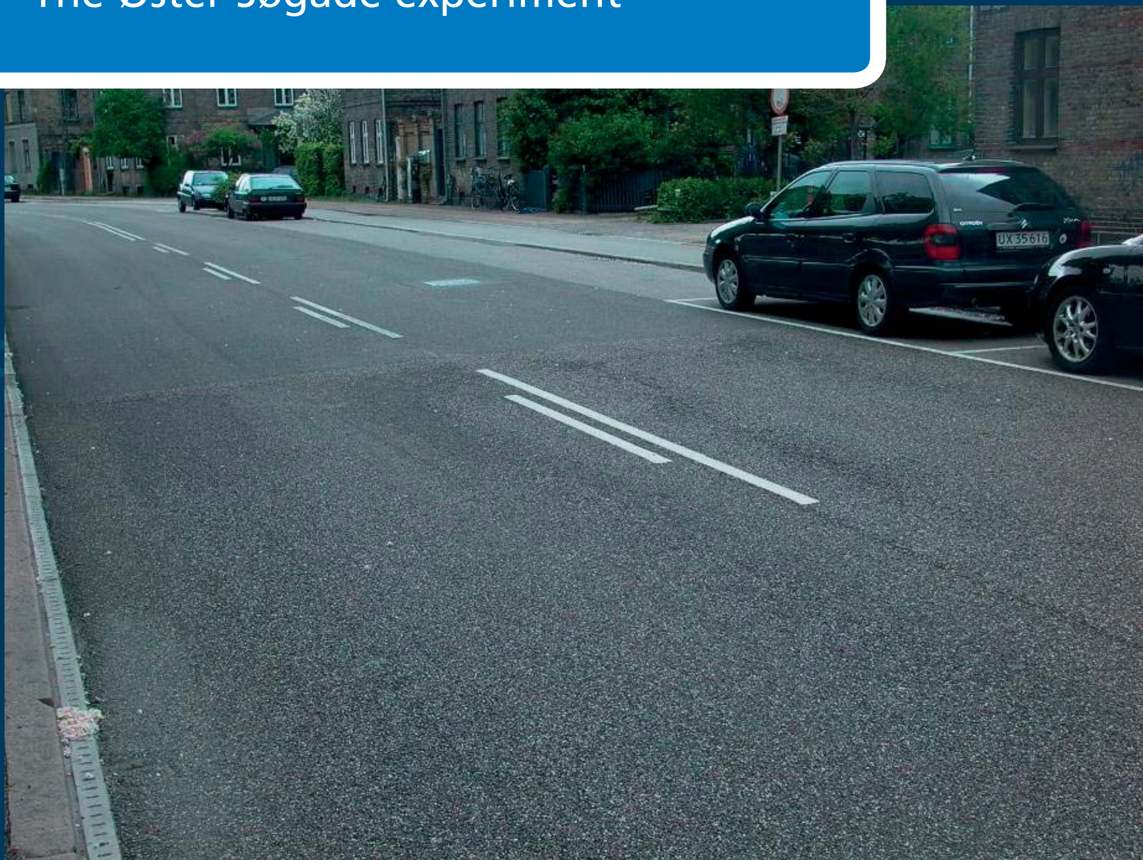
Two-layer porous asphalt – lifecycle

- The Øster Søgade experiment



Danish Road Institute
Report 165
2008

Road Directorate
Ministry of Transport and Energy

Road Directorate
Guldalderen 12
DK-2640 Hedehusene
Denmark

Telephone +45 7244 7000
Telefax +45 7244 7105
Roadinstitute.dk

Title	Two-layer porous asphalt – lifecycle - The Øster Søgade experiment
Dated	December 2008
Authors	Lars Ellebjerg, Hans Bendtsen
Published by	Road Directorate, Danish Road Institute

Photo	Hans Bendtsen, Jørn Raaberg, Lars Ellebjerg
Print	Electronic
ISBN electronic	978-87-92094-45-2

Reports published by the Danish Road Directorate
can be requested from the bookshop:
Telephone +45 4322 7300
Telefax +45 4363 1969
e-mail schultz@schultz.dk

Two-layer porous asphalt – lifecycle

- The Øster Søgade experiment

Lars Ellebjerg
Hans Bendtsen

Danish Road Institute
Report 165
2008

Road Directorate
Ministry of Transport and Energy

Contents

Summary

There is a need for cost effective tools to reduce road traffic noise in urban areas. This was the background for starting the "Øster Søgade Experiment" in 1998 with the objective to develop and optimize the noise reducing capacity of two-layer porous pavements and to perform full scale testing on an urban road. Øster Søgade in Copenhagen was selected for the experiment. The pavement optimization was performed on the background of – at the time – new Dutch experiences and in cooperation with Dutch experts. This report presents the results of 9 years of comprehensive measurements from before the test pavements were built in 1999 until the top layers were worn down in 2007.

Three types of two-layer porous pavements – denoted PA5-55, PA5-90 and PA8-70 – have been tested on an urban road with a speed limit of 50 km/h. Annual measurements including noise, permeability, texture (MPD - Mean Profile Depth) and air voids have been performed from the pavements were new in 1999 and until 2007. The pavements have been high pressure cleaned twice a year. High noise reductions of 4.5 to 6.0 dB – relative to a dense asphalt concrete reference pavement with 8 mm maximum aggregate size of the same age – were achieved from mixed traffic when the pavements were new.

Noise reduction

The noise reduction was mainly due to the following three factors:

1. Noise in the medium frequency range generated from vibrations in the tire was reduced by using small maximum aggregate size of 5 mm (PA5-55 and PA5-90) and 8 mm (PA8-70) in the top layer. The frequency spectra indicate reduced vibration generated noise when the pavements were new. As they age raveling occurs, first on the two PA5 pavements. These two pavements were sealed in 2005. This stopped the raveling process. Significant raveling was first observed on the PA8-70 pavement in 2007.
2. The high frequency aerodynamic noise was reduced by using high percentages built-in air voids of 23.7 to 26.6 percent to create high porosity in the pavements. When the pavements were new, there were high reductions of noise at frequencies above 1 kHz. The pores started to clog in the upper part of the top layer, which resulted in increasing high frequency noise. The PA8-70 pavement maintained the highest noise reducing capacity as the pavements aged.
3. The noise absorbing capacity of the pavements was optimized by the high percentage built-in air voids combined with thick pavement layers with communicating pores. High noise absorption was seen as noise level dips at frequencies between 400 and 800 Hz when the pavements were new. After two years these dips disappeared because of clogging of the upper part of the top layers. This "closed off" the connection to the porous structure in the pavements.

Surface characteristics

The MPD-results of the laser measurements indicate that raveling occurs and that the pavements turn rougher and thereby noisier as they age. There is a strong correlation between MPD and noise levels on the individual test pavements.

The Becker's tube measurements of permeability show that the PA8-70 pavement retains its permeability longer than the two PA5 pavements, which clog up after 3-4 years. At this time the noise reducing effect compared to the reference pavement is close to only 1 dB. The PA5 pavements do not appear to be suitable on urban roads as means of noise reduction unless a different cleaning strategy can produce better results at maintaining their porosity and thereby their acoustical lifetime.

On the PA8-70 pavement the correlation between permeability and noise emissions is quite high. There is also a fair correlation for the PA5-90 pavement, whereas it is poor for the PA5-55 pavement. A regression with permeability and MPD as independent variable for predicting L_{vehP} produces a model with a fair ability to predict noise levels, but there appears to still be one or more parameters, which influence the noise, which are not accounted for in the data.

On both PA5 and PA8 pavements the clogging starts where vehicles drive onto the porous pavements from dense pavements. This indicates that at least part of the clogging is due to material, which is dragged onto the porous pavements by vehicles. Thus, it is likely that longer sections of porous pavements will maintain their porosity and thereby their noise reducing effect longer than the short test sections in this project.

Although the Becker's tube method for measuring permeability gives clear results on the degree of clogging of the pavements, it should be considered whether a measure of clogging which is based on air flow will produce results that better reproduce the ability of the pavements to reduce aerodynamic noise.

It is clear from the CT-scans and the thin and plane sections of drilled cores that the clogging takes place in upper parts of the top layers. The bottom layers appear to maintain their porosity and thereby the ability to lead away water and dirt to the roadside. It is therefore possible that better cleaning strategies may be better at maintaining the permeability and thereby also the noise reducing effect of the porous pavements.

Bitumen tests show hardening of the binder in the porous pavements. In the thin and plane sections this can be seen to have lead to deterioration of the pavements with adhesion problems and cracks in the binder as the pavements age. This, together with some crushing of the aggregate, has lead to extensive raveling on the PA5 pavements after 5 years, which necessitated sealing of the pavements. This was not considered necessary for the porous pavement with 8 mm aggregate.

Hypotheses

The following seven hypotheses regarding the functionality of the porous test pavements were defined when the project was started:

1. *New two-layer porous pavements have high noise reducing capacities on urban roads compared to dense asphalt concrete.* Noise levels at the new porous pavements were between 4.5 dB and 6.0 dB lower than those at the reference pavement for mixed traffic and 4.6 to 6.5 dB lower for passenger cars. Thus, this hypothesis accepted as true.
2. *The two-layer porous pavement with the smallest aggregate size has the best noise reduction.* When the pavements were new, this was certainly the case, but seen over the whole test period the PA8-70 pavement has the highest noise reducing capacity with an average noise reduction over the eight year period of 2.7 dB for mixed traffic compared to 2.0 and 2.2 dB for the two PA5 pavements. Thus, this hypothesis is rejected. It may be true, if a cleaning strategy can be found, which can maintain the porosity of the PA5 pavements.
3. *The thickest of the two-layer porous pavements has the best noise reduction.* This was certainly true, when the pavements were new, but already after one year and throughout the remaining test period the PA5-90 pavement is the least noise reducing of the three porous pavements.
4. *Using yearly high pressure cleaning of the pavements will maintain their porosity and high acoustical absorption and for these reasons they will keep their high noise reducing capacities in their entire lifetime on urban roads.* As there are no test sections to compare with, which were not cleaned, it cannot be concluded whether the cleaning has had an effect on the clogging, but the full porosity and noise reducing capacities were not maintained throughout the test period. Therefore this hypothesis is rejected.
5. *Roads in urban areas with fine graded porous pavements have the same traffic safety quality (same risk levels) as ordinary roads.* This matter has not been treated in this report, but based on observations by the project group and on Greibe (2000), Greibe (2002) and Bendtsen, Larsen & Greibe (2002) this hypothesis is accepted as true.
6. *There are no special problems with winter maintenance connected to using fine graded porous pavements in urban areas.* This has not been treated in this report. Winter maintenance on Øster Søgade has been no different than on similar roads in Copenhagen, and the municipality has observed no special problems on the road. Thus, this hypothesis is accepted as true for this project.
7. *The lifetime of two-layer porous pavements is the same as that of ordinary dense pavements on urban roads.* As the top layers of the test pavements had to be sealed after six years and renewed after eight years due to serious raveling, this hypothesis is rejected.

Continuation

In June 2007, the top layers of the worn down pavements were milled off and replaced by new porous top layers with 8 mm maximum aggregate size. It is an objective to continue a measurement program on the new top layers.

Sammenfatning

Der er behov for omkostningseffektive virkemidler til at reducere vejstøj i byområder. Det var baggrunden for i 1998 at starte Øster Søgade-forsøget med det formål at udvikle og optimere støjreducerende tolags drænasfalt og udføre et fuldskala forsøg på en bygade. Øster Søgade i København blev valgt til forsøget. Belægningsoptimeringen blev udført på basis af – på dette tidspunkt – nye hollandske erfaringer i samarbejde med hollandske eksperter. Denne rapport præsenterer resultaterne af 9 års målinger, fra før forsøgsstrækningerne blev udlagt i 1999, og indtil toplagene var nedslidte i 2007.

Tre typer tolags drænasfalt – betegnet PA5-55, PA5-90 og PA8-70 – er testet på en bygade med en hastighedsbegrænsning på 50 km/t. Årlige målinger, som inkluderer støj, permeabilitet, tekstur (MPD - Mean Profile Depth) og hulrum, er udført. Belægningerne er blevet højtryksrenset to gange om året. Høje støjreduktioner – mellem 4,5 og 6,0 dB i forhold til en tæt asfaltbetonbelægning af samme alder med 8 mm maksimal stenstørrelse blev opnået ved blandet trafik, da belægningerne var nye.

