages to the structure and the surfacing. It goes without saying that to cover joints with gaps up to some decimetres cannot be made without serious noise and vibration problems.

There are several types of expansion joints, for example asphaltic plug, nosing joint, reinforced elastomeric joint, and cantilever comb [CBDG, 2003]. In [Sandberg & Ejsmont, 2002], reviewing a number of studies, an example is shown in which the overall noise level is increased by 10 dB at the joint compared to a place with conventional, even surface. By noise-reducing measures, the extra noise was reduced to half the initial value. Not only the level of noise is important but the temporal transient characteristics are even more important for the annoyance; for example, some joints may sound like r-r-r-r when rolling over them.

In Germany, research on noise-reducing expansion joints has been and is intensive. One type tested is the "finger" type (also called cantilever comb or tooth), another one is the "diamond" or "rhomboid" type. The latter has been subject to particular testing recently and was also subject of special study during the Hong Kong officials study tour to Germany in April 2007. Fig. 18.5 shows this type of expansion joint. The gap between each individual rhomb in its longitudinal direction may vary between 25 and 65 mm (± 20 mm) and with the 10 gaps in this set of joints, the difference in gap between the two adjoining bridge sections may vary between 250 mm (in summer) and 650 mm (in winter); i.e., 400 mm difference. When the photos were taken in April it was around 20 degrees so it was closest to summer conditions.

Fig. 18.5. Rhomboid expansion joint on the A4 (E40) motorway bridge over the Rhine in Cologne, Germany. The angle of each rhomb is 68° at the tips.

The results of measurements at 60, 80, 100 and 120 km/h in the PFF drum machine at BASt (see Fig. 6.26) showed the following [Glaeser, 2008]:

- The overall A-weighted noise level was approximately 5 dB higher in the winter (65 mm gap/rhomb) compared to the summer (25 mm gap/rhomb) conditions.

- No results compared to a regular asphalt surface without joint were presented. However, in a company document it is claimed that the noise increase is only 2 dB [Maurer, 2001] for the version with 68^o angle, as compared to 9 dB for regular lamellae expansion joints of the same width.

- The best shape of the rhomboid joints was obtained when the angle of the rhomb was 40 degrees, i.e. each rhomb was longer than it was wider, and creating an angle at the tip of 40 degrees (the ones in Fig. 18.5 had an angle of 68^o), as compared to 80^o and 68^o. The advantage was 1-4 dB both in winter and summer conditions.

- The best surface on each rhomboid plate was a surface dressing with very small chips glued on the metal plate, as compared to a milled and a forged surface. The latter two had a flat metal surface between milled or forged grooves parallel to the rhomb's sides. The surface dressing had a macrotexture which was near an optimum surface for low noise. The advantage was 0-2 dB depending on speed.

Hot applied joint sealants made of styrene-butadiene-styrene copolymer (SBS) modified bitumen are used for the sealing and filling of joints in concrete surfacing and for surfacing decks on bridges. Asphaltic plug joints (APJ) and waterproofing systems with Gussasphalt (GA - Mastic Asphalt) and polymer-bitumen membranes (PBM) are widely used for bridges and tunnels in Switzerland with good success. Research at the Swiss Federal Laboratories for Materials Testing and Research (EMPA) has resulted in such polymer-modified asphaltic material which allows relatively large expansions and compressions which can be used in joints. The content of polymer must be sufficiently large, and polymers should be resistant to ageing and temperature induced stresses. In Fig. 18.6, Dr Manfred N. Partl at the EMPA Road Engineering Center, Sealing Components Laboratory shows a sample of such asphaltic material.

As another example of expansion joints of low-noise type, a "finger-type" (sawtooth) expansion joint mounted at elevated sections of the motorway between central Bangkok (Thailand) and the new international airport impressed on the author for being almost totally quiet inside a car. See Fig. 18.7. The noise generation subjectively was lower than on similar elevated expressways in the Tokyo area. No technical information seems to be available in English.

Fig. 18.6. Dr Manfred Partl at EMPA in Switzerland demonstrates to the author a sample of polymer-modified asphaltic material with large expansion/compression capabilities applied in joints on concrete bridge decks.

Fig. 18.7. Low-noise expansion joint of the sawtooth type on elevated motorway between central Bangkok and the new international airport.

18.8 Differences in terminology between British and American English

It may be practical in presentations and discussions and when studying documents to observe that there are some terminology differences between North American and British English; i.e. between Europe and USA, where Hong Kong and Europe would be similar due to the British influence. Also terms in Australia and New Zealand would be closer to the British English. Practice in Canada would be closer to that in USA. Most notably this would concern the following terms compiled by the author:

British (and European and Australian)	**North American**
Tyre	Tire
Tyre/road	Tire/pavement, or pavement/tire
Road surface	Pavement
Low noise road surface	Quiet pavement, quieter pavement
Lorry	Truck
Car	Automobile
Stone Mastic Asphalt	Stone Matrix Asphalt
Dense asphalt concrete (DAC)	Hot Mix Asphalt (HMA), or Superpave or Dense-Graded Asphalt Concrete (DGAC)
Porous asphalt (PAC) or concrete	Open graded friction course (OGFC)
Chippings (= individual stones), aggregate	Aggregate
Noise barrier, noise screen	Noise wall

19. DISCUSSION CONCERNING RELEVANCE OF OVERSEAS EXPERIENCE FOR HONG KONG

The performance of road surfaces is affected by a number of factors related to climate, traffic conditions and type of vehicles used. Also demography, style of architecture, topography, and lifestyle affects how traffic noise propagates and is perceived and these influence how road surfaces may affect noise perception by residents.

The following are some issues one must consider when using experience from other regions and countries than Hong Kong S.A.R.:

- Binders and their modifiers used in colder or warmer climates than that in Hong Kong may not be suitable in Hong Kong

- Porous surfaces in wet climates with high traffic speeds will be self-cleaned by traffic and not much clogged, wereas in dry climates (or with long dry spells) and low speeds clogging will be a major problem

- Surfaces and materials optimized to resist the wear of studded tyres may not be suitable in Hong Kong

- Surfaces and materials optimized for best durability in Alpine or similar roads, where driving or braking forces on tyres may be exceptional, may not be suitable in Hong Kong

- Surfaces developed for traffic at high speed will not have similar properties at low speeds; i.e. surfaces being optimal for motorway speeds 100+ km/h may not be durable or effective at low speeds in urban areas

- Surfaces that will give omnidirectional noise emission might be less effective in high-rise building areas than surfaces where noise emission is directional, with less emission upwards (and it could also be the other way around in special cases).

- Surfaces optimized for heavy traffic may not be optimum for light traffic and vice versa.

- Surfaces which are efficient for noise reduction in countries with quiet vehicles (power units) will probably be less efficient in countries with noisy vehicles.

- Surfaces relying on very narrow gradations and used in some countries may not be easy or possible to produce in Hong Kong with the very few grades of chippings currently produced

- Surfaces effective in a country with few other noise sources may be less effective in countries with lots of other noise sources than traffic, this being influenced by population and industry density

Consequently, it might be tempting to say: "only experience of LNRS in a country or region mirroring the special climate and conditions in Hong Kong is relevant for us". One can argue about this, but when evaluating the information in this report for possible implications in Hong Kong one must always keep in mind that the special conditions in Hong Kong versus those in the region where the information comes from are of importance. Too often this is neglected.

The author believes that from the Hong Kong horizon, places like Phoenix, Arizona, California, large cities in southern Japan (including e.g. Tokyo, Yokohama, Nagoya, Osaka), Brisbane and Sydney would be the most relevant places from which information would be extra relevant and valuable for Hong Kong. Cities outside the scope of this report, such as Bangkok, Singapore, Shanghai, Rome, and Istanbul would also be interesting. Based on this, the information in this report from Arizona, California and Japan would be the most valuable. However, it is not that simple, since in Phoenix and California, they have different vehicle compositions and traffic conditions, they are using LNRS only at high speeds, and also demography and topography are very different. Remaining is only the experience from the Japanese big cities.

Therefore, this author would consider the information relating to the Japanese experience and policy as the most important for Hong Kong conditions. This should have the highest weight in all evaluations; even though yearly average temperature is 23 ^{o}C in Hong Kong but 14 ^{o}C in Tokyo and yearly rainfall is 50 % higher in Hong Kong than in Tokyo.

At the other end of the scale, the experience in northern Europe, northern UK, northern USA, and northern Japan should have the lowest relevance for Hong Kong conditions; especially since they mostly also are relatively sparsely populated and have few if any high-rise building areas.

Fortunately, the Japanese are very advanced in their research on LNRS and especially in applying this research on a large and systematic scale. Therefore, there is much to learn from them. The only problem is the language barrier which almost always makes one uncertain whether one has understood information from Japanese colleagues or Japanese documents (in English) correctly or if there is some misunderstanding, and also makes good and comprehensive documents from Japan written in English very rare to find.

20. RECOMMENDED APPLICATION OF THE OVERSEAS EXPERIENCE IN HONG KONG

20.1 Improving DAC and SMA surfaces

Stop using the conventional DAC 0/20 in Hong Kong, and switch over to SMA 0/10 or even better to SMA 0/8 or SMA 0/6. It may take a few years until the contractors have learnt how to achieve homegene SMA:s but they should succeed, as they have done in other countries.

Part of this would also be to produce aggregate gradings with the fine scale used in Europe and not just the 5, 10 and 20 mm as used so far in Hong Kong.

In the SMA:s consider using a modified binder.

20.2 Temporary reduction measures on cement concrete surfaces

Use the high-friction surface dressings as toppings on cement concrete as a temporary measure.

However, even better would be: purchase a diamond grinding machine and make diamond grinding on cement concrete.

20.3 Improving PMFC (PAC) surfaces for high-speed roads (70-110 km/h)

Use surfaces with higher air voids, which requires more narrow grading curves (see 20.1), as they do in most European countries. Aim at 22-25 %. Use 45-50 mm thickness. Use a maximum aggregate size of 8 mm. Use advanced modified binders for this. The most advanced binders can probably be found in Japan; if they are willing to share their knowledge.

Not to waste money on an extra basecourse, consider porous asphalt as a structural layer; perhaps counting its structural thickness as only 2/3 of the real thickness if some safety margin is wanted.

20.4 Improving PMFC (PAC) surfaces – low-speed roads (50 km/h)

Consider the suggestions in 20.3, but add the following:

- Increase crosslope by at least 1 % more than the conventional crosslope.
- Use an advanced drainage system at the kerbside like they do in Japan.
- Consider even more advanced drainage systems, as suggested in Section 16 in this report.

20.5 Trying double-layer PMFC surfaces

If the absolute maximum noise reduction is needed, use a double-layer surface with 8 mm aggregate in the top and 13-16 mm in the bottom layer; and a total thickness of about 75 mm (25 + 50 mm). Use warm-in-warm paving machines for this. But be aware of the extra cost for this, which probably gives a higher cost/benefit ratio than a good single-layer.

20.6 Introducing thin surfacings in Hong Kong

Start immediately trials with thin layers in Hong Kong. They might be a better option for low-speed roads in Hong Kong than porous asphalt (PMFC).

Try to get some of the European producers of thin layers to lay a few test sections in Hong Kong. There are skilled companies for this in France (Colas and Screg, most notably), as well as several in the Netherlands. In Denmark there is NCC Roads and in Sweden there is Skanska. In the U.K. there are several comaonies with HAPAS-approved products, see the section about the U.K. Many of these have branches or associated companies internationally. If they don't do this free-of-charge, be prepared to pay a substantial amount for it, since it may be worth a lot at the end. Make sure to the contractor that longterm performance will be evaluated, in order that he gives this priority.

Consider the French invention Nanosoft as one of the most desirable to test in Hong Kong.

If no company is willing to go to Hong Kong to lay their product, try to lay a thin layer by a Hong Kong contractor. Use the recipes of the DRI in Denmark. These are likely to be less effective than the proprietary surfaces, but the difference may not be large.

The hotter and more humid climate is of course a source of concern when it comes to reproduce the good results of Europe in Hong Kong. Most concern should be given to potential bleeding problems, such as have been seen on SMA surfaces in HK.

As a first stage consider organizing as follows:

- Organise a workshop in Hong Kong, inviting people from the companies mentioned above, with the purpose to get them to understand the special and severe conditions in Hong Kong, in order to be able to adapt their products to Hong Kong conditions (also inviting some local road constructors). The workshop should be organised when it is extra hot in Hong Kong (worst conditions?)
- Invite/engage the Dutch company to lay in Hong Kong the surface they had laid in Ede
- Invite/engage the Colas company in France to lay their Nanosoft surface in Hong Kong. Select a road with lowest possible heavy traffic.
- Choose the most promising Danish surface, designed by DRI, and try to reproduce it in Hong Kong by some local company.

It should be made clear that the thin surfacings in Hong Kong shall NOT rely too much on porosity to give low noise, since in the Hong Kong low-speed street conditions such porosity is likely to clog quite fast.

20.7 Trying asphalt rubber surfaces

Make new trials with asphalt rubber surfaces in Hong Kong. However, do no longer try the gapgraded one. Use the open-graded version with 20 % rubber in the binder and 8-10 % binder, aim at air voids 17-18 %. Try thicknesses of 15 and 30 mm to see which one is best. On cement concrete or uneven surfaces 30 mm must be used. Use maximum aggregate size of 8 mm. Ideally, engage Mr George Way in Arizona as a consultant (he has experience from such jobs in China).

Be prepared to lay at least one km as an exercise for the paving crew first before the actual test section is laid. Be careful with the glue under the layer; do not make any compromise.

20.8 Cleaning and maintenance of porous surfaces

The reported effects of cleaning have not been consistent and clear. Especially, cleaning has been tested thoroughly only in one major urban LNRS project, namely the DRI project in central Copenhagen, reported about above. The effects of cleaning recorded then were very limited and not really justifying the efforts. However, the more advanced equipment and frequency of cleaning applied in Japan recently promise better effects; although not yet tested on any urban low-speed street.

It is therefore suggested here to invite the Japanese company Seikitokyukougou Co. Ltd. to demonstrate their most advanced and recent cleaning equipment in Hong Kong, cleaning a full PMFC test section one time per month and comparing to a similar non-cleaned PMFC section. Measure both permeability and noise emission on the newly laid surface and then after each cleaning occasion. It is then necessary to measure with the highest possible precision since the effects would be small each time, although in total they would hopefully add up to a considerable amount.

Depending on the outcome of the above activities, it is suggested to try cleaning also a high-speed road, using the same equipment but not necessarily the same frequency and not necessarily doing it in all lanes.

If such cleaning operations turn out to be sufficiently effective, and justified with regard to costs, it is suggested to become common practice in relevant locations in Hong Kong.

20.9 Surfaces for future consideration - Epoxy-modified porous asphalt

In the short-term, consider the following:

At intersections, parking bays and exits/entrances from parking areas and at high gradients, use epoxy as a thin layer on top of the porous surface to increase the strength of it. See the Japanese trials. Begin with a few trial sections and evaluate the results.

In the long-term consider this:

There is hope for a much stronger porous surface type within a few years than the present PMFC, suitable also for intersections and where tyre forces are high, namely using an epoxy-modified binder, with approximately 75 % bitumen and 25 % epoxy.

Experiments have been conducted in New Zealand with this principle recently, which have so far been successful (one ongoing field test and some lab tests), with experiments with new surfaces continuing in December 2007. The author is in close contact with the NZ researchers to follow the progress.

Of course, such a material will not be possible to apply in normal production until a few years from now when enough experience has been collected, but results so far are very promising. It may be noted that "epoxy" is something which is politically in-correct in road use in some countries, for example in Sweden. However, chemical experts say that it is possible to control the undesirable hazards of this material.

If the New Zealand (new) experiment starting in December 2007 will be successful, and the first trial section is still in successful operation, Hong Kong might perhaps consider an own trial on this at the end of 2008 or in 2009. If so, it may be considered to make a study tour in 2008 to New Zealand.

20.10 Surfaces for future consideration – Poroelastic surfaces

Follow the European project PERSUADE (in which this author has a major role) and determine after the project whether this type of surface can be used in Hong Kong. Also follow any possible development in Japan.

20.11 Joints on bridges and flyovers

Consider trying the quieter joints developed by BASt in Germany. Invite a German company to mount such joints in Hong Kong.

Consider trying the Bangkok joints described at another place in this report; first go to Bangkok to study them and establish a contact with the company who produced them. This author has contacts and might help with this if wanted.

20.12 Investigating other ideas

Consider the use of expanded clay aggregate. Study the Italian experience on this.

Very seriously, consider using road surface properties for abatement of the Urban Heat Island effect, such as albedo, porosity, watering etc.

20.13 Selection of road surface considering all major environmental effects

As soon as possible, develop monetary evaluations of noise exposure relevant to Hong Kong.

For Hong Kong surfaces, estimate rolling resistance and CO_2 emissions, plus emission of particulate matter. Try to calculate the total effect for Hong Kong of using the most important HK road surfaces.

In a longer-term perspective, consider using the new Swedish procedure, adapted to HK conditions, for selecting the type of surface which is optimum from an overall environmental point of view.

20.14 Measurement methods, equipment and metrics

The following recommendations are made with regard to models, metrics and equipment:

- Change from using the CRTN noise prediction model to a modern model, such as the Nord2000, the HARMONOISE/IMAGINE or the newest Japanese ASJ model.
- Whichever model is selected, improve the model's performance at large heights above ground, to better represent typical Hong Kong high-rise residential areas.
- Use the L_{50} measure for evaluations of LNRS in urban areas, if a time-averaged level is measured, rather than L_{10} or L_{eq}.
- Measure during both daytime and night-time for evaluations of LNRS in urban areas; not just in daytime.
- Wait at least 24 hours after a rainfall before a noise measurement on PMFC is made.
- It is suggested that noise measurements are not made if ambient air temperatures are below 15 and above 35 ^{o}C. It is also suggested that both air and surface temperatures are always collected during the noise measurement period.
- Instead of having a "random" reference surface, sometimes poorly or not at all specified, start using consistently one (or at most two) reference surface(s) for any comparative testing of LNRS and make sure it/they can be further referenced to the HARMONOISE virtual reference.
- Be aware of the fact that the full noise-reducing effects of PMFC do not occur within about 50 m from a joint to a dense surface, due to spread of dirt from the dense section. Select the length of test sections and microphone location with this knowledge in mind.

20.15 Vehicle- and traffic-related measures with a potential of making LNRS more efficient

LNRS reduce noise generated at the tyre/road interface and to some extent absorb noise from other sources in the frequency range 500-2000 Hz. The latter apply only to surfaces having a substantial sound absorption, such as PMFC in good condition.

Heavy vehicles running at low or medium speeds have substantial parts of the noise emission coming from sources other than the tyre/road interaction. This applies also to light vehicles at very low speeds in accelerating mode. An LNRS will not be efficient to reduce such noise. It follows that an LNRS will be more efficient for noise reduction the more one reduces the other sources in order that the tyre/road noise will become more important or even dominant. Therefore, to make the LNRS policy more efficient, the anti-noise policy in total should include efforts to reduce the sound output from other sources than tyre/road. If this happens, the Hong Kong LNRS policy will become more and more efficient with time and LNRS can be applied at more locations. The following gives guidelines on how this can be achieved.

First it is noted that a very high proportion of the noise emission in central Hong Kong; especially at acceleration and in terms of annoyance, originates from the very large fleet of buses; albeit many of them are modern, double-deck vehicles. The density of buses in central Hong Kong traffic seems to be one of the highest in the world, if not the highest. Consequently, efforts should first focus on busses. Although the newer buses in recent years are less noisy than the older buses, there is still much to do until the older and noisier buses are phased out and it is also possible to require new buses to be quieter. To achieve this one can do the following.

- With regard to heavy buses for transit and local passenger transportation use, require that all new buses meet a limit of 78 dB(A) rather than the normal 80 dB(A). There are already such buses available, for example from Scania and Volvo in Sweden. Possibly, they must first be converted to double-deck versions, but it should not be any major problem.

- Simultaneously, it should be considered to shift from the conventional diesel-driven buses to hybrid diesel/electric buses; possibly using fuel cells. The hybrid buses would then be driven in the very quiet electric mode in locations sensitive to noise emission. Probably, at least all accelerations and decelerations can be made in electric mode. For example, the Swedish company Scania has a concept bus using fuel cell technology which is stated to emit only 70 dB(A) as compared to the limit of 80 dB(A). Shifting from the present bus fleet in Hong Kong to such a fleet of super-quiet hybrid buses could be the most effective single noise reduction measure that can ever be undertaken in Hong Kong. The Hong Kong market for buses is so huge that it alone will create a sufficient market for such buses. It is suggested to start by inviting Scania and Volvo to demonstrate their hybrid buses in Hong Kong and to have a competent consultant calculate the effects that a large-scale shift to such buses would have on various factors, including (but not limited to) noise, fuel consumption and air pollution (greenhouse gases).

- Note that New York City Transit (NYCT) has just completed a very successful trial with hybrid buses, with resulting huge savings in terms of fuel consumption and air pollution (final evaluation report published in October 2006). However, as far as the author is aware, they never evaluated the noise effect (which unfortunately seems typical of US policy). If this could be done successfully in New York, it can be done even better in Hong Kong.

- The above may not solve the problem of the medium-sized or small-sized private busses which are so numerous in Hong Kong. It is suggested that in the long-term perspective, such busses should also be required to be of the hybrid type. In the short-term perspective they should also be required to meet a vehicle noise limit of 78 dB. Since such bus services probably rely on inexpensive vehicles, this could kill the whole business. In order to avoid this, the Government may want to offer subsidies to companies for purchase of quieter vehicles or for retrofitting noise-reducing systems on old vehicles. It may seem politically undesirable to subsidise private companies like that but it could mean great benefits to society, which may be difficult or impossible to achieve by other means at a comparable cost.

Although, the author feels that the bus noise problem is the most important and urgent to solve in Hong Kong, one shall not forget the trucks. Along certain routes the trucks are worse noise offenders than busses. The following is what one may do to reduce the truck noise problem, which would also have an impact on LNRS efficiency:

- Consider the mandatory use in certain streets, perhaps during certain times, of special trucks having an optional quiet driving style program that can be selected by the driver and then does not allow any noisy driving operations. Such trucks were produced as a trial by DAF in the Netherlands already, but there was no significant market for them, so a regular production was never started. Within months, Japanese manufacturers could do the same. If Hong Kong creates such a market by requiring such trucks, perhaps in cooperation with some other major cities, there will soon be trucks available from either Japan or Europe that meet the objectives. The extra costs would be marginal and for the operators such extra purchase costs would probably be compensated or even balanced by associated reduced energy consumption.

- As far as the author is aware, no bus manufacturer has a bus with a similar quiet driving program, but technically it should be no problem to produce it. Initiate a discussion with a few bus manufacturers of introduction of such programs as mentioned above also for buses.

- In principle, one can introduce also hybrid trucks for mainly urban or suburban use. What can be made for buses can be made for trucks, and some hybrid trucks are already available (see e.g. http://www.hybrid-vehicles.net/hybrid-trucks.htm). Some other truck companies are working on concept hybrid trucks. For example, Volvo is near to offer commercially viable hybrids for heavy vehicles [Vassiliadis, 2007].

- As suggested above for busses, the Government may want to offer subsidies to companies for purchase of quieter vehicles, in order to make the shift faster.

Finally, it is proposed that requirements for maximum noise emission from vehicles in-use are introduced and that a program to check vehicles on-the-street is worked out and implemented.

20.16 Suggested new LNRS policy

A new LNRS policy is suggested in Section 12.2.2 in the other report in this project (Review and evaluation of the LNRS programme…). It is not reproduced here; please refer to the other report.

20.17 Final remark

A similar list of recommendations was included already in Section 12 in the other report in this project (Review and evaluation of the LNRS programme…). Section 12 there is somewhat more elaborated than this Section 20. Please consider also the recommendations there if not already included here. In a future version of this Section the two versions should be merged. There are plans to produce a separate report with such recommendations.

21. CONCLUSIONS

Conclusions are listed here in brief:

The literature related to low noise road surfaces is enormous and the production has accelerated in the latest years. In addition to the published literature there is a wealth of unpublished documents which are interesting.