Støjreduktion

Støjreduktionen skyldtes hovedsageligt følgende tre faktorer:

1. Støj i mellemfrekvensområdet fra vibrationerne i dækkene blev nedsat ved at anvende små maksimale stenstørrelser på 5 mm (PA5-55 og PA5-90) og 8 mm (PA8-70) i toplagene. Frekvensspektre indikerer, at der var mindre vibrationsgeneret støj, da belægningerne var nye. Efterhånden som de bliver ældre opstår der rivninger, først på de to PA5-belægninger. Disse to belægninger blev forseglet i 2005, hvilket standsede rivningsprocessen. Betydelige rivninger blev først observeret på PA8-70-belægningen i 2007.
2. Den højfrekvente aerodynamiske støj blev reduceret ved at benytte høje indbyggede hulrumsprocenter på 23,7 til 26,6 til at skabe porøsitet i belægningerne. Da belægningerne var nye, var der stor støjreduktion ved frekvenser over 1 kHz. Porerne begyndte at stoppe til i den øverste del af toplaget, hvilket resulterede i stigende højfrekvent støj. PA8-70-belægningen bevarede den højeste støjreducerende kapacitet, efterhånden som belægningerne ældedes.
3. Belægningernes støjabsorberende evne blev optimeret ved den høje procentdel indbyggede hulrum kombineret med stor belægningstykkelse med sammenhængende porer. Høj støjabsorption ses som dyk i støjniveauerne ved frekvenser mellem 400 og 800 Hz, da belægningerne var nye. Efter to år forsvandt disse dyk på grund af tilstopning af det øverste af toplagene. Dette "lukkede" forbindelsen til porestrukturen i belægningen.

Overfladekarakteristika

MPD-resultaterne fra lasermålinger viser, at rivninger opstår, og at belægningerne bliver mere ujævne og dermed mere støjende, når de ældes. Der er tydelig sammenhæng mellem MPD og støjniveauer på de enkelte prøvestrækninger.

Permeabilitetsmålingerne med Becker's tube viser, at PA8-70-belægningen bevarer permeabiliteten længere end de to PA5-belægninger, som bliver tilstoppet efter 3-4 år. På dette tidspunkt er den støjreducerende virkning i forhold til referencebelægningen kun ca. 1 dB. PA5-belægningerne virker ikke egnede som middel til støjreduktion på bygader, med mindre en anden rensningsstrategi kan levere bedre resultater med opretholdelse af porøsiteten og dermed den akustiske levetid.

På PA8-70-belægningen er korrelationen mellem permeabilitet og støjemissioner høj. Der er også en rimelig korrelation for PA5-90-belægningen, mens den er dårlig for PA5-55-belægningen. En regression med permeabilitet og MPD som uafhængige variable til forudsigelse af L_{vehP} giver en model med en rimelig evne til at forudsige støjniveauet, men der er tilsyneladende stadig en eller flere parametre, der påvirker støj, som ikke er omfattet af undersøgelsens data.

På såvel PA5- som PA8-belægningerne starter tilstopningen der, hvor køretøjer kører ind på drænasfaltbelægningerne fra tætte belægninger. Dette tyder på, at i det mindste en del af tilstopningen skyldes materialer, som er ført ind på drænbelægningerne af køretøjer. Således er det sandsynligt, at længere strækninger med drænasfalt vil bevare porøsiteten og dermed den støjreducerende effekt længere end de korte prøvestrækninger i dette projekt.

Selvom Becker's tube metoden til måling af permeabilitet giver klare resultater for tilstopningsgraden af belægningerne, bør det overvejes, om en måling af tilstopning, der er baseret på luftstrømme, kan give resultater, som bedre gengiver belægningers evner til at nedsætte aerodynamiske støj.

Det fremgår af CT-scanninger og tynd- og planslibene af borekernerne, at tilstopningen finder sted øverst i toplagene. Det nederste lag ser ud til at bevare porøsiteten og dermed evnen til at bortlede vand og snavs til vejsiden. Det er derfor muligt, at andre rensningsstrategier kan være bedre til at vedligeholde permeabiliteten og dermed også den støjreducerende virkning af drænasfaltsbelægninger.

Bitumenundersøgelser viser en hærdning af bindemidlet i drænasfaltsbelægningerne. I tynd- og planslibene kan dette ses at have medført nedbrydninger af belægningerne med vedhæftningsproblemer og revner i bindemidlet efterhånden som belægningerne ældes. Dette, sammen med nogen knusning af stenene i belægningerne, har ført til omfattende rivninger efter 5 år på de to PA5-belægninger, hvilket nødvendiggjorde forsegling af disse. Det blev ikke anset for var nødvendigt at forsegle belægningen med 8 mm sten i toplaget.

Hypoteser

Følgende syv hypoteser vedrørende funktionaliteten af drænasfaltbelægninger blev defineret ved projektets start:

1. *Ny to-lags drænasfalt har en god støjreducerende effekt på bygader i forhold til tæt asfaltbeton.* Støjniveauerne på de nye drænasfaltbelægninger var mellem 4,5 dB og 6,0 dB lavere end på referencebelægningen for blandet trafik og 4,6 til 6,5 dB lavere for personbiler. Således er denne hypotese accepteret som værende sand.
2. *To-lags drænasfalt med den mindste stenstørrelse i det øverste lag har den bedste støjreducerende effekt.* Da belægningerne var nye, var dette tilfældet, men set over hele forsøgsperioden havde PA8-70-belægningen den højeste støjreducerende evne med en gennemsnitlig støjreduktion over otte år på 2,7 dB for blandet trafik i forhold til 2,0 og 2,2 dB for de to PA5-belægninger. Dette betyder, at denne hypotese er forkastet. Hypotesen kan være korrekt, hvis en rensningsstrategi kan findes, som kan opretholde porøsiteten i PA5-belægningerne.
3. *Den tykkeste to-lags drænasfalt har den bedste støjreducerende effekt.* Det var rigtigt, da belægningerne var nye, men allerede efter et år og i hele den resterende prøvningsperiode, havde PA5-90-belægningen den mindste støjreduktion af de tre drænasfaltbelægninger.
4. *To gange årlig rensning af drænasfalten med højtryksspuling vil sikre, at belægningerne bevarer deres åbne porestruktur og høje akustiske absorption, således at belægningerne vil bevare deres støjreducerende effekt gennem hele deres levetid.*. Da der ikke findes nogen prøvestrækninger at sammenligne med, som ikke er blevet renset, kan det ikke konkluderes, at rensning har haft en indvirkning på tilstopningen, men den fulde porøsitet og støjreducerende evne blev ikke opretholdt i hele prøvningsperioden. Derfor er denne hypotese forkastet.
5. *Bygader med finkornet drænasfalt har samme trafiksikkerhedsmæssige niveau (risikoniveau) som tætte belægninger.* Dette spørgsmål er ikke blevet behandlet i denne rapport, men baseret på observationer fra projektgruppen og på Greibe (2000), Greibe (2002) og Bendtsen, Larsen & Greibe (2002;) kan den accepteres som sand.
6. *Der er ikke nogen specielle problemer med vintervedligeholdelse af belægninger med finkornet drænasfalt i byområder.* Dette har ikke været behandlet i denne rapport. Vintervedligeholdelse på Øster Søgade er ikke anderledes end på lignende veje i København, og kommunen har ikke bemærket nogen særlige problemer på vejen. Således er denne hypotese accepteret som sand for dette projekt.
7. *Levetiden for to-lags drænasfalt er den samme som for almindelige tætte belægninger på bygader.* Da de øverste lag af forsøgsstrækningerne måtte forsegles efter seks år og fornyes efter otte år på grund af alvorlige rivninger, er denne hypotese forkastet.

Fortsættelse

I juni 2007 blev øverste lag af de slidte belægning fjernet og erstattet af et nyt lag drænasfalt med 8 mm maksimal stenstørrelse. Det er målsætningen at fortsætte måleprogrammet på de nye lag.

Preface

There is a need for cost effective tools to reduce road traffic noise in urban areas. This was the background for starting the "Øster Søgade Experiment" in 1998 with the objective to develop and optimize the noise reducing capacity of two-layer porous pavements and to perform full scale testing on an urban road. Øster Søgade in Copenhagen was selected for the experiment. The pavement optimization was performed on the background of – at the time – new Dutch experiences and in cooperation with Dutch experts. This report presents the results of 9 years of comprehensive measurements from before the test pavements were built in 1999 until they were worn down in 2007.

A project group was established in 1998 to conduct the experiment with members from the Danish Road Directorate (the Danish Road Institute and the Road Project Planning Department), the Danish Environmental Protection Agency, the Municipality of Copenhagen, the consulting company Delta and Asfaltindustrien (the Danish asphalt pavement association) represented by NCC Roads A/S Danmark. For some periods also the Danish Transport Research Institute and Atkins Danmark A/S have been active in the project group. Over the ten year period the following experts have been members of the project group:

- Michael Rasmussen
- Hans Dahl Petersen
- Steen Kønigsfeldt
- Jørn Bank Andersen
- Hugo Lyse Nielsen
- Jørgen Horstmann
- Poul Greibe
- Lene Michelsen
- Jørn Raaberg
- Bjarne Schmidt
- Bent Andersen
- Jørgen Kragh
- Lars Ellebjerg
- Hans Bendtsen

A series of engineers and technicians from the participating organizations have performed important measurements and laboratory analyses.

In the first years the project was financed by the Ministry of Transport. Over the years the Øster Søgade experiment has been included in other projects such as the EU projects SILVIA and SILENCE as well as the "DRI-DWW noise abatement program". These other projects as well as the organizations participating in the project group have taken part in financing the project over a ten year period.

Without the willingness to support the project it would not have been possibly to continue the measurements over a nine year period.

International colleagues have given valuable contributions to the project with advice and comments. These are among others the Dutch experts Gebert van Bochove from Heijmans, Jos Heerkens from Heijmans Infra and Gijsjan van Blokland from M+P as well as Ulf Sandberg from VTI (Swedish National Road and Transport Research Institute). The authors would like to warmly thank everybody who has contributed actively and enthusiastically to the success of the "Øster Søgade Experiment".

In June 2007 the top layers of the worn down pavements were milled off and a new porous top layer with 8 mm maximum aggregate size was applied. It is an objective to continue the measurement program on the new top layer in the coming years.

Hans Bendtsen
Project leader
Road Directorate/Danish Road Institute

Forord

Der er et behov for omkostningseffektive værktøjer til nedsættelse af vejtrafikstøj i byområder. Dette var baggrunden for at starte "Øster Søgade forsøget" i 1998 med det formål at udvikle og optimere den støjreducerende effekt af to-lags drænasfalt og udføre et fuldskalaforsøg på en bygade. Øster Søgade i København blev udpeget til forsøget. Belægningsoptimeringen blev udført på basis af – på dette tidspunkt – nye hollandske erfaringer i samarbejde med hollandske eksperter. Denne rapport præsenterer resultaterne af 9 års målinger fra før forsøgsstrækningerne blev udlagt i 1999 og indtil de var nedslidte i 2007.

En projektgruppe blev nedsat i 1998 for at udføre forsøget med medlemmer fra Vejdirektoratet (Vejteknisk Institut og Planlægningsafdelingen), Miljøstyrelsen, Københavns Kommune, Delta Lys og Akustik samt Asfaltindustrien, repræsenteret af NCC Roads A/S Danmark. I perioder har Danmarks TranportForskning (i dag DTU Transport) og Atkins Danmark A/S desuden deltaget i projektet. I den ti-årige periode har følgende eksperter være medlemmer af projektgruppen:

- Michael Rasmussen
- Hans Dahl Petersen
- Steen Kønigsfeldt
- Jørn Bank Andersen
- Hugo Lyse Nielsen
- Jørgen Horstmann
- Poul Greibe
- Lene Michelsen
- Jørn Raaberg
- Bjarne Schmidt
- Bent Andersen
- Jørgen Kragh
- Lars Ellebjerg
- Hans Bendtsen

En gruppe ingeniører og teknikere fra de deltagende organisationer har udført vigtige målinger og laboratorieanalyser.

I de første år blev projektet finansieret af Trafikministeriet. I løbet af årene har Øster Søgade-forsøget været en del af andre projekter, såsom EU-projekterne SILVIA og SILENCE samt "DRI-DWW noise abatement program". Disse forskningsprojekter samt deltagerne i projektgruppen har bidraget til finansieringen af projektet i løbet af den tiårige periode.

Uden disse bidrag til at finansiere projektet ville det ikke have været muligt at fortsætte målingerne gennem ni år.

Internationale kolleger har bidraget til projektet med råd og kommentarer. Blandt disse er de hollandske eksperter Gerbert van Bochove fra Heijmans, Jos Heerkens fra Heijmans Infra og Gijsjan van Blokland fra M+P samt Ulf Sandberg fra VTI i Sverige. Forfatterne takker alle, som har bidraget aktivt og entusiastisk til gennemførelsen af Øster Søgade-forsøget.

I juni 2007 blev toplagene af de slidte belægninger fræset af og erstattet med et nyt toplag med 8 mm maksimal stenstørrelse. Det er målet at fortsætte måleprogrammet på det nye toplag i de kommende år.

Hans Bendtsen
Projektleder
Vejdirktoratet/Vejteknisk Institut

1. Introduction

In Denmark, as in other countries, there are tremendous problems with noise from road traffic. The majority of the 150,000 dwellings, which are subjected to noise levels exceeding 65 dB[1] $L_{Aeq, 24h}$ are located in urban areas, where noise reducing pavements are effective as means of noise abatement. Calculations carried out in 1998 in preparation of a policy on traffic noise indicate that such pavements are cost-effective when compared with other means of noise abatement such as noise barriers and facade insulation (Ministry of Transport & Environmental Protection Agency 1998).

In 1998 however, no pavements in Denmark had been proven to be effective for reducing noise on urban roads. In the early 1990s a test of one-layer porous asphalt was carried out on Østerbrogade, a 50 km/h street in Copenhagen (Bendtsen 1996). When new, the porous pavement had a noise reducing effect of 3 dB compared with a dense asphalt concrete. After two years the noise reduction was gone, presumably because the pores of the asphalt were clogged.

A similar test of one-layer porous asphalt was carried out on a highway with a speed of 80 km/h (Bendtsen 1996; Bendtsen 1998a). Annual noise measurements showed a 3 dB noise reduction throughout the lifetime of the pavement. The pavement was believed to be self-cleaning due to the speed of the traffic.

In the 1990s the Dutch road authorities set up an aim to use porous pavements on the entire motorway network. The intention was both to reduce noise and to improve traffic handling and increase road capacity in wet conditions. Usually one-layer porous pavements are used on motorways.

During the 1990s, the Dutch developed second and third generation of porous pavements, which can be used on urban roads. The idea is to combine two-layer porous pavements with high pressure cleaning and vacuum suction of water and dirt in order to prevent clogging off the pores in the pavement. The top layer of the pavement is made with small aggregate to secure an even surface and thereby a low noise level. The bottom layer is made with larger stones to secure that water and dirt which enters the pavement can run off to the roadside. This helps to reduce clogging of the pores in the pavement.

In December 1997 a Danish study tour to the Netherlands was conducted in order to collect the newest knowledge on the subject (Bendtsen 1998b). In the city of Breda a second-generation porous pavement – a two-layer pavement with a maximum aggregate size of 8 mm in the top layer – had been laid out on a street with a speed limit of 50 km/h. Four years after being laid the pavement still had a noise reducing effect of three dB. At the time, this type of payment had been used on 35-50 km of urban roads. Tests of third-generation porous pavements had just started.

---

[1] In this report dB always refers to dB(A), unless otherwise stated.

These are also two-layer pavements, but with a maximum aggregate size of 4 mm in the top layer. This gives a very even surface, which reduces rolling noise. At the time, the pavements were less than one year old and reduced noise by 6 dB.

On this basis the Danish Ministry of Transport launched a research project with the aim to develop and test noise reducing pavements for urban roads based on the newest Dutch technology. The project is necessary because it may not be possible to transfer Dutch experiences directly to Danish traffic, weather and road maintenance conditions. It is also an objective to try to further develop the pavement concepts. Furthermore the project aimed at a knowledge transfer from the Netherlands to Danish pavement companies.

In 1999 Øster Søgade in Copenhagen was paved with three different two-layer porous pavements and a reference pavement (dense asphalt concrete). Since then an extensive measuring program has been carried out, including various measures of noise and surface characteristics.

Due to serious raveling, the top layers of two of the three porous test pavements were sealed with a bitumen emulsion in September 2005. In 2007 all three top layers have been milled of and replaced by a new layer (Bendtsen & Kragh 2007). This report tells the story of the Øster Søgade experiment up to the point of the change of the top layer.

Hypotheses

At the start of the project the following seven hypotheses were formulated (Bendtsen 1999b):

1. New two-layer porous asphalt has a high noise reducing capacity on urban roads as compared to dense asphalt concrete.
2. The two-layer porous asphalt with the smallest aggregate size has the best noise reduction.
3. The thickest of the two-layer porous asphalt has the best noise reduction.
4. Using yearly high pressure cleaning of the pavements will keep their porosity and high acoustical absorption and for these reasons they will keep their high noise reducing capacity in their entire lifetime on urban roads.
5. Roads in urban areas with fine graded porous pavements have the same traffic safety quality (same risk levels) as ordinary pavements.
6. There are no special problems with winter maintenance connected to using fine graded porous asphalts in urban areas.
7. The lifetime of such pavements is the same as that of ordinary dense pavements on urban roads.

The basis for these hypotheses is mainly the previous Danish and Dutch experience on porous pavements, but also other international experience was taken into consideration.

Measuring program

At the start of the project an extensive interdisciplinary measuring program was set up. The program contains the following measurements:

Noise:

- along the road using the SPB method (ISO 11819-1 1997) and the CPX method (ISO 11819-2 2000)
- the noise absorbing characteristics of the pavements
- inside cars (ISO 5128 1980)

Pavement characteristics:

- surface texture
- built-in air voids
- permeability

Traffic safety:

- speed
- distance between vehicles
- friction

Other:

- questionnaire survey of the noise annoyance of those living along the road
- the cost-benefit evaluation of using two-layer porous asphalt

In addition to these surveys the winter condition and maintenance has been watched.

Previous publications and related projects

Preliminary results from this project were published in Danish in Bendtsen, Larsen & Greibe (2002). Please refer to this report for results of other noise measurements than SPB, traffic safety results and results on annoyance and cost-benefit. Results on annoyance and cost-benefit have been published in English by Larsen & Bendtsen (2001a), Larsen & Bendtsen (2001b) and Larsen & Bendtsen (2002). Results on traffic safety have been published in English by Greibe (2002).

Some results presented in this report have previously been published as part of the EU framework projects SILVIA and SILENCE, and within the joint Dutch-Danish Noise Abatement Program, which is part of the Dutch Innovation Programme on noise mitigation, IPG.

This project is the first major Danish test of noise reducing pavements for urban roads. Since the start of this project in 1999 further projects have been launched focused on testing thin layer asphalt pavements (Bendtsen & Nielsen 2008; Thomsen, Andersen & Bendtsen 2006; Thomsen, Bendtsen & Andersen 2008).

The contents of this report

The report begins with a presentation of the test pavements in Chapter 2. In Chapter 3 the road is described on which the test is carried out. Chapter 4 presents results of the pavement measurements which have been carried out within the project, and results of the acoustical measurements are presented in Chapter 5. Chapter 6 contains statistical analyses of pavement and acoustical measurements together, and Chapter 7 sums up the results from the previous chapters.

2. Design and optimization of test pavements

It is an objective of this project to develop pavements, which are noise reducing throughout their entire lifetime. Reduction of tire/road noise may be done through working with the mechanisms generating noise – vibrations and air displacement – and with those working to amplify or reduce the noise – the horn and acoustical impedance effects.[2] The physical characteristics of the pavements, which influence these mechanisms, are:

- surface texture,
- built-in voids of a porous pavement,
- thickness of a porous pavement, and
- elasticity.

The surface texture is of importance to the generation of vibrations. The smoother the surface, the less vibrations are generated in the tire on impact as it rolls on the road surface, and thus less noise is generated. Greater elasticity of the pavement has similar effects, but this is not of relevance to this project, where the elasticity is not included as a parameter to work with.

Built-in voids and the thickness of a porous pavement both influence the noise generated by the air displacement mechanisms. The higher the percentage of voids and the thicker the pavement is, the greater is its ability to reduce noise from air displacement, because the air can flow in and out of the porous pavement in addition to being displaced towards the surroundings.

The horn effect describes the amplification of the emitted noise, which is caused by the shape of an exponential horn formed by the tire and the pavement in front of and behind the tire. On a porous pavement one side of the "horn" is perforated, thus reducing the amplification. The acoustical impedance of a porous pavement is the sound absorbing property of the pavement allowing sound waves to be absorbed instead of being reflected on to the surroundings. Both the horn effect and the acoustic impedance increase with increasing percentage built-in voids and increasing thickness of the porous pavements.

Based on the previous Danish and international experiences with noise reducing pavements (see Chapter 1), it is therefore the aim in this project to develop pavements with a high percentage of built-in voids and a smooth surface combined with a high mechanical durability and lasting sound absorbing qualities. The latter is achieved through a design, which allows the pores in the pavement to be cleaned.

---

[2] Sandberg & Ejsmond (Sandberg & Ejsmont 2002) gives a more thorough description of these mechanisms.

As described in Chapter 1, previous Danish experiments with one-layer porous pavements on urban roads resulted in the pavements clogging up after the first years. The idea with two-layer porous pavements is that the pores can be kept open partly through self-cleaning by rainwater leading away dust and dirt in the bottom layer, and partly through high pressure washing and vacuum suction. The porous pavements on Øster Søgade are cleaned twice a year.

The water which is lead away down in the pavement follows the sideways slope of the road. On roads without curbstones this water can run off into a ditch, but on urban roads such as Øster Søgade drainage pipes are necessary to lead the water to the gully. On Øster Søgade Dutch Keradrain pipes are located between the asphalt and the curb. Ceramic Keradrain were used when the test sections were constructed, but due to durability problems they were replaced with similar pipes made of concrete after two years (see Section 2.6). Figure 2.1 presents the principle of the system and Figure 2.2 shows the result on Øster Søgade.

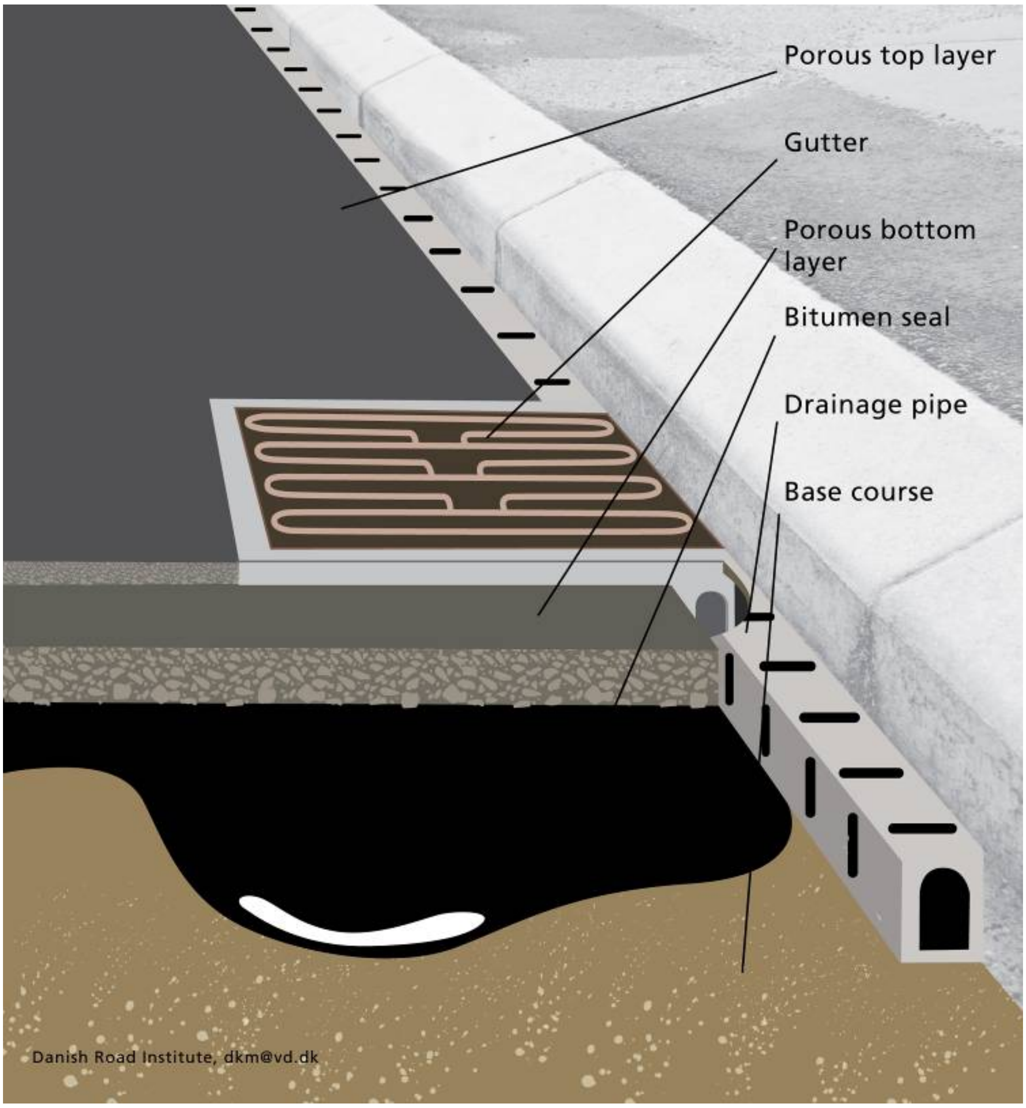


Figure 2.1. Schematic diagram of the drainage system for a two-layer porous pavement on an urban road.

Figure 2.2. The drainage system on Øster Søgade. The ceramic pipes were later replaced with concrete pipes.