There are several ongoing or upcoming projects on the subject. For example, there is a new great Dutch innovation programme called SSW, there is a third German program called LeiStra3, the Franco-German project DEUFRAKO is being finished in 2009, a new EU project PERSUADE on poroelastic road surfaces is probably starting in 2009, there is probably another EU project starting in 2009, there is a joint Nordic project on relation between texture and noise emission just started, a new ERA-NET project on thin layers is calling for tenders, a QPPP project is ongoing in Arizona, a new FHWA project on quiet pavements is starting in 2009, to name a few. Thus, anyone who wants to make a new report like this one, will have a lot if information to consider and can write another 300 pages in just two years or so.

In terms of acoustical effectiveness of low noise road surfaces, on an overall scale, the double-layer porous asphalt is still the leading surface type. The best ones in new condition may reduce noise by 6-7 dB compared to a DAC or SMA 0/11 for mixed traffic at high speeds. The best existing design would be 8 mm max aggregate size in the top layer, appr 75 mm thickness and air voids 22-25 %.

Equally high noise reductions may be achieved with a thin layer of type Nanosoft (produced by Colas), but only for light traffic. For heavy traffic, the Nanosoft surface would provide only a few dB of noise reduction.

It is a general trend that the smoother the surface texture is the worse it performs (in noise reduction) for heavy trucks. For cars, it is more complicated but there is a weak trend for the contrary effect.

The second best noise-reducing surface is the single-layer porous asphalt. The ones having an 8 mm aggregate, voids content of around 24-25 % and a thickness of 45 mm would give a noise reduction which would be only marginally lower than that of double-layer porous asphalt, say 5-6 dB compared to a DAC or SMA 0/11. This would be at high speeds. According to this author's estimation, the single-layer surface would therefore have a better cost/benefit ratio than the double-layer one.

For low-speed roads in new condition it seems that a noise reduction for a good single-layer porous asphalt may normally amount to about 3-4 dB. However, if the proportion of heavy vehicles is large (say, over 15 %), the noise reduction may drop to about 2-3 dB.

European results in some cities have indicated up to 7 dB of initial noise reduction in low-speed roads. These have used surfaces with extremely high voids content and well designed drainage system and it is uncertain whether such surfaces would work under Hong Kong traffic conditions. More "normal" constructions in Europe, mostly using thin layers, have indicated 5-6 dB of initial noise reduction on low-speed roads.

There is a multitude of thin layers, not equally noise-reducing as Nanosoft, but slightly less effective, the noise reduction of which cover the entire noise range between the Nanosoft and the SMA:s. However, a common feature is that they are slightly less efficient for heavy trucks than their porous asphalt counterparts, due to lower texture.

The long-term noise properties of thin layers are still insufficiently studied. It currently seems that they deteriorate approximately at the same rate as porous surfaces; probably due to clogging (many of the thin layers have a significant porosity).

A special type of thin layer is the asphalt rubber of the open-graded type (ARFC). They have performed especially well in Arizona, but successful trials have been and are being made in other parts of the world. Sometimes they also fail; there are several examples of this. The ARFC or its counterpart in other places than Arizona, offer a noise reduction of around 3-4 dB in comparison to DAC or SMA 0/11 in new condition. The noise reduction seems to drop by up to 1 dB per year during the first years and stabilize at around 1 dB noise reduction, according to the author's best estimation.

The effect on noise properties of rubber in the asphalt rubber surfaces is marginal. For similar air voids and aggregate size without rubber and normal binder content, the noise reduction is 1 or at most 2 dB higher; thus the rubber effect is 1-2 dB only.

However, the rubber has a greater potential than that. Trials in Sweden suggest that if the amount of rubber can be tripled, the rubber effect can be perhaps double that of the present designs. More research and development on this is needed; especially to check the durability.

The asphalt rubber surface of the gap-graded type has even lower noise reduction; it is essentially similar to SMA surfaces with the same aggregate size. The rubber effect in the gap-graded version is less than 1 dB.

As regards asphalt rubber, the Austrian “LSMA” surfaces challenge the previous statement, as the version with 1 % rubber seems to give 2-3 dB noise reduction compared to the baseline SMA. It is worth investigating the construction of these surfaces more to see if this positive result would be reproduced at another place.

It shall be noted that the rubber in the road surfaces may have other positive effects than noise, such as better durability and it constitutes a way to recycle rubber from scrap tyres instead of burning or disposing them.

There are a few indications suggesting that asphalt rubber surfaces may be less noise-reducing for heavy vehicles than for light vehicles.This needs further verification.

All low-noise road surfaces need to use advanced modified binders, normally PMB, to achieve an acceptable durability.

The Japanese paving industry seem to have very effective modified binders used in the urban streets.

The clogging effect on porous surfaces on high-speed roads is only minor in the wheel tracks, due to self-cleaning by traffic in wet weather. However the road shoulders get clogged.

On low-speed roads self-cleaning is negligible. Exceptional drainage facilities must be applied to reduce the clogging effect in urban areas with low speed roads.

The deterioration of the noise reduction with time has been found to be about 0.25 dB on high-speed roads in the Netherlands and Germany using the latest generation of advanced LNRS. In a more global scale, however, 0.5 dB per year is a more realistic value to use.

On low-speed roads, Japanese pavements have appeared to deteriorate at about 0.25 dB per year too.

In Hong Kong, on low-speed roads, the deterioration rate may be up to 1 dB per year. The same applies for high-speed roads in Sweden where clogging occurs rapidly due to dirt generation and wear from studded tyres in wintertime. Thus one may consider a deterioration rate of 1 dB/year as normal for any case where dirt generation is substantial and proper drainage is not provided.

Cleaning of porous surfaces has only a marginal effect. If cleaning is made several times per year it may be effective; otherwise most studies of cleaning show a marginal or no effect at all. In the Netherlands cleaning is made widely and systematically, but only on road shoulders.

In Japan they have developed an efficient low-cost drainage system running alongside the kerb. In Germany and Denmark very advanced and rather costly kerbside systems to drain away water and dirt have been tried, with good results.

The author recommends that an increased crosslope be applied on low-speed roads having a porous asphalt pavement to help drain away water and dirt quicker.

It has been observed that within about 50 m from any joint with a dense surface a porous surface has a reduced noise reduction. This is probably due to transport of dirt from the dense to the porous section. One should be aware of this when the location of a noise measuring point is determined.

The variation in noise properties along a porous asphalt section is generally considerable. The peak-to-bottom variation of noise level may be equally big as the average noise reduction. This means that extreme care shall be observed when selecting a measuring point for any roadside noise measurement. The CPX method to check this variation is a desirable supplement to any roadside measurement.

Some of the transversely tined cement concrete surfaces in USA are extremely noisy. Any other surface compared to such surfaces will seem to be a low noise surface and "noise reductions" of 10 dB can easily be recorded even for quite moderately efficient LNRS. It therefore is very important to use a common reference surface worldwide against which one can calculate a "noise reduction".

It is possible to give cement concrete surfaces better low-noise properties; for example by diamond grinding, in which case they may become somewhat quieter than SMA 0/11. To get comparable noise reduction to porous asphalt, they must be made porous.

This author thinks that it is necessary to consider also rolling resistance of road surfaces; not the least to reduce effect on climate change. Most of the LNRS also have good rolling resistance properties, so compromises may not need to be made.

In hot climates, the Urban Heat Island effect needs to be considered. The porous asphalt surfaces may contribute to a reduction of the heat island effect; more or less depending on the technology used. In Japan the heat island effect is systematically abated by the use of porous asphalt in big cities, which gives a noise-reducing bonus effect.

22. REFERENCES

Abbot, Phil; Nelson, P.M. (2001): "Revising CRTN Road Surface Correction for Medium and High-Speed Roads". PR/SE/289/2001 3/176, TRL Limited, U.K.

Abbot, Phil; Morgan, P.A.; Balsom, M.; Taylor, K. (2003): "Extension of CRTN road surface correction to lower speeds". Unpublished project report PR/SE/707/03, TRL Limited, U.K.

ADOT (2006): "Progress Report No. 2 Quiet Pavement Pilot Program". Progress report, December 20, 2005, revised December 28, 2006, Arizona DoT, Phoenix, Arizona, USA.

Altreuther, B.; Bartolomaeus, W. (2008): "Acoustical characterisation and life-cycle of porous road surfaces". Proc. of Acoustics'08, June 29 - July 4, 2008, Paris, France.

Andersen, Bent; Bendtsen, Hans; Thomsen, Sigurd N. (2008): "Optimized thin layers for urban roads". Presentation at Acoustics '08, Paris, France, June 29-July 4, 2008.

Anderson, Keith W.; Pierce, Linda M.; Uhlmeyer, Jeff S.; Weston, Jim (2008): "Evaluation of Long-Term Pavement Performance and Noise Characteristics of Open-Graded Friction Courses – Project 2". Report No. WA-RD 691.1, Washington State Department of Transportation Materials Laboratory, MS-47365 11, Olympia, WA 98504-7365, USA.

Anfosso-Lédée, Fabienne; Haberl, Jürgen; Watts, Greg (2005): "Task 5.4 final report: combination of low noise road surfaces with road and building equipments". SILVIA report SILVIA-LCPC_TUW-009-02-WP5-020205. Downloadable from: http://www.trl.co.uk/silvia/silvia/pdf/Associated_Reports/SILVIA-LCPC_TUW-009-02-WP5-020205.pdf

Anfosso, Fabienne (2007): Personal communication with Mrs Fabienne Anfosso, LCPC, Nantes, France.

Angst, Christian; Beltzung, Francoise; Bosshardt, Dieter; Grolimund, Hans-Jörg; Pestalozzi, Hansueli (2008): "Low-noise road surfaces in urban areas - Final report 2007 – Condensed Version". Report DIV-6003-E, Federal Office for the Environment (FOEN) and Federal Roads Office (FEDRO), Bern, Switzerland (no printed version is available). Downloadable PDF file at www.environnement-suisse.ch/div-6003-e

Anon. (2003): "Quality of Life on HertsDirect - Noise". Article at the Hertsfordshire (UK) website: http://www.hertsdirect.org/hcc/environment/planning/forwdplan/qol/noise/

Anon. (2005): "Pilot Program Evaluates Quiet Pavements in Arizona". Focus, June 2005 (pp 4-5), FHWA, USA.

Anon. (2008): "Highways Agency lists actions". Article in the Noise Bulletin, April 2008, Issue 21, page 3.

Aspro (2005): "Silence in Arizona". Article in Asphalt Professional, official Journal of the Institute of Asphalt Technology, No 16 August 2005.

Auerbach, Markus (2006): "Prediction and Propagation of Rolling Noise (P2RN): A joint French-German project". Presentation at the TRA 2006 conference (TRA = Transport Research Arena Europe), Gothenburg, Sweden (only abstract available).

Auerbach, Markus; Bérengier, Michel (2008): "DEUFRAKO - Prediction and Propagation of Rolling Noise". Paper published at the TRA 2008 conference (TRA = Transport Research Arena Europe), Ljubljana, Slovenia.

Balsom, M.H.; Nelson, P.M.; Summers, C. (2005): "Comparison of tyre/road noise for a range of surfaces on the A47, A447, A511 and B582 in Leicestershire". Published Project Report PPR023, TRL Ltd, Wokingham, U.K.

Bartolomaeus, Wolfram (2008): "Review of current practice and prospects in European countries - INQEST-Workshop on classification procedures & systems - Experiences in Germany". Presentation at the INQUEST workshop 25 April 2008, Ljubljana, Slovenia. Will be published on the web later in 2008.

Baxter, Andrew (2000): "Highways from Hell." Electronic Telegraph, Tuesday 8 February 2000, United Kingdom (from www.telegraph.co.uk).

BBA-ULM (2005): "UL-M thin surfacing systems for highways". Roads and Bridges Agrément Certificate No 01/H047, British Board of Agrément, United Kingdom. Downloadable from: http://www.bbacerts.co.uk/certs/hapas/H047i3_web.pdf

Beckenbauer, Thomas (2006): "IPG Road Surface Monitoring Projects Evaluation workshop". PowerPoint presentation at the "Optimization of Noise Reducing Pavements Invited evaluation workshop" (part of the Dutch IPG program); 23-24 November 2006, Danish Road Institute (DRI), Hedehusene, Denmark.

Bendtsen, Hans (1998): "Drainage asphalt and noise reduction over a long period". Proceedings from Euro-Noise 1998, Munich, Germany.

Bendtsen, Hans; Larsen, Lars Ellebjerg (2002): "Two-layer porous pavements and noise reductions in Denmark". Proc (CD-ROM) of the 9th International Conference on Asphalt Pavements (ISAP), 17-22 August 2001, Copenhagen, Denmark.

Bendtsen, Hans; Andersen, Bent (2005): "Experiences with thin noise reducing pavements". Proc of Forum Acusticum, Budapest 2005 (www.fa2005.org).

Bendtsen, Hans; Raaberg, Jørn; Thomsen, Sigurd N. (2005): "International Experiences with Thin Layer Pavements". Technical note 29, Road Directorate, Danish Road Institute, Hedehusene, Denmark.

Bendtsen, Hans; Raaberg, Jørn (2007): "Clogging of Porous Pavements - International Experiences". Technical note 55, Road Directorate, Danish Road Institute, Hedehusene, Denmark.

Bendtsen, Hans; Andersen, Bent; Råberg, Jørn; Ellebjerg Larsen, Lars; Kragh, Jørgen (2005a): "Two-layer porous asphalt for urban roads". Proc of Forum Acusticum, Budapest 2005 (www.fa2005.org).

Bendtsen, Hans; Ögren, Mikael; Sandberg, Ulf (2007): "Possibilities to reduce tyre/road noise emission on paving stones and other block surfaces". Deliverable F.D2 in the SILENCE project; see www.silence-ip.org (also available from VTI in Sweden or DRI in Denmark).

Bendtsen, Hans; Andersen, Bent; Thomsen, Sigurd N. (2007-2): "Optimized thin layers for highways – Inter-noise paper 2007". Report 153, Road Directorate, Danish Road Institute, Hedehusene, Denmark.

Berbee R, Rijis G, de Brouwer R and van Velzen L (1999): "Characterization and treatment of runoff from highways in the Netherlands paved with impervious and pervious asphalt". Water Environment Research 71(2) (March-April): 183-190.

Berengier, M.; Droste, B.; Gauvreau, B.; Duhamel, D.; Auerbach, M. (2008): "DEUFRABASE: A German-French acoustic database on road pavements". Proc. of Acoustics '08, Paris, France, June 29-July 4, 2008.

Biligiri, Krishna Prapoorna (2008): "Asphalt Mixtures' Properties Indicative of Tire/Pavement Noise". PhD Thesis, Arizona State University, Phoenix, Arizona, USA.

Biligiri, Krishna Prapoorna; Kaloush, Kamil E.; Zareh, Ali; Way, George B.; Carlson, Douglas D. (2008): "Tire/Pavement Noise Characteristics of Wearing Course Asphalt Mixtures". Presentation at the Transportation Research Board ADC40 (Transportation-Related Noise & Vibration) Summer Meeting July 2008, Key West, Florida, USA.

Bischoff, Deb (2008): "Investigative Study of the Italgrip™ System". WisDOT Report # WI-04-08, Wisconsin Dept. of Transportation, Madison, WI, USA. Downloadable from: http://on.dot.wi.gov/wisdotresearch/database/reports/wi-04-08italgrip.pdf

Brandberg, Jan (2006): "Bullermätningar före och efter asfaltering med bullerdämpande asfalt på Högsboleden 2006". PM 2006-11-18, Miljöförvaltningen, Göteborgs Stad, Sweden.

Brandberg, Jan (2007): "Rapport över mätningar av trafikbuller vid Eklandagatan, Göteborg, före och efter asfaltering med bullerdämpande asfalt". PM October 2007, Dnr 7190/07, Miljöförvaltningen, Göteborgs Stad, Sweden.

Canale, Sascia; Malgarini, Mauro; Puzulle, Giuseppe; Ricci, Riccardo (1990): "The differences of sound pressure level on Italian highway pavements". Proc. of the International Tire/Road Noise Conference 1990, Gothenburg, Sweden (book nowadays available only from Dr Sandberg, VTI).

Canestrari, Francesco (2007): Personal communication with Prof Francesco Canestrari at the Highway, Railways and Airports Engineering department, of the Institute of Hydraulics and Transportation Infrastructures, at the Università Politecnica delle Marche in Ancona, Italy.

Canestrari, F.; Bocci, M.; Ferotti, P.; Pasquini, E. (2007): "Mechanical characterization of environmentally friendly mixtures". Paper presented at the International Conference on Advanced Characterisation of Pavement and Soil Engineering Materials, Athens, 20-22 June 2007.

Camomilla, Gabriele; Luminari, Marcello (2004): "SIlent Road for Urban and Extra-Urban USe: the innovative resilient and resonant pavements". Proc. of SURF 2004, Toronto, Canada (see http://www.jegel.com/surf/).

De Souza, Jim (2008): Personal communication with Mr Jim de Souza, Highways Policy Manager, London Streets, Transport for London.

DMBR Vol 7 (1999): "Stone Mastic Asphalt". Chapter 7 in Volume 7 Section 5 Part 2 HD 37/99 of the Design Manual for Roads and Bridges (U.K). Downloadable from: http://www.standardsforhighways.co.uk/dmrb/vol7/section5/hd3799.pdf

DoE (1999): "HIGHWAY RECONSTRUCTION - “Whisper Concrete” in Austria and the UK". Department of the Environment, Digest No. 061 (3:1/99), London, U.K.

DRI-DWW (authors: Hans Bendtsen, et al) (2005): "The DRI-DWW Noise Abatement Program". VI Notat 24, Danish Road Institute, Hedehusene, Denmark. Downloadable from: http://www.vejdirektoratet.dk/publikationer/VInot024/html/entire_publication.htm

Donavan, Paul; Reyff, James; Scofield, Larry (2005): "Reduction of Traffic and Tire/Pavement Noise: Initial Results of the Arizona Quiet Pavement Program". Proc. of Inter-Noise 2005, Rio de Janeiro, Brazil.

Donavan, Paul (2005): “Comparative Measurements of Tire/Pavement Noise in Europe and the United States: a Summary of the NITE Study”. Report from the California Dept. of Transportation, Sacramento, California, USA.

Dravitzki, Vince (2006): “Road Traffic Noise – Determining the Influence of New Zealand Road Surfaces on Noise Levels and Community Annoyance”. Land Transport New Zealand Research Report 292. 76 pp.

Dravitzki, V.; Kvatch, I. (2007): “Road surface effects on traffic noise: stage 3 – selected bituminous mixes”. Land Transport New Zealand Research Report 326. 40 pp.

Duhem, Berhard (2003): Presentation in English on the PREDIT website by the Permanent Secretary of PREDIT 3; see
http://www.predit.prd.fr/predit3/menu.fo?cmd=statique&redirect=en_presentation

Ejsmont J A, Mioduszewski P, Gardziejczyk W, Wisiorek A, Sandberg U, Padmos C, Roovers M S, Morgan P and Anfosso-Lédée F (2004): "Development of procedures for certifying noise testing equipment". SILVIA Project Report SILVIA-TUG-006-10-WP2-160104. A special booklet can be ordered from Technical University of Gdansk, Poland, by writing to jejsmont@pg.gda.pl . May also be downloaded at:
http://www.trl.co.uk/silvia/silvia/pdf/Main_Outputs/SILVIA-TUG-006-10-WP2-160104.pdf

Elvik, R.; Greibe, P. (2005): "Safety aspects related to low noise road surfaces". SILVIA-DTF-ATKINS-001-03-WP3-050505. May be downloaded at:
http://www.trl.co.uk/silvia/silvia/pdf/Main_Outputs/SILVIA-DTF-ATKINS-001-03-WP3-091203.pdf

EPD Plan (2006): "A Draft Comprehensive Plan to Tackle Road Traffic Noise in Hong Kong". April 2006, EPD, Hong Kong. There is both a "Digest" with the main text and various annexes, of which Annex 3 deals with the low-noise road surface programme.

FHWA (1995): "Highway Traffic Noise Analysis and Abatement Policy and Guidance". US Dept. of Transportation, Federal Highway Administration (FHWA), Washington, DC, USA. Downloadable at http://www.fhwa.dot.gov/environment/polguid.pdf

FHWA (2005): "Information: Highway Traffic Noise - Guidance on Quiet Pavement Pilot Programs and Tire/Pavement Noise Research". Memorandum January 19, 2005, US Dept. of Transportation, Federal Highway Administration (FHWA), Washington, DC, USA. See http://www.fhwa.dot.gov/environment/noise/qpppmem.htm

Fichtner, Johann (2002): “Umweltindikatoren für den Bereich Lärmschutz”. Zeitschrift für Lärmbekämpfung, 49 (2002), No. 4, July 2002 (in German).

Gillespie, Rob [2008]: “Rubber stamp of approval”. Article in Surveyor, 22 Nov. 2008. See www.surveyormagazine.com

Glaeser, Klaus-Peter (2008): "Measurement of noise emissions and rolling resistance on real surfaces in the new drum test facility (PFF) at BASt". Presentation at the Tire Technology Expo 2008, Cologne, Germany. The presentation is downloadable (password needed) at http://www.tiretechnology-expo.com/conference.html

Goubert, Luc; Hooghwerff, Jan; The, Peter; Hofman, Rob (2005): "Two-layer porous asphalt: an international survey in the frame of the Noise Innovation Programme (IPG)". Proc. of Inter-Noise 2005, Rio de Janeiro, Brazil.

GStLV (2003): “Research Network Quiet Traffic”. Can be downloaded from http://www.fv-leiserverkehr.de/pdf-dokumenten/Overview.pdf

Gustafsson, Mats (2007): Personal communication in March 2007 with Mr Mats Gustafsson, Swedish Road and Transport Research Institute (VTI), Linköping, Sweden.

Haberl J, Pucher E, Litzka J and Kalivoda M, (2003): "Reale lärm-emissionsfaktoren des straßenverkehrs und reduktionsszenarien durch gesamtsystemoptimierung (Real-life noise emissions factors for street traffic and noise reduction scenarios through complete system optimisation)". Final Report of the Austrian Advanced Automotive Technology A3 Programme, FFF Project No. 806215, Vienna, Austria.

Haberl, J.; Litzka, J. (2008): "Use of noise reducing pavements on the Austrian road system". Proc. of the Transport Research Arena Europe (TRA) 2008 conference, Ljubljana, Slovenia.

Haberl, Jürgen (2008): "Austrian noise measurement results". Presentation at the INQUEST workshop 25 April 2008, Ljubljana, Slovenia. Will be published on the web later in 2008.

HAPAS H048 (2003): "Bardon Thinpave 10 mm Thin Surfacing System for Highways". HAPAS Certificate No 01/H048, British Board of Agrément, United Kingdom. Downloadable from: http://www.ribaproductselector.com/Docs/AGCerts/AG01H048.pdf?ac=

HAPAS (2008): "Highway Authorities Products Approval Scheme (HAPAS)". British Board of Agrément (BBA), United Kingdom. The homepage of HAPAS is http://www.bbacerts.co.uk/hapas.html

HD 37/99 (1999): "Design Manual for Roads and Bridges, Volume 7: Pavement Design and Maintenance – Bituminous Surfacing Materials and Techniques". Advice Note HD 37/99, from the Highways Agency, the Scottish Office Development Department, the Welsh Office Y Swyddfa Gymreig, and the Department of the Environment for Northern Ireland (February 1999).

Heinzelmann, Peter Jörg (2006): "Traffic noise reduction – main focus and goals of research in Germany". Paper SS23 - 184, Proc. of EURONOISE 2006, Tampere, Finland.

Henning, Theuns (2009): "Pavement deterioration models for asphalt-surfaced pavements in NZ". Report RR 367, Land Transport New Zealand.

Herrington, P.; Alabaster, D.; Arnold, G.; Cook, S.; Fussell, A.; Reilly, S. (2007): "Epoxy modified open-graded porous asphalt - Economic evaluation of long-life pavements: Phase II, Design and testing of long-life wearing courses". Report RR 321, Land Transport New Zealand.

Highways (2001): "Battle of the resurfacers". Highways, January/February 2001, pp 17-21.