2.1 The test pavements

In order to test a variety of solutions, three different porous pavements and one reference pavement were chosen for the project. The reference pavement is included to make sure that the reference is the same age and carries the same traffic as the test pavements. The three porous pavements are all two-layer pavements with 22 to 27 percent built-in voids. The pavements are between 55 and 90 mm thick, and the top layers are made up of 5 or 8 mm aggregate. Figure 2.3 illustrates the principle of a two-layer porous pavement, and Table 2.1 gives an overview of the layer thickness and aggregate size of each pavement.

Table 2.1. The pavements on the Øster Søgade test section.

Pavement name	Type of Asphalt	Total thickness	Top layer		Bottom layer	
			Thickness	Aggregate	Thickness	Aggregate
PA8-70	Porous	70 mm	25 mm	5/8 mm	45 mm	11/16 mm
PA5-55	Porous	55 mm	20 mm	2/5 mm	35 mm	11/16 mm
PA5-90	Porous	90 mm	25 mm	2/5 mm	65 mm	16/22 mm
DAC8 (reference)	Dense	30 mm	30 mm	0/8 mm	–	–

Dutch two-layer porous pavements are usually based on 4 or 8 mm aggregate. The choice of 5 mm aggregate on Øster Søgade is made because this aggregate size is standard in Denmark. The sieve size used for the 5 mm aggregate is actually 5.6 mm.

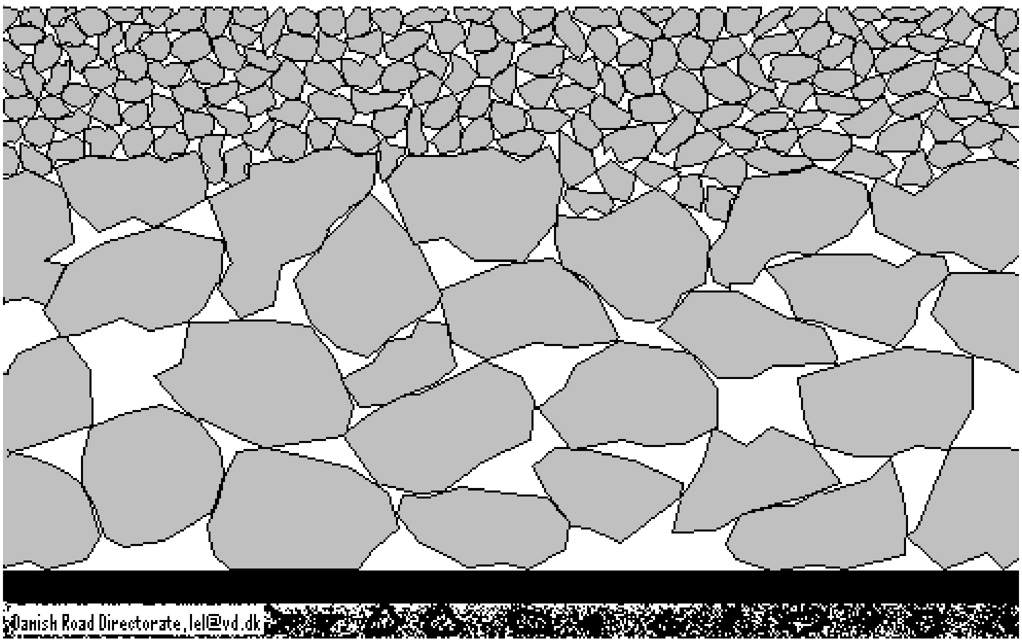


Figure 2.3. Principles of layout of two-layer porous pavements. The top layer is made with small aggregate in order to produce a smooth surface and prevent stones and large dirt from entering the pavement. The bottom layer is made with larger aggregate to allow water to lead dirt and dust to a drainage system. At the bottom is the base course, sealed with a bitumen seal to prevent water from entering the base course.

2.1.1 PA8-70

PA8-70 is a 70 mm thick pavement with 5 to 8 mm aggregate in the top layer. In the bottom layer 11 to 16 mm aggregate are used to secure large voids. The top layer is 25 mm thick. The bottom layer is 45 mm. These layer thicknesses are chosen so that they are approximately three times the aggregate size. This is normal procedure for asphalt pavements, as it secures each layer good stability and bearing capacity.

The test of a pavement with 8 mm aggregate is chosen because pavements with this aggregate size have performed well in previous Danish tests of noise reducing porous pavements.

2.1.2 PA5-55

The aim with the PA5-55 pavement is to design as thin a two-layer porous asphalt pavement as possible. Thin pavements are of interest, as the total pavement thickness may be of importance on many urban locations where the curbstone height is limited.

The bottom layer consists of aggregate with sizes between 11 and 16 mm. The layer is only 35 mm thick, which is less than three times the aggregate size. The top layer, which consists of aggregate sized between 2 and 5 mm, is 20 mm thick. This is more than three times the aggregate size. This is because it was assessed that three times the aggregate size would be too little to achieve stability, when the top layer was to be laid on the fairly coarse bottom layer.

2.1.3 PA5-90

With the 90 mm thick PA5-90 pavement the aim is to optimize the noise reduction of the two-layer porous asphalt pavement. Such a pavement had not previously been tested. To increase the thickness, 16 to 22 mm aggregate are used in the bottom layer, which is 65 mm thick. To achieve a stable top layer of 2-5 mm aggregate on this coarse bottom layer, it was decided to make the top layer 25 mm thick.

2.1.4 Reference (DAC8)

As a reference pavement is used a 30 mm thick dense asphalt concrete with maximum aggregate size of 8 mm. The surface structure of this pavement is comparable to that of many other dense asphalt pavements used on urban roads.

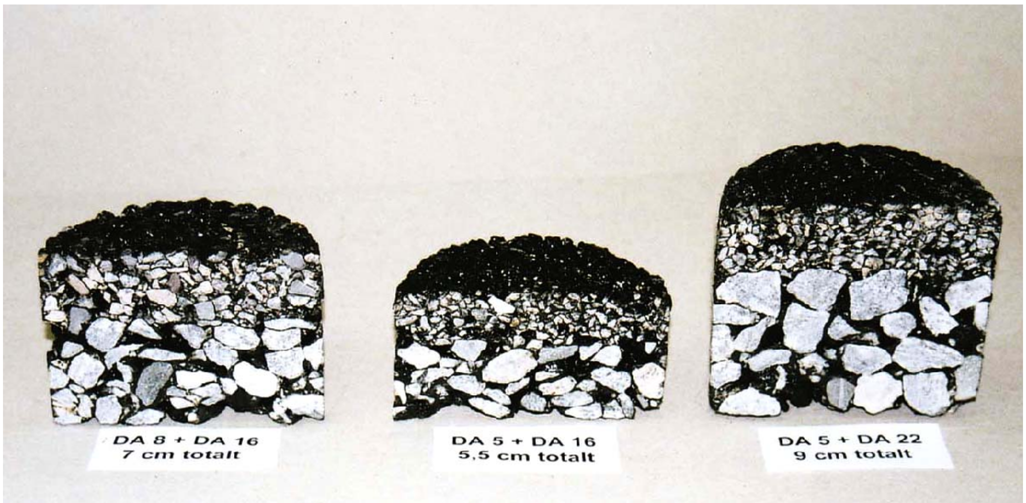


Figure 2.4. Drill-cores from the three test pavements taken right after the laying of the pavements.

2.1.5 Pavement composition

Before the pavements were laid, Marshall specimens were made for laboratory testing. Crushed rock aggregate is used for the test pavements. The distribution of these on size is shown in Table 2.2 and Figure 2.5. PA5 and PA8 represent the top layers and PA16 and PA22 represent the bottom layers. The very steep grain-size curves for the porous asphalt show the use of aggregate of one size, which secures the high percentage air voids and connected pores. The slope of the curve for the reference pavement is gentler as the stone material is more varied in size.

Table 2.2. Specifications of the stone material in the pavements presented in weight percentages (Phønix Asphalt Laboratory 1999a; Phønix Asphalt Laboratory 1999b; Phønix Asphalt Laboratory 1999c; Phønix Asphalt Laboratory 1999d; Phønix Asphalt Laboratory 1999e)

Material	**PA5 (top)**	**PA8 (top)**	**PA16 (bottom)**	**PA22 (bottom)**	**DAC8 (ref.)**
0/2 mm sand/stone powder					25.0 %
0/4 mm mixed rock aggregate					25.0 %
2/5 mm rock aggregate	100.0 %				18.0 %
5/8 mm rock aggregate		100.0 %			32.0 %
11/16 mm rock aggregate			100.0 %		
16/22 mm rock aggregate				100.0 %	

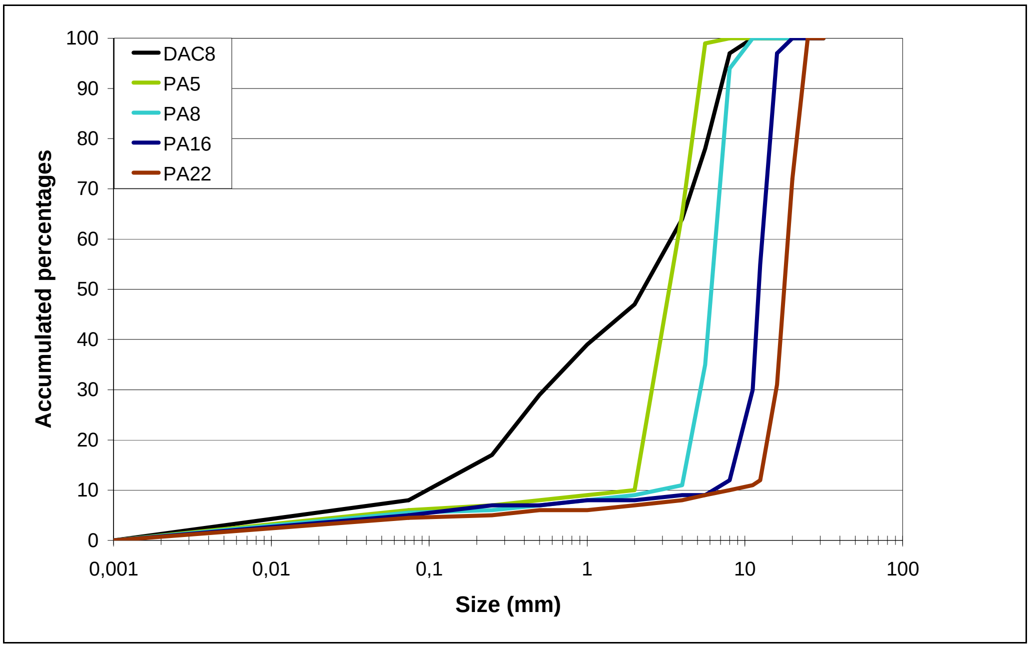


Figure 2.5. Grain-size curves for the test pavements (Phønix Asphalt Laboratory 1999a; Phønix Asphalt Laboratory 1999b; Phønix Asphalt Laboratory 1999c; Phønix Asphalt Laboratory 1999d; Phønix Asphalt Laboratory 1999e).

The materials used in the pavements are shown in Table 2.3. An admixture of light colored stones in the porous top layers is used to increase the reflection of light. A SBS-modified bitumen (Styren-Butadien-Styren) complying with the Danish voluntary sector standard for polymer-modified bitumen type 50/100-75 (S293 2001) is used for the porous pavements. 1.5 percent hydrated lime has been added to increase the viscosity of the filler-bitumen mixture and to utilize the increased adhesiveness, which the hydrated lime gives. Lime filler has also been added. 0.3 percent cellulose fibers have been added to keep the bitumen from running of the stone materials during storage and transport of the ready-mixed asphalt.

Due to the open structure with communicating pores, the bitumen in the porous pavements will oxidize and harden faster than in other types of pavements. The hydrated lime and cellulose fibers ensure that the stone material is surrounded with thick membranes of bitumen-filler.[3] This should counteract fast hardening, thereby increasing the lifetime of the pavement, and increase resistance to mechanical action on the pavement surface.

Table 2.3. The materials used in the test sections(Phønix Asphalt Laboratory 1999a; Phønix Asphalt Laboratory 1999b; Phønix Asphalt Laboratory 1999c; Phønix Asphalt Laboratory 1999d; Phønix Asphalt Laboratory 1999e)

Material	**PA5 (top)**	***PA8* (top)**	**PA16 (bottom)**	**PA22 (bottom**	**DAC8 (ref.)**
Stone material	95.0 %	95.5 %	97.0 %	97.5 %	97.5 %
Hydrated lime	1.5 %	1.5 %	1.5 %	1.5 %	1.5 %
Lime filler	3.5 %	3.0 %	1.5 %	1.0 %	1.0 %
Cellulose fibers (Karacell)	0.3 %	0.3 %	0.3 %	0.3 %	–
Bitumen	6.2 %	5.4 %	3.9 %	3.6 %	5.6 %
Marshall cavity	23.5 %	24.0 %	24.0 %	25.0 %	3.5 %

2.2 Acoustical test

Acoustical characteristics of the pavements were tested through measurements of sound absorption using an impedance tube and the transfer-function method (ISO 10534-2 1998). According to Dutch criteria, porous pavements should have the first absorption maximum in the frequency band between 500 and 800 Hz and the maximum value of the absorption coefficient should be greater than 0.85.[4] Tests were done on Marshall specimens before the pavements were laid. Afterwards tests were repeated on drilled cores from the road.