Hiramatsu, T. (2007): "Noise insulation of buildings for road traffic noise and its measurement method". Presentation made at the symposium "An overall approach to reduction measures for road traffic noise" organized by JARI, 14-15 November 2007, Japan Automobile Research Institute (JARI), Tsukuba City, Japan.

HITEC (2004): "Evaluation of the Italgrip Overlay System – Interim Report". CERF Report June 2004, the Highway Innovative Technology Center (HITEC), part of the Civil Engineering Research Foundation (CERF), USA.

Hofman, Rob (2008): "Possible measures at urban level"**.** Presentation at the conference "Noise in the City" in Amsterdam, the Netherlands, March 2008. Downloadable from the website http://www.noiseinthecity.eu/.

Hosokawa H.; Gomi A.; Okuno T.; Goto F.; Tanaka S.; Kasahara A. (2006): "Development of Hot In-Place Transforming of Dense Graded Asphalt Mixture to Porous Asphalt Concrete". Proc. of ISAP 2006, Quebec, Canada.

Ishii, Mitsugi (2007): "Activities for Noise Controls in Local Governments". Presentation by Mitsugi Ishii, Kanagawa Environmental Research Center, Kanagawa Prefecture, Yokohama, Japan, at JARI Symposium "An overall approach to reduction measures for road traffic noise", Tokyo, November 2007 (see http://www.jari.jp/pdf/jido/JARI547.pdf).

Ingolstadt (2007): "Stadt Ingolstadt – Westliche Ringstrasse – Pilotprojekt zweischichtiger offenporiger Asphalt – Eine Handreichung". PowerPoint presentation from the City of Ingolstadt, Germany, in cooperation with a number of local companies. Downloadable at: http://www.lfu.bayern.de/laerm/forschung_und_projekte/opa/projektbeschreibung/doc/2opa.pdf

IPG (2008): "IPG knowledge, ready for use". Final Seminar of the IPG Programme, 17-18 June 2008, Zandvoort, the Netherlands. See: http://www.innovatieprogrammageluid.nl/GBpage.asp?id=1082

James, E. (2003): "A literature review on the effect of porous asphalt roads on water pollution". SILVIA Project Report SILVIA-TRL-008-01-WP3-260204. Downloadable at: http://www.trl.co.uk/silvia/silvia/pdf/Associated_Reports/SILVIA-TRL-008-01-WP3-240703.PDF

Jarvastaden (2009): "Tyst Asfalt" (in Swedish, meaning "Quiet asphalt" in English). Brief article published on the website: http://www.jarvastaden.se/Tyst-Asfalt/

Jespersen, Malene S; Ohm, Anne; Goubert, Luc; Descornet, Guy (2006): "Report from the Workshop held on 1 August 2006 at the premises of the European Commission (Charlemagne Building)". COWI, Kongens Lyngby, Denmark, website www.cowi.dk. The document and some other related documents are downloadable from http://www.cowiprojects.com/noiseclassification/Workshop_report.html

Johansson, Christer (2006): "Betydelsen av bullerreducerande beläggning för partikelhalterna (The importance of low-noise road surfaces for percentages of particulates)". SLB rapport 2006:3, Miljöförvaltningen, Stockholm City, Sweden. Downloadable at: http://www.slb.nu/slb/rapporter/pdf/pm10_buller_red_belaggn_2006_03.pdf

Kaloush, Kamil (2009): "Pavements and the Urban Heat Island Effect". Presentation at the 88th Annual Meeting of TRB, January 11-15, 2009, Washington, D.C., USA.

Kinsey, Peter (2000): Personal communication with Mr Peter Kinsey, Highways Agency, London, United Kingdom.

Kragh, Jørgen (2007): Personal communication with Mr Jørgen Kragh, Danish Road Institute, Denmark.

Kragh, Jørgen (2007-1): "1st Generation System for Inviting Tenders and Documenting Noise Reduction of Wearing Courses". Presentation at the "TRB ADC40 Noise & Vibration Summer Meeting 2007". Downloadable at the following address: http://www.adc40.org/summer2007/07%20Danish%201st%20Generation%20System_23Jul07.pdf

Kragh, Jørgen (2007-2): "Noise Classification - Asphalt pavement". Danish Road Institute Technical Note 61, 2007, Danish Road Institute, Hedehusene, Denmark. May be downloaded from: www.Roadinstitute.dk

Kragh, Jørgen (2008): "Noise Classification Methods for Urban Road Surfaces - Classification Methodology". SILENCE Deliverable F.D14C, Danish Road Institute, Hedehusene, Denmark.

Kragh, Jørgen; Bendtsen, Hans (2008): "Traffic noise levels after replacing the top of two-layer porous asphalt at Øster Søgade". Presentation at Acoustics '08, Paris June 29-July 4, 2008.

Krieger, Beata; Schmidt, Holger (2003): "German joint project "Leiser Straßenverkehr", "Silent traffic" exposé of the first research results". Proc. of Inter-Noise 2003, Jeju, Seogwipo, Korea.

Larsen, L. E.; Bendtsen, H. (2002): "Noise reduction with porous asphalt". Paper presented at the 9th International Conference on Asphalt Pavements 2002, Copenhagen, Denmark.

Leandri, Pietro (2007): Personal communication with Mr Pietro Leandri, PhD student at the Department of Civil Engineering, University of Pisa, Italy.

LfU (2006): "Schalltechnische Untersuchungen an der Westlichen Ringstraße in Ingolstadt vor und nach dem Einbau eines zweischichtigen, offenporigen Asphalts". Report BayLfU 2006 – 28, from the Bayerisches Landesamt für Umwelt (Bavarian Department of Environment Protection), Munich, Germany. Downloadable at:
http://www.lfu.bayern.de/laerm/daten/messberichte/doc/messbericht_2opa_ingolstadt_05.pdf

LfU (2007): "Schallpegelmessungen 2007 an der Westlichen Ringstrasse in Ingolstadt nach dem Einbau eines zweischichtigen offenporigen Asphalts". Report LfU-Ref.28 from the Bayerisches Landesamt für Umwelt (Bavarian Department of Environment Protection), Munich, Germany. Downloadable at:
http://www.lfu.bayern.de/laerm/daten/messberichte/doc/messbericht_2opa_ingolstadt_07.pdf

LfU (2008): "Lärmminderung an Straßen mit OPA". Short project summary from the Bayerisches Landesamt für Umwelt (Bavarian Department of Environment Protection), Munich, Germany. Downloadable at
http://www.lfu.bayern.de/laerm/forschung_und_projekte/opa/projektbeschreibung/index.htm

Lorenzen, Arne (2007): "Low Road-Traffic Noise - The German Research Program Leistra2 - an Overview". Proc. of Inter-.Noise 2007, Istanbul, Turkey.

Lorenzen, Arne (2008): "Low Noise Road Traffic - The German Research Program Leistra2". Proc. of TRA 2008, Ljubljana, Slovenia (TRA = Transport Research Arena Europe).

LoTAG (2007): "London wide asphalt specification: Guidance on the selection and recommendations for the use of road surfacing materials and European Standards for Asphalt". Job No. 9948, The London Technical Advisors Group (LoTAG), Transport for London; published by Jacobs U.K. Ltd. Downloadable at the website:
http://www.lotag.com/lotasphalt2.htm

Lowery, Pam (2007): E-mail to the author in March 2007 from Pam Lowery, Senior Technical Advisor - Noise, Environment and Sustainable Development Group, Highways Agency, London, United Kingdom.

Luminari, Marcello (2006): Personal communication with Mr Marcello Luminari, at Autostrade per l'Italia S.p.A. in Rome, Italy (in 2007 Autostrade changed name to Atlantia).

Luminari, Marcello (2008): Personal communication with Mr Marcello Luminari, at Atlantia S.p.A., Rome, Italy.

Malker, Henrik; Hojer, Martin; Nilsson, Nils-Ake (2007): "Field studies of the poroelastic road surface". Deliverable D 3.26, QCITY project (http://www.qcity.org). Downloadable at: http://www.qcity.org/downloads/SP3/D3-26_NCC_24M.pdf

MASTERpave (2001): "MASTERpave thin surfacing system for highways". HAPAS Certificate No 01/H052, British Board of Agrément, United Kingdom. Downloadable from: http://www.ribaproductselector.com/Docs/AGCerts/AG01H052.pdf?ac=

Maurer (2001): "Geräuschminderung an Fahrbahnübergängen in Lamellenbauweise durch wellenförmigen Fugenverlauf". Maurer Info Nr. 24, 01/2001, Maurer Söhne, Postfach 440145, D-80750 Munich, Germany.

Mercier-Handyside, Patrick (2005): "QCITY - Quiet City Transport - Short Project Presentation". Presentation at the CALM Workshop "European Noise Research Projects", Workshop with RTD Project Coordinators, Brussels, June 16, 2005. See http://www.calm-network.com/preports03.htm

Milford, Ingunn (2006): "Nasjonalt støymål og handlingsplaner mot støy (National noise target and action plans against noise)". Presentation at NVF Seminar 9-10 November 2006 "Støj på Vej - Problemer, Løsninger & Værktøjer for vejforvaltningen", Nordisk Vejteknisk Forbund (NVF); website:
http://nvf.vejdirektoratet.dk/document.asp?page=document&objno=73295

Modern Asphalt (2008): "Quiet surfacing draws public praise". Article in Modern Asphalt, Spring 2008 Issue no. 22.

Morgan, Phil A. (2008-1): "Scientific Strategy Document - End Report". Report DVS-2008-016, Road and Hydraulic Engineering Division of Rijkswaterstaat, P.O. 5044, 2600 GA Delft, the Netherlands.

Morgan, Phil A. (2008-2): "IPG Research Report - Innovative mitigation measures for road traffic noise". Report DVS-2008-018, Road and Hydraulic Engineering Division of Rijks-waterstaat, P.O. 5044, 2600 GA Delft, the Netherlands.

Morgan, Phil (2008-3): Personal communication with Mr Phil Morgan, TRL Limited, Wokingham, U.K..

Mouchel (2007): “JV pioneers recycled surfacing on the national network”. News article from the Mouchel company; see:
http://www.mouchelparkman.com/80256DA90041DA3E/httppublicpages/C1A73AA100ACACD180257375005573A0?open

Namikawa, Yoshiharu (2007): "Introduction to Japanese Noise Abatement Policy". Presentation at seminar in study tour of Hong Kong officials in Japan, May 2007.

Naus, Robbert (2007): Personal communication with Mr Robbert Naus, Dura Vermeer Infrastructuur BV, Hoofddorp, the Netherlands.

Navrud, S. (2002): "The state-of-the-art on economic valuation of noise. Final Report to European Commission, DG Environment, 14 April 2002". Department of Economics and Social Sciences, Agricultural University of Norway, Aas, Norway.

NCC (2005): "Støyreducerende vejbelaegninger (Noise reducing pavements)". Article in Danish in Asfaltposten, No. 2, 2005 (51), NCC Roads A/S, Denmark.

NCHRP (2007): "Methodologies for Evaluating Pavement Strategies and Barriers for Noise Mitigation". NCHRP 10-76 [RFP], Transportation Research Board, Washington, DC, USA.

Nerhagen L.; Forsberg B.; Johansson C.; Lövenheim B. (2005): "Luftföroreningarnas externa kostnader, förslag på beräkningsmetod för trafiken utifrån granskning av ExternE-beräkningar för Stockholm och Sverige". VTI Report No. 517, Swedish Road and Transport Research Institute (VTI), Linköping, Sweden.

Ng, Ping-sum; Tse, Alvin (2005): "Experience on Use of Low Noise Road Surface to Reduce Road Traffic Noise in Hong Kong". Proc of Forum Acusticum 2005, Budapest, Hungary.

Nicholls, J.C.; Carswell, I.; Gibbl, M. (2004): “Durability of thin surfacings in the United Kingdom”. Proc. of the Eurasphalt & Eurobitume Congress, Vienna, Austria.

Nicholls, J.C.; McHale, M.J.; Griffiths, R.D. (2008): “Best practice guide for durability of asphalt pavements”. Road Note 42, TRL Limited, Wokingham, U.K..

Nielsen, Carsten Bredahl (2007-1): “Ravelling of porous pavements - Assessment of test sections”. Technical note 48, Road Directorate, Danish Road Institute, Hedehusene, Denmark.

Nielsen, Carsten Bredahl (2007-2): “Clogging of porous pavements - The cleaning experiment”. Technical note 60, Road Directorate, Danish Road Institute, Hedehusene, Denmark.

Nielsen, Carsten Bredahl (2007-3): “Clogging of porous pavements - Assessment of test sections”. Technical note 54, Road Directorate, Danish Road Institute, Hedehusene, Denmark.

Nilsson, Mats E.; Botteldooren, Dick; De Coensel, Bert (2007): “Acoustic Indicators of Soundscape Quality and Noise Annoyance in Outdoor Urban Areas”. Proc. of ICA 2007, 2-7 September 2007, Madrid, Spain.

Nilsson, Nils-Ake (2008): "How the project QCITY can help cities to mitigate noise". Presentation at the conference "Noise in the City" in Amsterdam, the Netherlands, March 2008. Downloadable from the website http://www.noiseinthecity.eu/.

Nilsson, Nils-Ake (2009): "EU-projekt QCITY – Quiet City Transport". Presentation at the conference "Transportforum 2009" in Linköping, Sweden, January 2009. Downloadable from http://www.vti.se/epibrowser/Webbdokument/Transportforum/TP-föredrag%202009/18%20QCITY-projektet.pdf

Nodes, Julie E (2005): Letter to the editor of Asphalt Professional, official Journal of the Institute of Asphalt Technology, No 16 August 2005. Dr Nodes works at the Arizona Department of Transportation, Phoenix, Arizona, USA.

Ögren, Mikael; Sandberg, Ulf (2007): Database for noise characteristics of road surfaces for project SILENCE: http://195.35.82.202/silencedb/php/ (when this is written it is still protected but it will be opened for public access in 2008). If needed, ask the author for information.

Öngel, Aybike; Kohler, Erwin; Harvey, John (2008): "Evaluation of Effects of Pavement Characteristics on the OBSI Levels Using Principal Components Regression". Presentation made July 2nd, 2008, at the conference Acoustics'08, Paris, France.

Padmos, Cristo; Abbott, Phil, Morgan, Phil (2006): "The SILVIA classification system for road surfaces". Proc. of Inter-Noise 2006, Honolulu, Hawaii, USA.

Pagotto C, Legret M and Le Cloirec P (2000): "Comparison of the hydraulic behaviour and the quality of highway runoff water according to the type of pavement". Water Resources 34(18): 4446-4454.

Paje, S.E. (2008): Personal communication with Mr Santiago Exposito Paje, at LA^{2}IC, Castilla-La Mancha University, Ciudad Real, Spain.

Paje, S.E.; Bueno, M.; Terán, F.; Viñuela, U.; Luong, J. (2008): "Assessment of asphalt concrete acoustic performance in urban streets". J. Acoust. Soc. America 123 (3), March 2008, pp 1439-1445.

Peyrard, D. (2001): "Utilisation combinée des revêtements de chaussée et des écrans anti-bruit". Journées d'Etude Bruit du Trafic Routier, Comité Français AIPCR / PIARC, Nantes, France.

Poulikakos, Lily D.; Gubler, R.; Partl, Manfred N.; Pittet, M.; Junod, A.; Arnaud, L.; Simond, E. (2006): "Current State of Porous Asphalt in Switzerland". Proc. of the 10th International Conference on Asphalt Pavements (ISAP), Québec City, Canada, August 12-17.

Poulikakos, Lily; Takahashi, Shigeki; Partl, Manfred (2006): "Evaluation of Improved Porous Asphalt by Various Test Methods". Report Nr. 113/13 (EMPA No. FE 860076), EMPA, Switzerland. Download at http://www.empa.ch/plugin/template/empa/*/54476/---/l=2

Rasmussen, Robert; Mun, Eric; Ferragut, Ted; Wiegand, Paul (2006): "A comprehensive field study on concrete pavement solutions for reducing tire-pavement noise". Proc. of Inter-Noise 2006, Honolulu, Hawaii, USA.

Rasmussen, Robert (2007): Personal communication with Dr Robert Otto Rasmussen, The Transtec Group, Austin, Texas, USA.

Rasmussen, Robert (2008): Personal communication with Dr Robert Otto Rasmussen, The Transtec Group, Austin, Texas, USA.

Rasmussen, Robert; Whirledge, Robert; Ferragut, Ted; Wiegand, Paul (2007): "Measuring and modeling tire-pavement noise on various concrete pavement textures". Article submitted 2007 for publication in the Noise Control Engineering Journal.

Rasmussen, Robert; Garber, Sabrina I.; Fick, Gery J.; Ferragut, Ted; Wiegand, Paul (2008): "How to Reduce Tire-Pavement Noise: Interim Better Practices for Constructing and Texturing Concrete Pavement Surfaces". Report for Pooled Fund TPF-5(139), March 2008, National Concrete Pavement Technology Center, Ames, Iowa, USA.

Ringway (2008): "ULM Thin Surfacing - High performance from the market leader". Product note on the Ringway website:
http://www.ringway.co.uk/page.php?show=17&highlight=page&terms=noise&bool=OR

Rochat, Judy (2007): "Volpe Center Updates on Tire/Pavement Noise Studies". Presentation at the Summer meeting (July 2007) of TRB Committee ADC40, San Luis Obispo, California, USA.

Rochat, Judy (2009): "Quiet Pavement Pilot Program in Arizona". Sidebar article in TR News, April/May 2009 (to be published).

Rodehack, Gernot; Beckenbauer, Thomas (2006): "Möglichkeiten und Grenzen von offen-porigen Asphaltdeckschichten (Possibilities and limits of open porous asphalt wearing courses)". Paper presented at the German Road and Traffic Congress, Karlsruhe, Germany, 27-29 September 2006. Programme available at the website:
http://www.fgsv.de/veranstaltungen_aktuelle.0.html?&no_cache=1&tx_julleevents_pi1[showUid]=3&tx_julleevents_pi1[sub]=248

Roovers, M.S.; Doorschot, J.J.J. (2005): "Pavement Noise Translator - a comparison of the acoustical properties of Dutch and German road surfaces". Report number DWW-2005-045, Road and Hydraulic Engineering Division of Rijkswaterstaat (DWW), Delft, the Netherlands.

Rymer, Bruce; Donavan, Paul (2005): "Quiet Pavement & Noise Research in California". Presentation at the Summer meeting (July 2005) of TRB Committee ADC40, Seattle, Washington, USA.

Saelensminde, K.; Veisten, K. (2005a): "SILVIA Deliverable D16: Cost-benefit analysis". SILVIA Project Report SILVIA-TOI-004-01-WP3-030505. May be downloaded at:
http://www.trl.co.uk/silvia/silvia/pdf/Main_Outputs/SILVIA-TOI-004-01-WP3-030505.pdf

Saelensminde, K.; Veisten, K. (2005b): "Cost-Benefit Analysis Tool". MS Excel Spreadsheet, SILVIA Project Output SILVIA-TOI-004-01-WP3-030505. May be downloaded at:
http://www.trl.co.uk/silvia/silvia/pdf/Main_Outputs/SILVIA-TOI-004-01-WP3-030505.xls

Samuels, Stephen; Hall, Arthur (2006): "The Long Term Road Traffic Noise Attributes of Pavement Surfaces in Queensland". Proc. of ACOUSTICS 2006, 20-22 November 2006, Christchurch, New Zealand.

Sandberg, Ulf (1990): "Road Macro- and Megatexture Influence on Fuel Consumption". Surface Characteristics of Roadways: International Research and Technologies, ASTM STP 1031, W.E. Meyer and J. Reichert, Eds., American Society for Testing and Materials (ASTM), Philadelphia, USA. Also available from the Swedish National Road and Transport Research Institute (VTI), Linkoping, Sweden.

Sandberg, Ulf (1997): "Influence of Road Surface Texture on Traffic Characteristics Related to Environment, Economy and Safety - A State-of-the-Art Study Regarding Measures and Measuring Methods". VTI Notat 53A-1997, Swedish National Road and Transport Research Institute (VTI), Linkoping, Sweden.

Sandberg, Ulf; Masuyama, Yukiei (2005): "Japanese machines for laying and cleaning double-layer porous asphalt - Observations from a study tour". Report produced by direction of Rijkswaterstaat – DWW, DWW/IPG order number 64520946. Also available from the Swedish National Road and Transport Research Institute (VTI), Linkoping, Sweden.

Sandberg, Ulf; Kalman, Björn; Nilsson, Roger (2005): "Design Guidelines for Construction and Maintenance of Poroelastic Road Surfaces". Report No. SILVIA-VTI-005-02-WP4-14/10/05 of the SILVIA project. See http://www.trl.co.uk/silvia/ .

Sandberg, Ulf (2006): "The Concept of Virtual Reference Surface for Noise Prediction and Comparison Purposes". Proc. of Inter-Noise 2006, Honolulu, Hawaii, USA. Also available from the Swedish National Road and Transport Research Institute (VTI), Linkoping, Sweden.

Sandberg, Ulf (2007a): "Vägytans inverkan på trafikbulleremission och rullmotstånd (The influence of the road surface on traffic noise emission and rolling resistance)". Unpublished project report (in Swedish), Swedish Road and Transport Research Institute (VTI).

Sandberg, Ulf (2007b): "Possibilities to reduce noise emission from the tyre/road interaction with emphasis on the Swedish situation". Unpublished report, Swedish Road and Transport Research Institute (VTI) and Chalmers University of Technology.

Sandberg, Ulf (2008-1): "Review and evaluation of the low-noise road surfacing programme for low-speed roads in Hong Kong". Final report to Hong Kong EPD and HyD, 2008-03-10.

Sandberg, Ulf (2008-2): "The New Green Swedish Road Surface Selection Policy". PowerPoint presentation at the Workshop on classification procedures & systems, 25th April 2008, Ljubljana, Slovenia. This presentation may still be available for download at: ftp://ftp.brrc.be/pub/INQUEST%20WORKSHOP%20LJUBLJANA%20APRIL%202008/

Sandberg, Ulf; Ejsmont, Jerzy A. (2002): "Tyre/Road Noise Reference Book". Informex, SE-59040 Kisa, Sweden (www.informex.info).

Sandberg, Ulf; Kalman, Bjorn (2005): "The Poroelastic Road Surface – Results of an Experiment in Stockholm". Proc of Forum Acusticum 2005, Budapest, Hungary.

Sandberg, Ulf; Bendtsen, Hans (2007): "Possibilities for reducing tyre/road noise emission on paving stones and other block surfaces". Deliverable F.D1 in the SILENCE project; see www.silence-ip.org (also available from VTI in Sweden or DRI in Denmark).

Sandberg, Ulf; Masuyame, Yukiei (2005): "Japanese machines for laying and cleaning double-layer porous asphalt – Observations from a study tour." Swedish National Road and Transport Research Institute (VTI) and Chalmers University of Technology, Sweden. Report produced by direction of Rijkswaterstaat – DWW, DWW/IPG order number 64520946; see: http://www.stillerverkeer.nl/stillewegdekken/IPG2laagszoab/downloads/2lmachine_rapportJapan.pdf

Schguanin, Gregor (2008): "Pavement classification - The Swiss approach". Presentation at the meeting on the classification of pavement noise characteristics, 16-17 Sept. 2008 in Copenhagen, Denmark.

Schmidt, Bjarne (2007): Interim report 2007-02-27 from SP F in SILENCE. From Danish Road Institute (DRI), Hedehusene, Denmark.

Scott, D.M.B. (2007): "A26 Tonbridge – Cornwallis Avenue: Road Surface Noise Study". Report No. B0814600, Kent Highway Services, Jacobs UK Limited, Maidstone, Kent ME15 6GB, United Kingdom.

SILVIA (ed. by Phil Morgan) (2006): "Guidance Manual for the Implementation of Low-Noise Road Surfaces". FEHRL Report 2006/02, FEHRL, Brussels. Downloadable at: http://www.trl.co.uk/silvia/silvia/pdf/silvia_guidance_manual.pdf

SLB (2006): "The Stockholm Trial - Effects on Air Quality and Health". SLB-analys 4:2006, City of Stockholm Environment and Health Administration, Stockholm, Sweden. Downloadable at: http://www.slb.nu/slb/rapporter/pdf/TheStockhTrial_engSLB_4_2006.pdf

Sliwa, Nina (2005): "Experience with porous Concrete on Highway B56 in Germany". Report SILVIA -BASt-006-00-WP4-14/04/2005 which may be downloaded from the SILVIA website (http://www.trl.co.uk/silvia/).