Tests were carried out on 3-6 Marshall specimens of each of the three pavement types. The results are shown in Table 2.4. The PA5-55 pavement complies with the Dutch criteria, whereas both the PA8-70 and the PA5-90 pavements have too low absorption coefficients. The coefficient for the PA5-90 also occurs at too low frequencies. Based on these results the recipes for the top layers were modified in order to increase the percentage built-in voids.

[3] Thin sections done on drilled cores from the porous pavements show that the cellulose fibers are well dispersed in the bitumen (see Section 4.6.2).

[4] Personal communication with Gijsjan van Blokland, M+P on December 16 1998.

Table 2.4. Frequency and absorption coefficient of the first absorption maximum for Marshall specimens of the three porous test pavements (DELTA 1999b).

	Frequency of the first maximum absorption	Value of first maximum absorption coefficient
PA8-70	500 Hz	0.78
PA5-55	630-800 Hz	0.87
PA5-90	315-400 Hz	0.71

3-6 drilled cores from each pavement were tested (Table 2.5). The PA8-70 pavement almost complies with the Dutch criteria, whereas the absorption coefficient for the PA5-55 pavement is too low. The PA5-90 pavement is even further from complying with the criteria than when tests were done on Marshall specimens. The thickness of the PA5-90 pavement is likely to be the reason for the low frequency of the first maximum absorption.

Table 2.5. Frequency and absorption coefficient of the first absorption maximum for cores drilled from the three porous test pavements (DELTA 1999a).

	Frequency of the first maximum absorption	Value of first maximum absorption coefficient
PA8-70	500-630 Hz	.84
PA5-55	500-630 Hz	.72
PA5-90	315 Hz	.54

2.3 Laying of the pavement

Figure 2.6. The porous asphalt mix was transported from the asphalt works to the site in special transporters to prevent the bitumen from running of the aggregate during transport.

During a study tour to the Netherlands in May 1999 the project group gathered practical experience with laying of two-layer porous asphalt (Bendtsen 1999). These experiences together with usual Danish practice founded the basis for the chosen laying procedures.

The test sections were laid in August 1999. In the previous months repair and replacement of pipes and cables in the road had been carried out. The whole road base was renewed with a bituminous base, as Øster Søgade was an old road with low bearing capacity. Along the curb a furrow was made in the base to make room for the Keradrain pipes. These were laid in cement and the joint between the pipes and the curb was sealed. To prevent water from entering the base, it was sealed before the porous asphalt was laid.

Figure 2.7. Keradrain pipes mounted in a furrow in the road base along the curb.

The two layers of porous asphalt were laid using a normal black top spreader. No adhesive was used between the bottom and top layers in order not to seal of the bottom layer. The top layer was spread the day after the bottom layer. The weather during the laying was sunny, 25°C and a light breeze. It is important that the top layer is laid as fast as possible after the bottom layer has cooled in order to prevent pollution and soiling between the two layers. Thus, traffic cannot be allowed to drive on the bottom layer. To avoid heavy machinery damaging the newly laid porous asphalt, these should be laid after all other works on bicycle paths and sidewalks are finished.

Figure 2.8. The large aggregate of a bottom layer laid right up to the Keradrain pipes. During the road works the pipes were sealed of with heavy duty adhesive tape on top to prevent dirt, stones and asphalt from entering the cavities.

Figure 2.9. Compaction along the Keradrain pipes using a small roller.

A seven-ton plain static roller was used for compaction. It is important not to use vibration or rubber rollers on porous asphalt as these may cause bitumen pumping leading to patches with too much bitumen and no porosity. The top layer was laid with the surface 10 mm higher than the top side of the Keradrain pipes to make sure that the pipes were not damaged during the compaction. A small roller was used for compaction next to the pipes.

Figure 2.10. Newly-laid bottom layer with 22-mm aggregate and top layer with 5-mm aggregate.

2.4 Data on the actual pavements

The built-in voids and the actual thickness of each of the two layers were measured from drilled cores of each pavement (Andersen 2001). The results are presented in Table 2.6. It is seen from the results that large built-in voids were achieved, especially in the top layers, where the percentage is between 24 and 27. The built-in voids in the top layers are comparable to those found in the laboratory tests of the Marshall specimens (see Table 2.3). For the bottom layers of the PA8-70 and PA5-90 pavements the void contents are 3-4 percent lower than in the Marshall specimens. Table 2.6 shows that the compactness of these two bottom layers is higher than 100 percent, which explains the lower void percentage. All void percentages are at or above 22, which was the minimum requirement set up.

Table 2.6. Built-in voids and compactness measured on drilled cores taken from the test sections shortly after these were laid in summer 1999 (Andersen 2001).

	Layer	Built-in voids (%)	Compaction degree (%)
PA8-70	PA8 (top)	26.5	99
	PA16 (bottom)	22.8	104
PA5-55	PA5 (top)	26.6	99
	PA16 (bottom)	25.2	100
PA5-90	PA5 (top)	23.7	102
	PA22 (bottom)	21.8	105
DAC8 (reference)		4.2	98

2.5 Cleaning of the pavement

Figure 2.11. The porous pavements are high-pressure cleaned with water and subsequent vacuum suction of water and dirt twice a year.

To avoid clogging of the pores, the porous pavements are cleaned twice annually using a cleaning vehicle washing with water at high pressure and subsequent vacuum suction of water and dirt (see Figure 2.11). The cleaning vehicle drives at a speed of only 2-3 km/h, and to secure a thorough cleaning the section is cleaned three times.

The cleaning is done at the end of winter in April and when leaf fall is over in late November or early December before winter sets in. This cleaning sequence is chosen based on advice from Dutch experts (Bendtsen 1999). The Keradrain pipes also need to be cleaned once a year in autumn. This is done with water at high pressure from a hose, which is pushed through the pipes from gully to gully.

Japanese experience indicates that different cleaning strategies using lower water pressure, water and air combined or only air at cleaning frequencies down to once a week may be more effective. The new Japanese strategies are referred to as ‘function maintenance’ cleaning, whereas the strategy used on Øster Søgade is referred to as ‘function recovery’ cleaning (Nielsen et al. 2005).

2.6 Problems with Keradrain

Figure 2.12. A beginning degeneration of some of the ceramic Keradrain pipes was observed in winter 1999-2000.

In the beginning of the first winter after the pavements were laid, problems with the ceramic Keradrain pipes were observed. Approximately twenty percent of the pipes had damages due to cracks and crackling on the surface (see Figure 2.12) which could be caused by freezing water. On the rest of the pipes nothing unusual was to observe. The damaged blocks were spread along the test section.

The project group established cooperation with the Department of Structural Engineering and Materials at the Technical University of Denmark to have the Keradrain pipes examined.

A working hypothesis was set up, stating that the pipes were from two separate productions and that there were differences in the temperature at which the two productions had been baked. To test this hypothesis, six samples without (series 1) and six samples with (series 2) damages were collected from the road.

Laboratory tests of the two series were carried out. The ability of the samples to absorb water was measures, as was the temperature at which the samples had originally been baked. It was concluded (Hansen & Hansen 2000) that the two series came from two separate productions with differences in both the clay material and the baking temperature. It was also concluded that the damaged pipes were of poorer quality than the undamaged, and that it had to be expected that the poor quality pipes would be subject to frost damages due to a high ability to absorb water.

To avoid future problems of this sort the project group decided that all the ceramic Keradrain pipes be replaced by similar pipes (same dimensions) made from fiber reinforced concrete. The pipes were replaced in the summer 2001. No problems have been observed with the new concrete pipes.

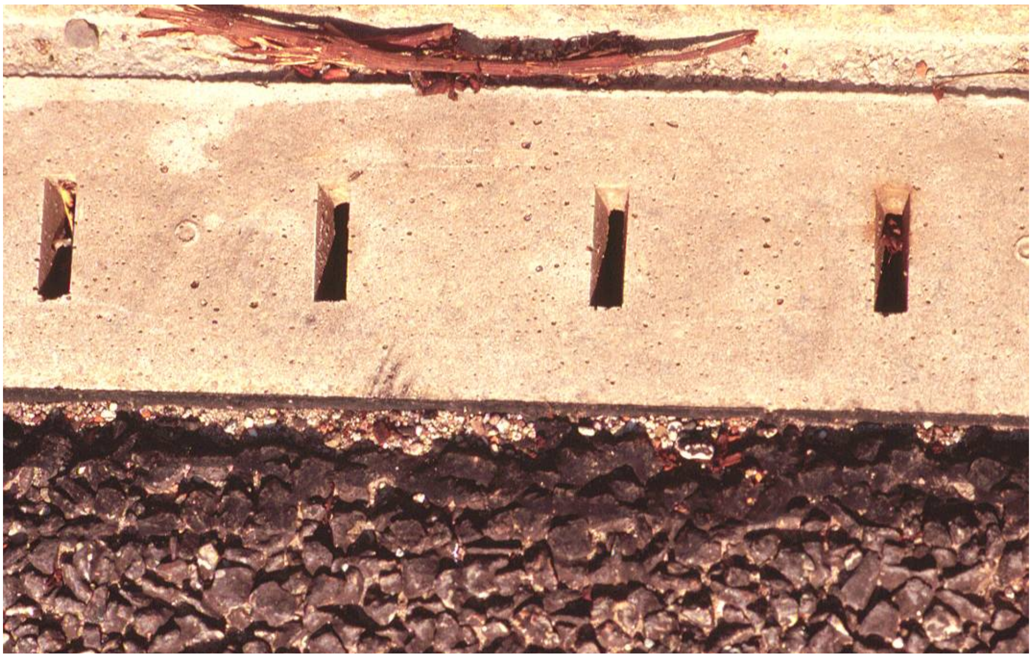


Figure 2.13. The ceramic Keradrain pipes were replaced by similar pipes made from fiber reinforced concrete in summer 2001.

2.7 Sealing of the pavements

In 2005, when the test pavements were six years old, raveling had started in the wheel tracks of the two pavements with 5 mm aggregate in the top layers. Very little raveling was seen on the pavement with 8 mm aggregate in the top layer.

In order to increase the structural lifetime of the two PA5 pavements, the Copenhagen road administration decided to perform a sealing in September 2005. The sealing was carried out by spraying 400 g/m^2 bitumen emulsion on the pavement. The bitumen content was 160 g/m^2.

Figure 2.14. Raveling in the wheel tracks of the six years old two layer porous pavement before sealing in 2005.

At a visual inspection one year after the sealing the raveling process of the sealed pavements had stopped. The pavements even seemed to have less raveling after the sealing than before. In 2007 it was decided to change the top layers because of clogging of the porous structure and raveling (Bendtsen & Kragh 2007).

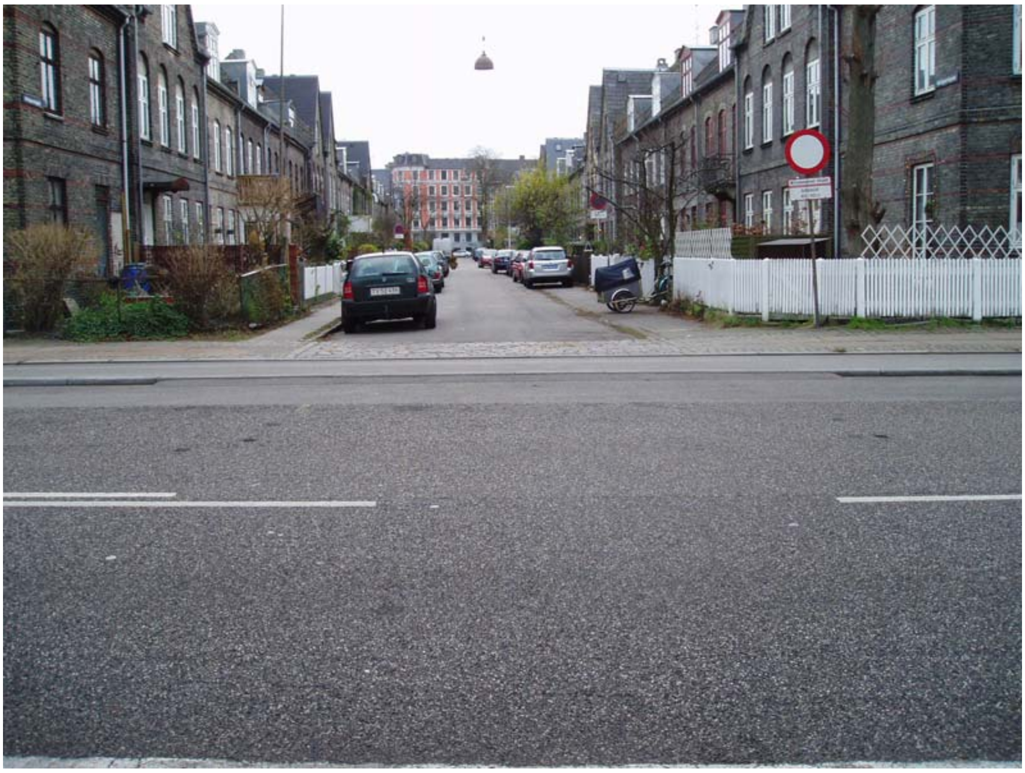


Figure 2.15. View across Øster Søgade down a side road.