Sotil, Andres, Biligiri, Krishna P.; Kalousch, Kamil E.; Golden, Jay S. (2006): "The Dynamic Complex Modulus (E*) Test as a Potential Indicator for an Asphalt Mixture's Tire-Road Noise Characteristics". TRB paper 06-3088, Transportation Research Board, Washington, DC, USA.

SRA (2007): "Råd för val av beläggning med hänsyn till slitage, emission av buller och partiklar, samt rullmotstånd". Interimsutgåva 2007-10-26, Swedish Road Administration (SRA), Borlänge, Sweden (in Swedish only). Downloadable from: http://www.vv.se/filer/17591/val_av_belaggning_mht_miljo_rev_10_okt_2007.pdf

Stait, Richard (2002): "HAPAS – Highways Authorities Products Approval Scheme". Presentation to the project SILVIA by Mr Richard E. W. Stait, TRL Limited, Wokingham, U.K..

Stait, Richard (2007): Personal communication with Mr Richard E. W. Stait, TRL Limited, Wokingham, U.K., who is Project Manager.

Swedish EPA (2007): "Environmental Quality Standards". The Swedish Environmental Protection Agency (Naturvårdsverket), Stockholm, Sweden.
Website: http://www.internat.environ.se/documents/legal/standard/quality.htm

Thomsen, S.N.; Bendtsen, H.; Andersen, B. (2006-1): "Noise reducing thin pavements - urban roads". Report 149, Road Directorate, Danish Road Institute, Hedehusene, Denmark.

Thomsen, S.N.; Bendtsen, H.; Kragh, Jørgen (2006-2): "Test of thin layers on highway - Year 1 measurement report". Technical note 35, Road Directorate, Danish Road Institute, Hedehusene, Denmark.

TOPR (2004): "Task Order Proposal Request (TOPR) No. 2 – Development and Delivery of "Tire/Pavement Noise 101" Workshop". FHWA, Washington, DC, USA.

Ulmgren, Nils (2007): PowerPoint and oral presentation at Transportforum 2007 (a large Nordic congress), Linköping, Sweden. The PowerPoint presentation is downloadable from: http://www.vti.se/epibrowser/Webbdokument/Transportforum/TP-foredrag%202007/43.%20Tyst%20asfalt%20Q-city.pdf

Ulmgren, Nils (2008): Personal communication with Mr Nils Ulmgren at NCC Roads AB, Solna, Sweden.

van Blokland, G.J. (2008): "Acoustic Optimisation Tool". Presentation at the final IPG Seminar, see further [IPG, 2008]. See also the special website if the AOT: www.speron.net

van Bochove, G. G. (2008): Personal communication with Mr G. G. van Bochove, Heijmans Infrastructuur B.V., Rosmaien, the Netherlands.

van Dommelen, Arthur (2007): "Prefabricated modular concrete pavements". Leaflet from the Road and Hydraulic Engineering Division of Rijkswaterstaat, P.O. 5044, 2600 GA Delft, the Netherlands.

van Keulen, Wim (2008): Personal communication with Mr Wim van Keulen of VANKEULEN advies, Vlijmen, the Netherlands (based on a manuscript for a conference paper by Mr Van Keulen with the title "Monitoring 20 Silent Roads Over 10 Years In The Municipality Of Groningen").

van Loon, R.C.L. (2006): "Bepaling van de wegdekcorrectie Microflex 0/6". Report M+P.WHE.05.3.9, M+P - raadgevende ingenieurs, Vught, the Netherlands.

Vašina, M.; Hughes, D.C.; Horoshenkov, K.V.; Lapčík, Jr. L. (2005): "The acoustical properties of consolidated expanded clay granulates". Applied Acoustics, Volume 67, Issue 8, August 2006, Pages 787-796.

Vassiliadis, Marie (2007): "Volvo one step nearer commercially viable hybrids for heavy vehicles". Press release 2007-03-20 from Volvo Trucks, Volvo AB, Gothenburg, Sweden (http://pnt.volvo.com/pntclient/PressRelease.aspx?pubid=3133).

Veisten, K.; Saelensminde, K. (2004): "SILVIA Deliverable D06: Summary of net impacts on sustainability from a change to porous asphalt". SILVIA Project Report SILVIA-TOI-002-06-WP3-300304. May be downloaded from:
http://www.trl.co.uk/silvia/silvia/pdf/Main_Outputs/SILVIA-TOI-002-06-WP3-300304.pdf

Walsh, Ian (2008): Personal communication with Mr Ian D. Walsh, Jacobs Engineering (UK) Ltd, Aylesford, Kent ME20 7BU, UK.

Watts, Greg R.; Morgan, Phil A. (2005): "Predicting the additional benefits of porous asphalt within street canyons and confined spaces". Proc. of Inter-Noise 2005, Rio de Janeiro, Brazil.

Weissenberger, W.; Beckenbauer, T.; Grüner, R.; Huber, L.; Männel, M.; Müller, D. (2006): "Weiterentwicklung offenporiger Asphalte – Schalltechnische und bautechnische Untersuchungen an den realisierten Strecken in Bayern – Schlussbericht". Müller BBM report M61 795/5, Müller-BBM, Planegg (Munich), Germany.

World Highways (2007): "Autostrade invests". News article Friday 28 December 2007 in the journal World Highways.

World Highways (2008): "Recycling asphalt". Discussion by Cliff Nicholls of the UK's TRL Ltd, Thursday 22 May 2008, in the journal World Highways.

Würzel, Dieter (2006): "More traffic – less noise. An interdisciplinary approach to reducing transportation noise". Proc. of Inter-Noise 2006, Honolulu, Hawaii, USA.

APPENDIX I : CONTACT DATA FOR IMPORTANT PERSONS AND ORGANIZATIONS

The Netherlands:

Rob Hofman, *Dr. ir., Senior Project Leader IPG*
Ministry of Transport, Public Works and Water Management (DWW), Directorate-General of Public Works and Water Management. Postal address: Road and Hydraulic Engineering Institute, P.O. Box 5044, NL-2600 GA, Delft, The Netherlands
Web page: http://www.innovatieprogrammageluid.nl/page.asp?id=1002 and
http://www.innovatieprogrammageluid.nl/gbdefault.asp e-mail: rob.hofman@rws.nl
Office telephone: +31 (0)15 2518 504 Mobile telephone:

Cristo Padmos, *Dr. ir., Project Leader IPG*
Ministry of Transport, Public works and Water Management (DWW), Delft, the Netherlands
Web page: http://www.innovatieprogrammageluid.nl/page.asp?id=1035 and
http://www.innovatieprogrammageluid.nl/gbdefault.asp e-mail: cristo.j.padmos@rws.nl
Office telephone: +31 (0)15 2518 456 Mobile telephone:

Willem-Jan van Vliet, *Project Leader IPG, Senior Consultant, Section Noise Abatement*
Ministry of Transport, Public works and Water Management (DWW), Delft, the Netherlands
Web page: http://www.innovatieprogrammageluid.nl/page.asp?id=1044 and
http://www.innovatieprogrammageluid.nl/gbdefault.asp e-mail: willemjan.van.vliet@rws.nl
Office telephone: +31 (0)15 2518 457 Mobile telephone: +31 (0)6 55160411

Germany:

Beata Krieger, *Dr., Head of Unit S 3: Concrete Pavements, Low-noise Surface Textures*
Federal Highway Research Institute (BASt), Unit S 3, Brüderstrasse 53, DE-51427 Bergisch-Gladbach, Germany
Web page: http://www.bast.de/nn_43710/EN/e-BASt/e-bast-node.html
e-mail: Beata.Krieger@bast.de
Office telephone: +49 (0)2204 43 730 Mobile telephone:

Klaus-Peter Glaeser, *Dr.Ing., Head of Unit F 3: Vehicle Pavement Interaction*
Federal Highway Research Institute (BASt), Section Vehicle Pavement Interaction, Brüderstrasse 53, DE-51427, Bergisch-Gladbach, Germany
Web page: See above e-mail: glaeser@bast.de
Office telephone: +49 (0)2204 43 630 Mobile telephone:

Arnold Hemmert-Halswick, *Dr.Ing., Head of Unit B 2: Steel Structures, Corrosion Protection*
Federal Highway Research Institute (BASt), Section Steel Structures, Brüderstrasse 53, DE-51427, Bergisch-Gladbach, Germany
Web page: See above e-mail: hemmert-halswick@bast.de
Office telephone: +49 (0)2204 430 Mobile telephone:

Ulrike Stöckert, *Dr.Ing., Unit S 3: Concrete Pavements, Low-noise Surface Textures*
Federal Highway Research Institute (BASt), Section Concrete Pavements, Brüderstrasse 53, DE-51427, Bergisch-Gladbach, Germany
Web page: See above e-mail: stockert@bast.de
Office telephone: +49 (0)2204 430 Mobile telephone:

Wolfram Bartolomaeus, *Dr.Ing., Unit V 3: Environmental Protection, Noise Protection*
Federal Highway Research Institute (BASt), Section Environmental Protection, Brüderstrasse 53, DE-51427, Bergisch-Gladbach, Germany
Web page: See above e-mail: Bartolomaeus@bast.de
Office telephone: +49 (0)2204 43 536 Mobile telephone:

Denmark:

Hans Bendtsen, *Senior Researcher, Programme Manager "Noise"*
Danish Road Institute (DRI), Guldalderen 12, P.O. Box 235, DK-2640 Hedehusene, Denmark
Web page: www.roadinstitute.dk e-mail: hbe@vd.dk
Office telephone: +45 7244 7164 Mobile telephone: +45 2091 6164

Bent Andersen, *Senior Researcher, Road Traffic Noise*
Danish Road Institute (DRI), Guldalderen 12, P.O. Box 235, DK-2640 Hedehusene, Denmark
Web page: www.roadinstitute.dk e-mail: bea@vd.dk
Office telephone: +45 7244 7184 Mobile telephone: +45 2084 7184

Carsten Bredahl Nielsen, *PhD*
Danish Road Institute (DRI), Guldalderen 12, P.O. Box 235, DK-2640 Hedehusene, Denmark
Web page: www.roadinstitute.dk e-mail: can@vd.dk
Office telephone: +45 7244 7146 Mobile telephone:

Hans Jørgen Ertman Larsen, *Head of Department*
Danish Road Institute (DRI), Guldalderen 12, P.O. Box 235, DK-2640 Hedehusene, Denmark
Web page: www.roadinstitute.dk e-mail: hje@vd.dk
Office telephone: +45 7244 7000 Mobile telephone:

California:

Judy Rochat, *PhD*
John A. Volpe National Transportation Systems Center, Acoustics Facility, Kendall Square, 55 Broadway, Cambridge, MA, USA
Web page: http://www.volpe.dot.gov/index.html e-mail: Judy.Rochat@Volpe.dot.gov
Office telephone: +1 310 833 1711 or +1 617 494 6338 Mobile telephone:

Jeff Lewis, *Senior Transportation Engineer*
Federal Highway Administration (FHWA), California Division Office, 980 Ninth Street, Suite 400, Sacramento, CA 95814, USA
Web page: http://www.fhwa.dot.gov e-mail: Jeff.Lewis@fhwa.dot.gov
Office telephone: +1 916-498-5035 Mobile telephone:

Bruce Rymer, *MEngr, TE, PE, Senior Engineer*
California Department of Transportation (CALTRANS), Division of Environmental Analysis, Noise & Vibration Unit, 1120 N Street, MS27, Sacramento, CA95814, USA.
Web page: http://www.dot.ca.gov/ e-mail: Bruce_Rymer@dot.ca.gov
Office telephone: +1 916 653 6073 Mobile telephone: + 1 916 826 4310

Jin S. Lee, *P.E., PMP, Branch Chief/Noise & Vibration Branch*
California Department of Transportation (CALTRANS), Office of Environmental Engineering & Corridor Studies, Division of Planning, Public Transportation and Local Assistance, 100 S. Main Street, Los Angeles, CA90012, USA.
Web page:http://www.dot.ca.gov/dist07/ e-mail: jin_s_lee@dot.ca.gov
Office telephone: +1 213 97 3312 Mobile telephone:

Arizona:

Mike Dennis, *Air/Noise Team Leader*
Arizona Dept. of Transportation, 205 South 17th Avenue, Mail Drop 619E, Room 213E, Phoenix, AZ 85007, USA
Web page: www.azdot.gov/Highways/EEG e-mail: MDennis@azdot.gov
Office telephone: +1 602 712 7114 Mobile telephone:

Doug Carlson, *Executive Director, RPA*
Rubber Pavements Association (RPA), 1801 South Jentilly Lane, Suite A-2, Tempe, AZ 85281-5738, USA.
Web page: http://www.rubberpavements.org/ e-mail: dougc@rubberpavements.org
Office telephone: +1 480 517 9944 Mobile telephone:

Japan:

Seishi Meiarashi, *Dr., Senior Researcher, Special Research Project*
Public Works Research Institute (PWRI), 1-6, Minamihara, Tsukuba Ibaraki, 305-8516, Japan
Web page: http://www.pwri.go.jp/eindex.htm e-mail: mei@pwri.go.jp
Office telephone: +81 29 879 6710 Mobile telephone: +81 (0)90 7263 7399

Yoshiharu Namikawa, *Head, Road Environment Division*
National Institute for Land and Infrastructure Management (NILIM), 1, Asahi, Tsukuba City, Ibaraki Prefecture, Japan
Web page: http://www.nilim.go.jp/ e-mail: namikawa-y92di@nilim.go.jp
Office telephone: +81 (0)29 864 2274 Mobile telephone: +81 (0)90 3065 1539

Mr Yukie Masuyama, *Vice Director*
Seikitokyu Kogyo Co., Ltd., 2081-2, Seiwa, Iwafune-cho, Shimotsuga-gun, Tochigi, Japan
Web page: http://www.seikitokyu.co.jp e-mail: masuyama@seikitokyu.co.jp
Office telephone: +81 (0)282 55 2711 Mobile telephone: +81 (0)90 3332 7743

Tomonao Okubo, *Dr.*
Kobayasi Institute of Physical Research, 3-20-41 Higashi-Motomachi, Kokubunji, Tokyo 185-0022, Japan
Web page: http://www.kobayasi-riken.or.jp/english/english_frame_top.htm
e-mail: okubo@kobayasi-riken.or.jp
Office telephone: +81 42 321 2841 (switchboard) Mobile telephone:

Kohei Yamamoto, *Prof.*
Kobayasi Institute of Physical Research, 3-20-41 Higashi-Motomachi, Kokubunji, Tokyo 185-0022, Japan
Web page: http://www.kobayasi-riken.or.jp/english/english_frame_top.htm
e-mail: yamamoto@kobayasi-riken.or.jp
Office telephone: +81 42 321 2841 (switchboard) Mobile telephone:

APPENDIX II : POLICY DOCUMENTS RELATED TO THE USE OF LNRS

This will be supplied separately in order not to load this report with many more pages.

APPENDIX III : OVERSEAS STUDY TOURS FOR HONG KONG OFFICIALS

Summary Report made in response to
Hong Kong Environmental Protection Department project No. AN 06-004
"Reviewing the Trial of Low Noise Road Surface (LNRS) in Hong Kong and Benchmarking the Experience on the Use of LNRS in Overseas Countries"

AIII-1 ABSTRACT

In April-May 2007, study tours to three continents were made by noise and paving experts from Hong Kong with the purpose to study overseas experience in the application of low noise road surfaces. They were designed by this author who also was invited to take part in them. The study tours went to the following regions and countries:

- European tour: The Netherlands, Germany and Denmark
- American tour: The states of California and Arizona in the United States of America
- Asian tour: Japan

The visits to the countries and states had somewhat different focus, depending on the experience in the region. For example, the visit to the Netherlands focused on double-layer porous asphalt on medium and high-speed roads, the visit to Germany focused on single-layer porous asphalt and on various paving solutions including also cement concrete on high-speed roads, while the visit to Denmark focused on thin layers and porous asphalt on low-speed roads. The visit to the USA focused on asphalt rubber pavements on high-speed roads and the visit to Japan focused on porous asphalt in urban areas and cleaning of clogged surfaces.

It was the common experience of all participants in the study tours that they were very successful and gave a lot of valuable experience and knowledge which will be essential for an improved low noise policy in Hong Kong.

This report presents a summary of the study tour with focus on the administration. With regard to the concrete experiences as understood and remembered by this author, the information is integrated into the main report and is not repeated here.

It was concluded that several of the paving technologies studied should be applicable in and/or adoptable to Hong Kong conditions. This is, in particular, the case for three types of surfaces; namely single-layer porous asphalt of German and Japanese design, thin layers of Danish and Dutch design and asphalt rubber of the Arizona design principles. Further, for the "noisy" cement concrete surfaces still in wide use in Hong Kong, the grinding technique studied in Arizona may be a low-cost solution; especially in cases where horizontal forces in the tyre/road interface (such as sharp curves, steep inclinations and busy intersections) may make the use of the asphalt solutions too weak.

AIII-2 ACKNOWLEDGEMENTS

This work has been conducted as part of the project "Reviewing the Trial of Low Noise Road Surface (LNRS) in Hong Kong and Benchmarking the Experience on the Use of LNRS in Overseas Countries" (No. AN 06-004) for the Hong Kong Environmental Protection Department (EPD).

The author is grateful to the Hong Kong EPD for sponsoring the study tours reported here.

The author is also grateful to all research colleagues and others involved in road research and management, who have been so kind in supplying information during and after the study tours. The individuals assisting with this are so many that it is difficult to list them all.

The author is Senior Research Scientist at the Swedish Road and Transport Research Institute (VTI), in Linköping, Sweden, and also Adjunct Professor at Chalmers University of Technology, Division of Applied Acoustics, in Gothenburg, Sweden. However, this project was conducted independently by the author by special agreements. Nevertheless, the author is grateful to VTI and Chalmers for making this work possible.

AIII-3 INTRODUCTION

In April-May 2007, study tours to three continents were made by noise and paving experts from Hong Kong with the purpose to study overseas experience in the application of low noise road surfaces. The tours were designed by this author who also was invited to take part in them[83]. The study tours went to the following regions and countries:

- European tour: The Netherlands, Germany and Denmark
- American tour: The states of California and Arizona in the United States of America
- Asian tour: Japan

The visits to the countries and states had somewhat different focus, depending on the experience in the region. For example, the visit to the Netherlands focused on double-layer porous asphalt on medium and high-speed roads, the visit to Germany focused on single-layer porous asphalt and on various paving solutions including also cement concrete on high-speed roads, while the visit to Denmark focused on thin layers and porous asphalt on low-speed roads. The visit to the USA focused on asphalt rubber pavements on high-speed roads and the visit to Japan focused on porous asphalt in urban areas and cleaning of clogged surfaces.

The main interest from the Hong Kong side was on low-speed roads, but where such experience was poor, the situation for high-speed roads was studied with a view to using this experience and knowledge for low-speed applications too.

Only this author took part in all the visits. From Hong Kong, different people took part in different tours; always one or two from the EPD and one or two from the HyD. It was the common experience of all participants in the study tours that they were very successful and gave a lot of valuable experience and knowledge which will be essential for an improved low noise policy in Hong Kong.

This report presents a summary of these experiences as understood and remembered by this author.

AIII-4 PURPOSE OF THE STUDY TOURS

The purpose of the study tours was to gather state-of-the-art information and hands-on experience of the use of low noise road surfaces in overseas countries. In particular, the practical aspects of the application of such surfaces, the performance and costs over a life-cycle, as well as the potential for an effective use of them in a Hong Kong were of interest.

The selection of countries to visit was made in order to cover the subject as well as possible; i.e. to study the major promising surfaces and the most comprehensive experience of them, at a reasonable travel cost and time.

---

[83] Details of the visiting program and contact persons are presented in:
Sandberg, Ulf (2007): "Scanning tour for Hong Kong officials to study overseas experience concerning low-noise road surfaces ". Final program by Ulf Sandberg, Kisa, Sweden, 8 May 2007.

AIII-5 SELECTED COUNTRIES OR STATES FOR THE TOURS

Due to the special knowledge, skills and experience, the following countries or states were chosen to be targets for the study tour:

Country or state	Justification
Arizona	Arizona has been instrumental in developing and implementing asphalt rubber friction courses (ARFC) and has a whole network of such surfaces in the Phoenix Valley; i.e. mainly the freeway system in and around the capital Phoenix
California	California (CALTRANS) has also been instrumental in the development of ARFC, but has not implemented them at such an extensive level. A visit to California would also be an opportunity to study some diamond ground cement concrete and longitudinally tined cement concrete
Denmark	Denmark has made some notable and very well documented long-term experiments with porous asphalt, but would be most interesting to visit because of the systematic and scientific work with thin surfacings. They also apply world-class methods to study the clogging process.
Germany	Germany, at first having bad experience with porous asphalt, in recent years has embarked on very comprehensive programs to study porous asphalt. The large number of surfaces studied over a relatively long time makes it extra interesting to visit Germany. Germany is also one of the few countries in which porous cement concrete has been studied successfully, albeit not yet with full success.
Japan	Japan has a tremendous network of porous asphalt concrete, mostly of the single type, but also several sections having the double type of porous asphalt. Recently, such surfaces have been applied very extensively in central urban districts. Japan is also the country that took over the development of the poroelastic surface and for the last decade has made substantial development efforts including several field studies.
The Netherlands	The world's most comprehensive research program ever in the noise area (IPG) is taking place in the Netherlands, with a budget of around 54 million Euros (time period 2004-2007). The most prominent feature of the IPG project is the refinement of the double-layer porous asphalt surfacing. Experiments with futuristic solutions are also being made; for example with prefabricated rolls of asphalt to be applied on roads with a minimum of traffic interruption. The Dutch highway network is already covered at an extent of more than 70 % with porous asphalt and the target is 100 %. A great number of experiments with double-layer porous asphalt surfaces are ongoing, presently 100 km of roads.

The suggested countries or states thus together cover the most promising solutions for noise reduction by road surface measures. Nothing of serious interest will be missed. The selection was also intended to optimize/minimize the length of travels and time consumption needed.

AIII-6 OVERVIEW OF THE TOURS

The following is an outline of the study tours with its three parts (the year was 2007):

First tour: Europe	
17 April	*Flight from Hong Kong to Amsterdam*
18-22 April	**Visit to the Netherlands**
22 April	*Train or flight from Amsterdam to Cologne*
23-25 April	**Visit to Germany**
25 April	*Flight from Cologne to Copenhagen*
26-27 April	**Visit to Denmark**
28-29 April	*Flight from Copenhagen to Hong Kong*

Second and third tours: USA and Japan	
8 May	*Flight from Hong Kong to Los Angeles*
9-12 May	**Visit to California and Arizona**
13-14 May	*Flights Los Angeles to Hong Kong and Hong Kong to Tokyo*
15-19 May	**Visit to Japan**
19 May	*Flight from Tokyo to Hong Kong (Saturday)*

It was recommended that both the EPD and the HyD officials visit all places. The reason is that it would make it possible to compare all low-noise solutions without individual bias, always exposing them to the same critical review, utilizing the full competences of all participants. However, for various reasons, the visitors from Hong Kong were different on the different tours. It was only this author who visited all the places.

Fig. III-1. Illustration of the study tours.

AIII-7 CONCLUSIONS

It was concluded by this author that several of the paving technologies studied should be applicable in and/or adoptable to Hong Kong conditions. This is, in particular, the case for three types of surfaces; namely single-layer porous asphalt of German and Japanese design, thin layers of Danish and Dutch design and asphalt rubber of the Arizona design principles. Further, for the "noisy" cement concrete surfaces still in wide use in Hong Kong, the grinding technique studied in Arizona may be a low-cost solution; especially in cases where horizontal forces in the tyre/road interface (such as sharp curves, steep inclinations and busy intersections) may make the use of the asphalt solutions too weak.