3. The test road

Early in the project work was commenced together with the Copenhagen Municipality to find a suitable road for the pavement test. The municipality wanted a road with dwellings along it, which were subjected to noise levels exceeding 65 dB, and also a road which was so worn down that there were plans to renew the pavement in the near future.

The project group wanted an 800 meters long road section where it was possible to lay 3 different test pavements and a reference pavement, each with a length of 200 meters. Traffic should be uniform and free flowing along the whole section and the building structure should be homogenous in order to secure uniform acoustical conditions without reflecting building facades at the four test sections. The optimal condition would be dense developments with apartment houses or row houses along one side and spread or no buildings on the other. It should also be secured that there was no background noise which could influence the noise measurements.

3.1.1 Optimal conditions

The following optimal conditions for the traffic conditions on the test road were set up:

- Speed limit and actual speed of 50 km/h.
- An even and uniform driving patters along the whole road to secure that differences in driving pattern does not influence the results of the noise measurements.
- Weekday traffic of 6000-8000 vehicles to make sure that it within a reasonable time span is possible to measure noise from single passing vehicles at the measuring points.
- A percentage heavy vehicles (over 3.5 tons) of at least 8-10 percent to secure that this category is reasonably represented in the noise measurements.
- City busses on the road, as these are typical on urban roads.
- No signalized intersections on the road as these influence the driving pattern.
- Only minor side roads with little crossing or turning traffic so that these intersections only influence a small part of the traffic.
- Uniform cross section on the whole road when it comes to road width, number of lanes, parking, bicycle path and pavement.

As it was the plan to follow the pavements throughout their entire lifetime, it was necessary in the entire period from 1999 to approximately 2009 to secure:

- That there are no expected repairs of cables, pipes etc. beneath the test pavements, and that necessary repairs are carried out before the test sections are established.
- That there in the entire period are no plans to establish new cables, pipes etc. This means that there must be up-to-date pipes for district heating, cables for telecommunications etc.
- That there are no expected major construction works on sites along the road, which may lead to the road being dug up or change in the sound reflection conditions due to new facades.

3.1.2 Øster Søgade

After inspecting a number of roads, Øster Søgade on Østerbro in Copenhagen was chosen for the test. The road section is 700 meters long and runs between Dag Hammerskjölds Allé and Webersgade. There are two minor curves on the section which were assessed to have very little influence on the driving pattern. There is one lane in each direction plus bicycle path and sidewalk on both sides.

Figure 3.1. Conditions at the apartment houses on Øster Søgade before the test sections were established.

Along the east-side of the road the northern part is characterized by 5-6 story ribbon development (see Figure 3.1) and the southern part has row houses in three stories with the end houses facing the road (see Figure 3.2). There is no development along the western side of the road which faces Sortedams Søen (Sortedam Lake). Along the lake is a row of large chestnut trees which are assessed not to influence the noise. According to the municipalities noise mapping the noise levels at the facades of the dwellings was 64 dB.

The weekday traffic on Øster Søgade has been counted to 7800 vehicles per day of which seven percent are heavier than 3.5 tons. There are no bus lines on the road. Speeds have been measured to 52.3 km/h in the northbound lane and 49.4 km/h in the southbound lane.

The pavement on both carriageway and bicycle paths were in very poor condition with cracks, holes and patches. It was an old road with very poor bearing capacity. It had therefore been planed as part of the municipality's road maintenance to renew the pavement. Due to the poor bearing capacity it was necessary to rebuild the entire road bed down to a depth of up to one meter. The work commenced in April 1999. During the road works it proved necessary to renew an old gas pipe and repair sewers.

As part of the road works, small changes were made to the road geometry:

- Along the row houses on the east side of the road marked parking spaces were established. These were further marked through islands with plantation. On the parking area dense asphalt concrete was used.
- At a pedestrian crossing at the northern of the two road curves a refuge was established.

Figure 3.2. Conditions at the row houses on Øster Søgade before the test sections were established.

3.1.3 Measuring points

In a project with noise measurements which are planned to continue for a period of up to 10 years it is important that nothing but the “natural” aging of the pavements influence the results of the measurements. The continuity of the measurement series will be disrupted if the pavement is dug up due to repairs of pipes or cables or to install new infrastructure.

To secure the project against such problems it was decided to establish three measuring points on each of the four test pavements, so that at least one point should remain intact for the duration of the project.

The measuring positions can be seen in Figure 3.4. The PA8-70 section starts at Wiedeweltsgade, approximately 70 meters further south than shown in the figure. The reference pavement DAC8 (ref.) continues all the way to the intersection at Dag Hammerskjölds Allé at the northern end of the road.

Figure 3.3. Parking spaces at the row houses after the rebuilding of Øster Søgade.

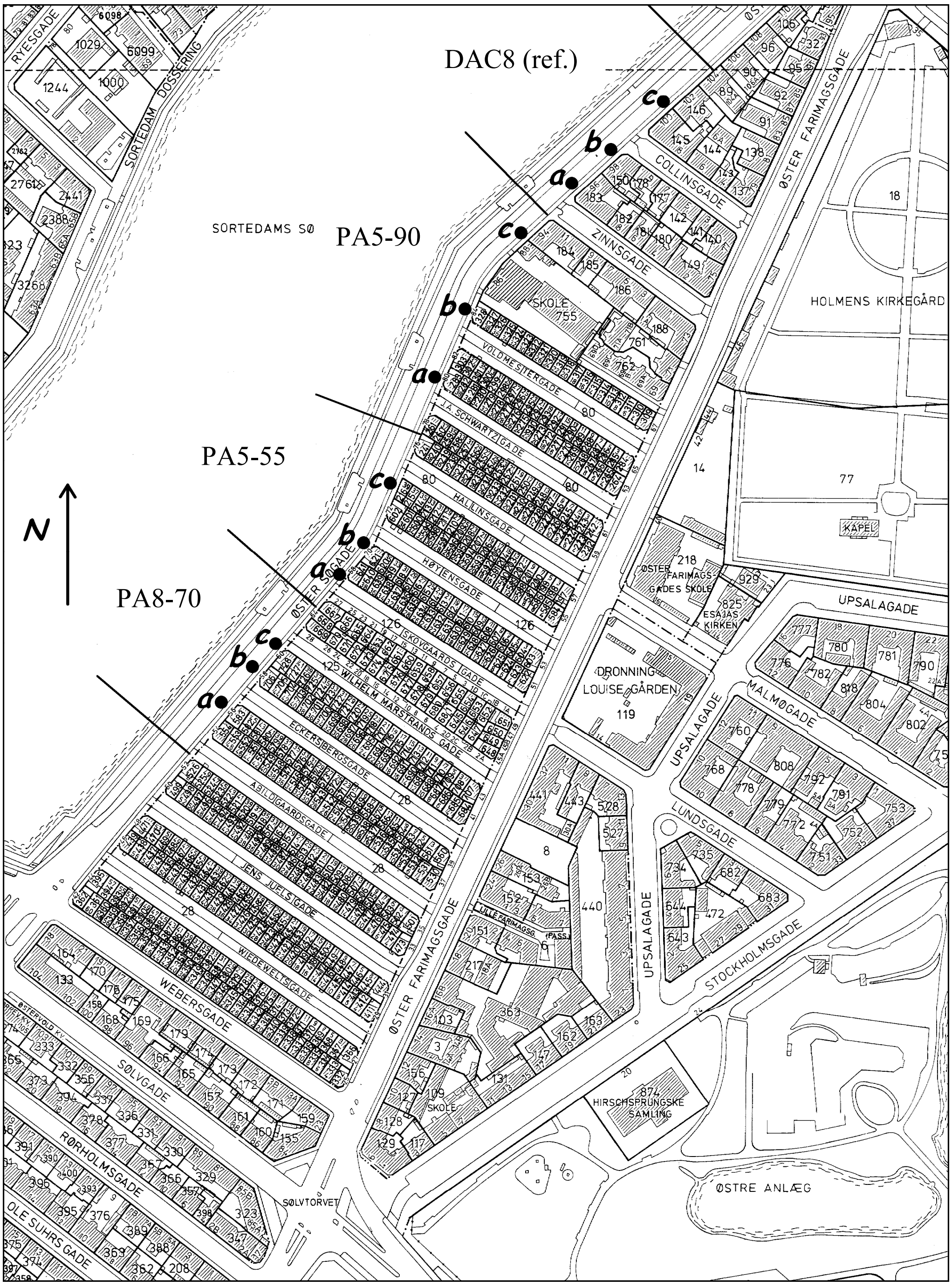


Figure 3.4. The test road – Øster Søgade – with indications of the measuring points, for each section termed a, b and c.

Figure 3.5. Pedestrian crossing with refuge at the northern road curve after rebuilding Øster Søgade.

4. Pavement measurements

The physical structure and state of the pavements are important to the noise emission when vehicles pass a given road section. Therefore, regular measurements of various kinds have been carried out to follow the development in the surface structure, built-in voids and permeability of the test pavements. Table 4.1 provides an overview of the pavement measuring methods and their purpose.

Table 4.1. The applied methods for measuring the physical structure and state of the test pavements.

Measuring method	Purpose	Measuring organization
Laser measurements	Surface texture	Danish Road Institute – Road Directorate
Sand patch	Surface texture	NCC
Becker's tube	Permeability	Danish Road Institute – Road Directorate
Measurements of drilled cores	Percentage built-in voids	NCC
Asphalt analyses of drilled cores	Amount of fine material and bitumen state	NCC
Thin and plane sections	State of pores and distribution of modifier in bitumen	Danish Road Institute – Road Directorate
CT-scans	Physical structure of the pavement	Danish Road Institute – Road Directorate and TU-Delft

The repeated series of measurements allow following the aging process of the pavements as well as relating the noise measurements to the physical state of the pavements. In this chapter the applied methods and the results are presented and analyzed. In Chapter 6 the results of the pavement measurements are used to analyze the development in the noise emissions from the test sections.

4.1 Surface texture

The surface texture of the pavements has been measured by the Danish Road Institute using laser equipment. The equipment sends a laser beam towards the pavement, where it is reflected back to a sensor. The equipment is mounted on a vehicle which measures in the wheel tracks while driving (see Figure 4.1). The equipment measures a point on the road for every approximately 0.4 mm with an accuracy of approximately 0.01 mm. Tests performed by the Danish Road Institute show a good repeatability of this type of measurements.

ISO 13473-1 (1997) provides a method for determining the mean profile depth (MPD, in mm) of a road surface from optically measured surface profiles.

The MPD is calculated from the profile subdivided into baselines with a length of 100 mm. The calculation method is shown in Figure 4.2.

Figure 4.1. Vehicle with lasers for measuring surface texture mounted on the front bumper.

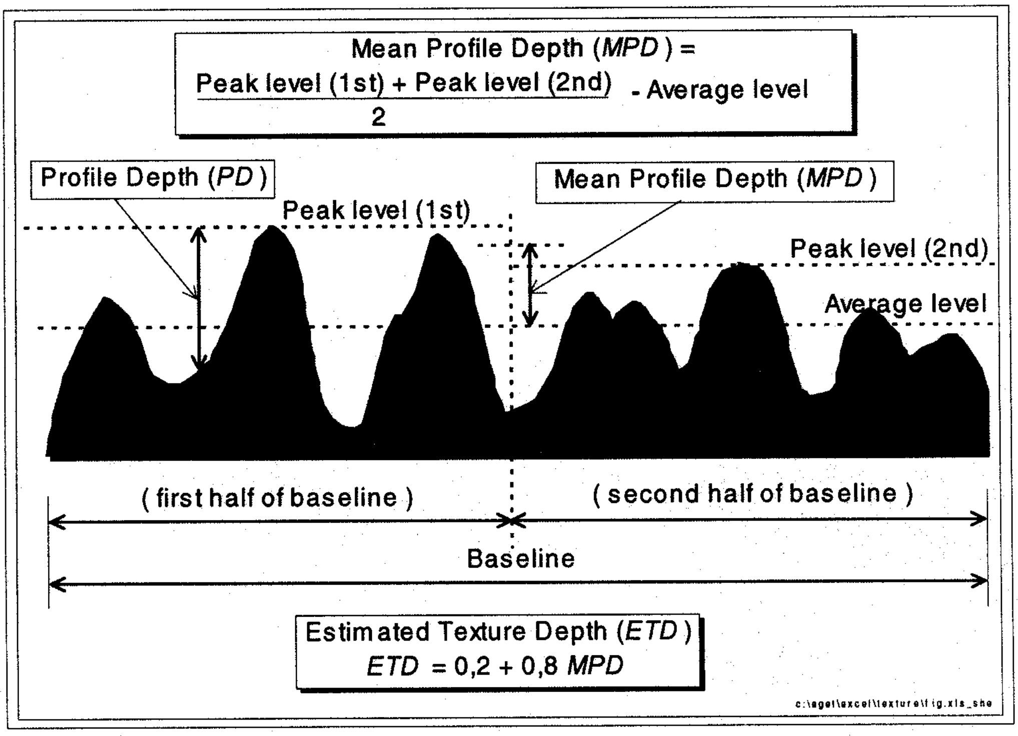


Figure 4.2. Illustration of the method for calculating MPD from surface profiles of road pavements obtained by laser measurements (ISO 13473-1 1997).

The correlation between MPD values from laser measurements and MTD values obtained through the common sand patch method is good (Lund 1997).

Figure 4.3 and Figure 4.4 shows results of MPD measurements on the old worn-down surface on Øster Søgade before rebuilding and on the test pavements

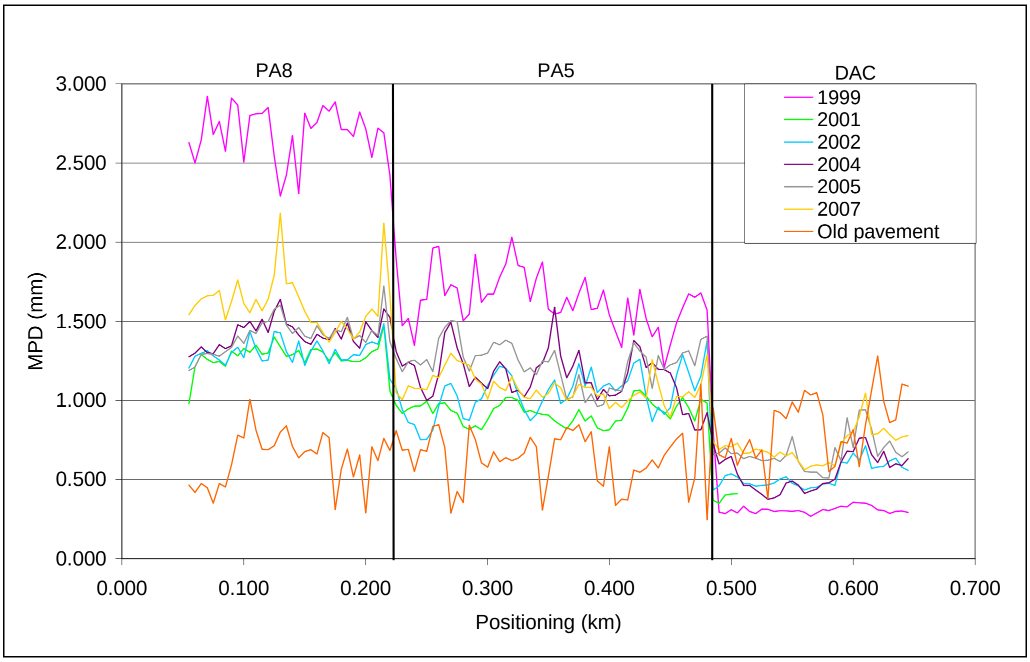


Figure 4.3. Measurements of MPD values on the left wheel track of the north bound lane of Øster Søgade.

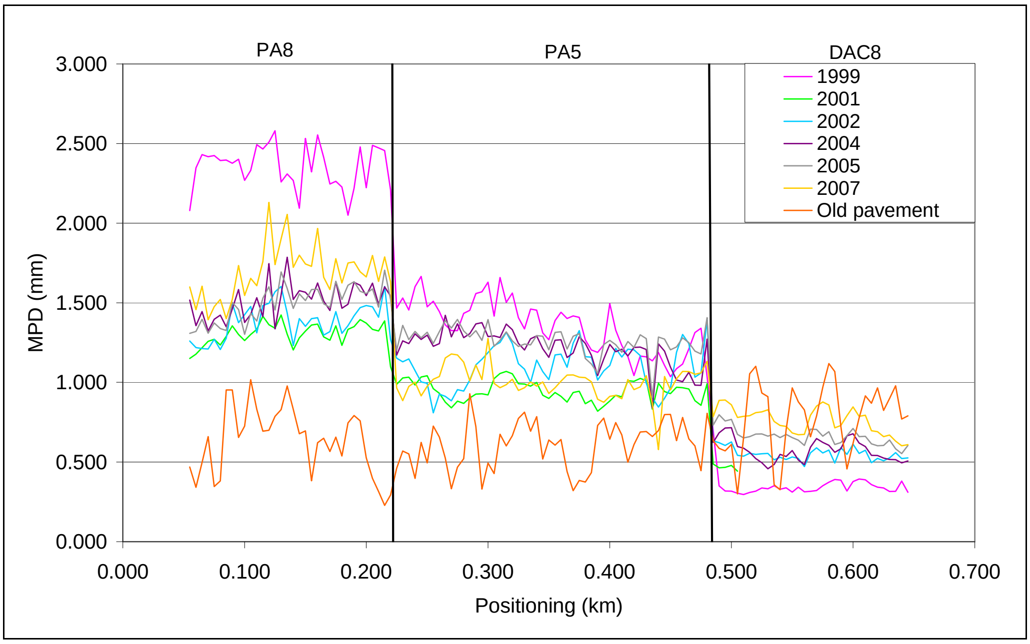


Figure 4.4. Measurements of MPD values on the right wheel track of the north bound lane of Øster Søgade.

The measurements begin in the southern end of the test road at Webersgade (km 0.05) and ends in the northern end at Dag Hammerskjölds Allé (km 0.65). Figure 4.5 shows average MPD values for each test section year by year.

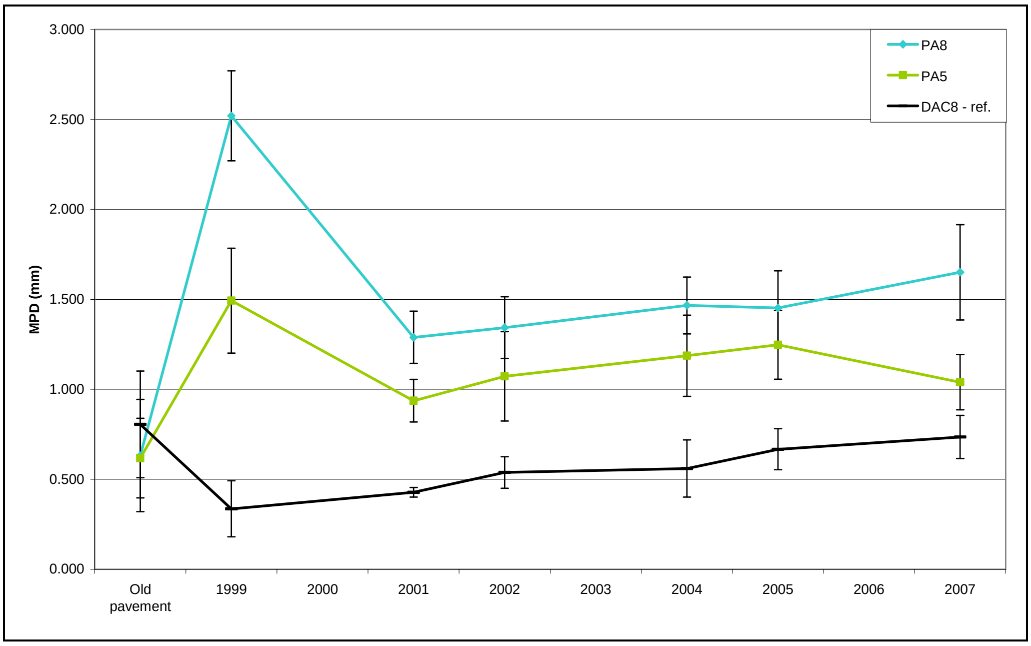


Figure 4.5. Average MPD values and two times the standard deviation for each section of the north bound lane of Øster Søgade.

The MPD values for the old pavement vary greatly between 0.3 mm and 1.3 mm. This indicates an uneven pavement with cracks and holes. In the southern end the average is approximately 0.6 mm and in the northern end it is approximately 0.8 mm. The MPD value for the new reference pavement is between 0.30 mm and 0.40 mm (avg. 0.34 mm). This corresponds well with sand patch measurements from august 1999 which show the reference pavement to have a structure depth between 0.31 mm and 0.34 mm. The MPD value for the reference pavement increases throughout the period to between 0.55 and 0.85 mm (avg. 0.74 mm) with a small peak of 1.05 mm at position 0.610 km. The increase in MPD indicates increasing roughness of the surface structure due to wear and tear.

The MPD values for the porous test pavements are much higher than those for both the new and the old dense pavements, with the highest values measured for the pavement with 8-mm aggregate in the top layer. This is not surprising, as the laser is likely to measure some distance into the pores of the porous pavements, thereby registering the open surface texture. This is somewhat supported by the greater variance in the MPD values of the porous pavements as compared with the dense pavement.

The measurements on the newly laid porous pavements in 1999 show much higher MPD values than the later measurements and the values for the left wheel track of the northbound lane are significantly higher than those for the right wheel track. After two years the values for the two wheel tracks are the same. This phenomenon is not seen for the dense reference pavement. The explanation for the very high values in 1999 may be that a post compaction takes place on the newly laid pavement, and perhaps also that some of the stones in the pavement are turned (Lefebvre 1993). This however does not explain the difference between the wheel tracks.

The MPD values increase slightly year by year on both of the porous pavements. This may to some extent be explained by raveling, especially in 2004 and 2005 on the pavements with PA5 in the top layer and in 2007 on the PA8-70 pavement. The pavements with PA5 in the top layer were sealed in September 2005. After this the MPD values decrease to a level comparable to 2001 and 2002. This is in accordance with the result of the visual inspection in 2006 (see Section 2.7), according to which there was an apparent reduction in the raveling of the PA5 pavements.

Although pronounced, the raveling which has been observed on the test pavements only leads to slight increases in the MPD values. A likely explanation is that the method for calculating the MPD values[5] evens out the variations in surface texture, which are registered by the lasers. As raveling can be expected to significantly affect the rolling noise from vehicles, the lack of changes in MPD values indicate that MPD may not be a reliable measure of surface texture in relation to noise.

All in all there are some very large shifts in the MPD-values, which – although they may be explained theoretically by post compaction – cannot be attributed to changes that can be observed through visual inspections, and some visually observed large shifts in texture, which only lead to small shifts in MPD-values. Thus, there is a need for further studies of MPD – and texture measurements all together – in relation to porous pavements.

4.2 Permeability

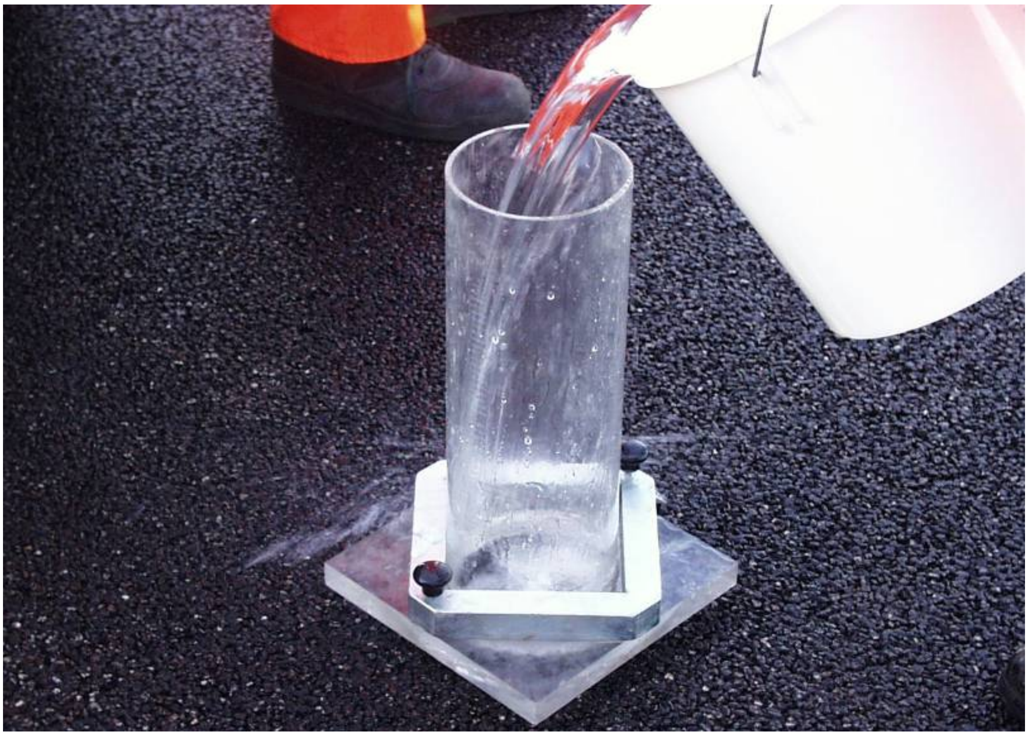


Figure 4.6. Becker's tube which is used for measuring the permeability of porous pavements.

---

[5] 1 or 5 meter average values of the variation in surface texture per 10-cm interval.

The permeability of the pavements has been measured by the Becker's tube method, which is a simple and effective method (Leest et al. 1997; Raaberg 2000). A transparent tube with a diameter of 140 mm is placed on the road, and the joint between the tube and the road is sealed with putty. A measurement is done by filling the tube with water and registering how long it takes 100 mm of water to drain down into the pavement (see Figure 4.6). The measurements are repeated three times at points close to each other. The result is calculated as the average of the three measurements.

Dutch criteria for assessing the porosity of porous asphalt are given in Table 4.2. If the draining time is less than 30 seconds, the pavement is in a good state with high permeability. Draining times between 30 and 50 seconds indicate that the pavement is partly clogged with only medium permeability, but that it will be possible to clean it. Draining times higher than 75 seconds indicate that the pavement is clogged, and that high pressure cleaning is not possible. In this project measurements are stopped when the time passes 75 seconds, and the results are given as 75 seconds.

Table 4.2. Dutch criteria for assessing the permeability of porous pavements based on the Becker's tube method (Leest et al. 1997).

Degree of clogging	**Draining time**	**Permeability**
New porous asphalt	< 30 seconds	High
Partly clogged, can be cleaned	30 – 50 seconds	Medium
Clogged, cannot be cleaned	> 75 seconds	Low

The permeability is measured at the same time as the noise measurements are done and also every half year both before and after the cleaning of the pavement. In order to reduce costs and for practical reasons, measurements have not been done at all nine measuring points on every day of measurements. In each lane permeability has been measured in the right wheel track and between the tracks. In 2005 permeability has only been measured on the PA8-70 pavement.

4.2.1 Results of the Becker's tube measurements

The results of the Becker's tube measurements of permeability for the northbound and southbound lanes are shown in Figure 4.7 and Figure 4.8. The figures show results as an "average" of the measures for measuring points a, b and c on each section.[6] The results for each measuring point are presented in Appendix 1. There are clearly noticeable differences between the performances of the PA5 pavements in the two directions, whereas the PA8 pavement performs equally in both directions.

Along the western side of Øster Søgade – next to the southbound lane – there is a gravel path and large chestnut trees, both of which may supply material which can clog the pores of the pavement. This may explain the poorer performance of the PA5 in the southbound lane, but in that case it is remarkable that it does not affect the PA8

[6] As all draining times exceeding 75 seconds have been recorded as 75 seconds, the values are not true averages.

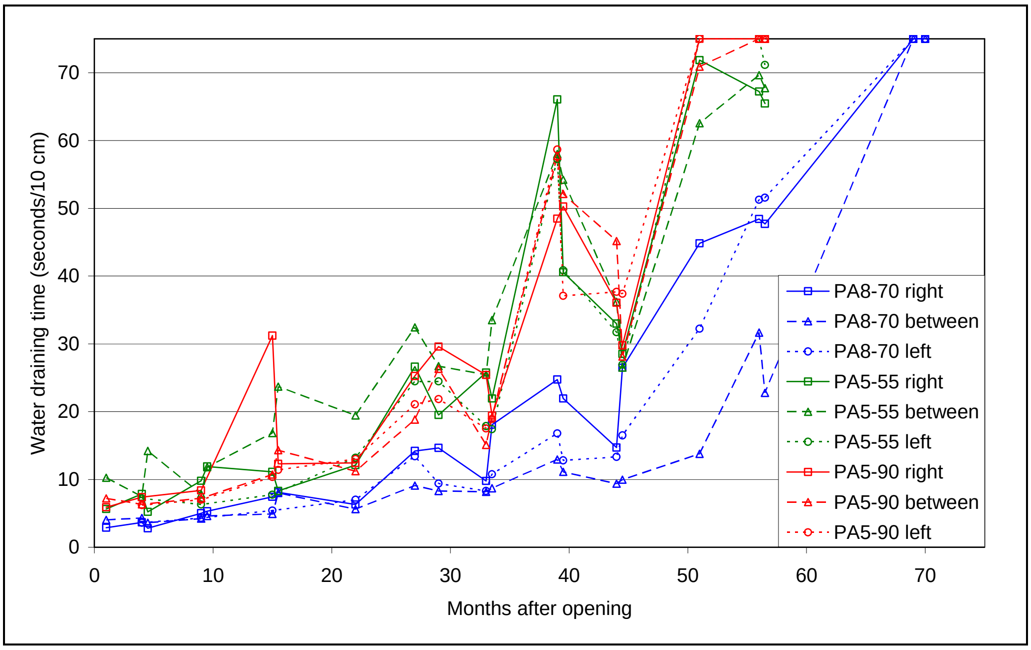


Figure 4.7. Measurements of permeability with the Becker's tube method in the northbound lane. "Average" results for each test section.

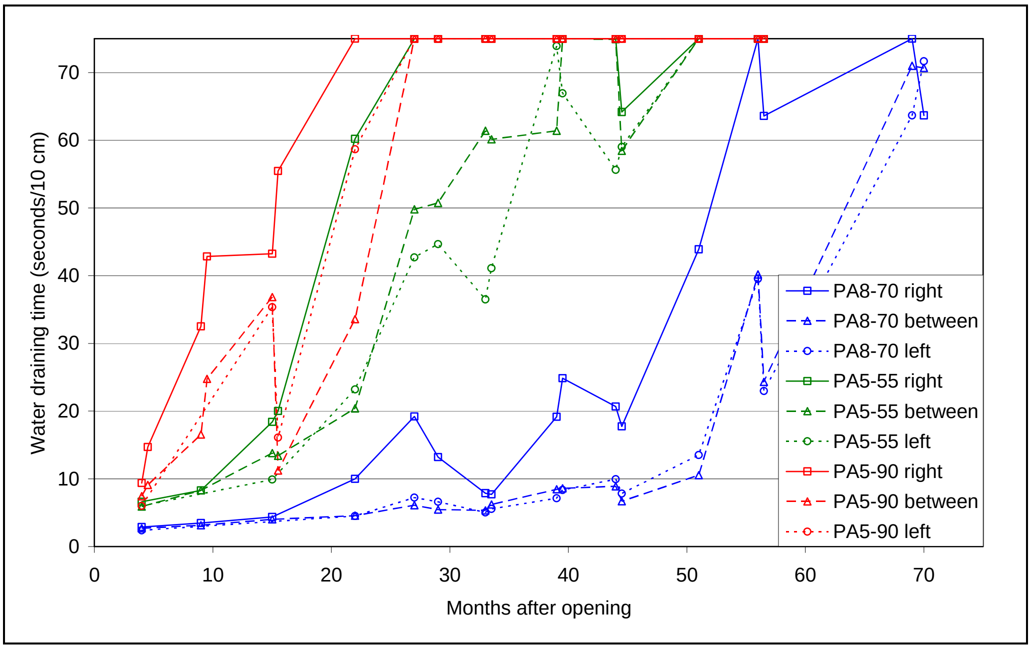


Figure 4.8. Measurements of permeability with the Becker's tube method in the southbound lane. "Average" results for each test section.

Another explanation may be that dust and dirt is brought onto the porous pavements from the reference pavement by the driving vehicles. This explanation is supported by the fact that clogging on the PA5 pavements is observed first at measuring point PA5-90c, as this is the point closest to the shift from the reference to the PA5 pavement.

The same tendency is seen on the PA8, where the wheel tracks at point PA8-70a in the northbound lane – the point closest to the beginning of the test section – clog up before the other measuring points.

Apart from the difference in the northbound lane at point PA8-70a – where the pavement in the wheel tracks is clogged before the pavement between the tracks – there are no major differences in the permeability measured in the wheel tracks compared with between the wheel tracks. This could indicate that the speed of 50 km/h is insufficient for self-cleaning to take place in wet weather through pressure on and suction of water by the tires rolling on the pavement.

Throughout the entire test period the permeability of the PA8-70 pavement is better than that of the two pavements with PA5 in the top layer. As the percentages built-in voids are the same for the two pavements, equal permeability could be expected when the pavements are new. A likely explanation for the better performance of the new PA8 compared to the new PA5 is that the larger pores of the PA8 pavement offers less resistance to the draining water than the pores of the PA5 do. As the pavements grow older, it becomes clear that the PA8 is more resistant to clogging than the PA5.

On the PA5 some cases are seen where a clogged pavement with a draining time exceeding 75 seconds/10 cm is cleaned sufficiently to perform as well as the comparable pavements, but the overall picture on both PA5 and PA8 pavements is that clogging, when measured with the Becker's tube method, is an accelerating process which can be described by exponential functions.

4.3 CT-scans – locating the clogging

In cooperation with TU Delft in the Netherlands a number of drilled cores taken in 2005 have been CT-scanned. The CT-scans produce 2D images consisting of 512 by 512 pixels representing an area of 150 mm by 150 mm. Such image scans are produced with a distance of 1 mm throughout the core. This makes it possible to produce a 3D image of the core with a resolution of 293 µm by 293 µm by 1000 µm. (Nielsen 2007b)

Analysis of the CT-scans make it possible to assess the percentages aggregate, mortar and air voids at various depths in the cores. The material, which is registered as mortar in the scans, constitutes both the original mortar – from when the pavements were laid – and dirt which has settled in the pores. Figure 4.10, Figure 4.11 and Figure 4.12 show examples of the results of CT-scans of cores from each test section. Results of all the scans can be seen in Appendix 2.

The general picture, which is seen in all the scans of the three porous test pavements, is that the amount of aggregate is constant – except for an increase at the top of the bottom layer – throughout the depth of each of the two layers of the pavement. In the bottom layer the percentages mortar and voids are also constant, whereas the percentages mortar increase and voids decrease towards the top of the top layer.

This indicates[7] that clogging of the pavements mainly occurs at the very top of the pavements. This is further supported by the thin and plane sections (see Section 4.6).

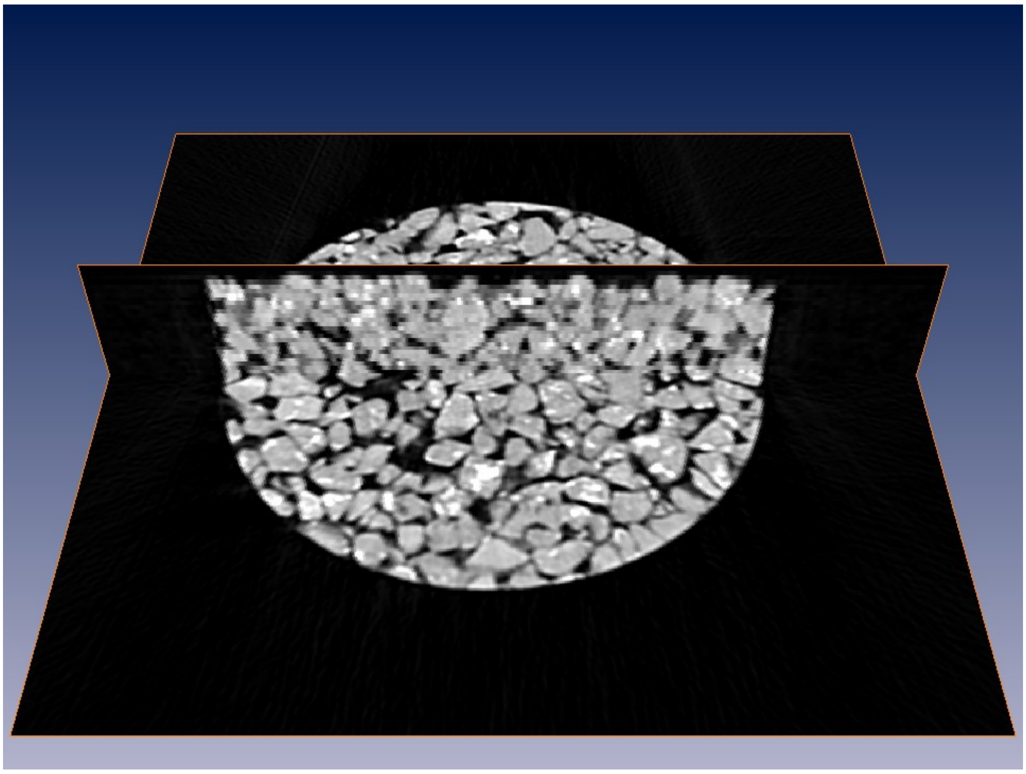


Figure 4.9. CT-scan image 33 mm down in a drilled core from the PA8-70 pavement

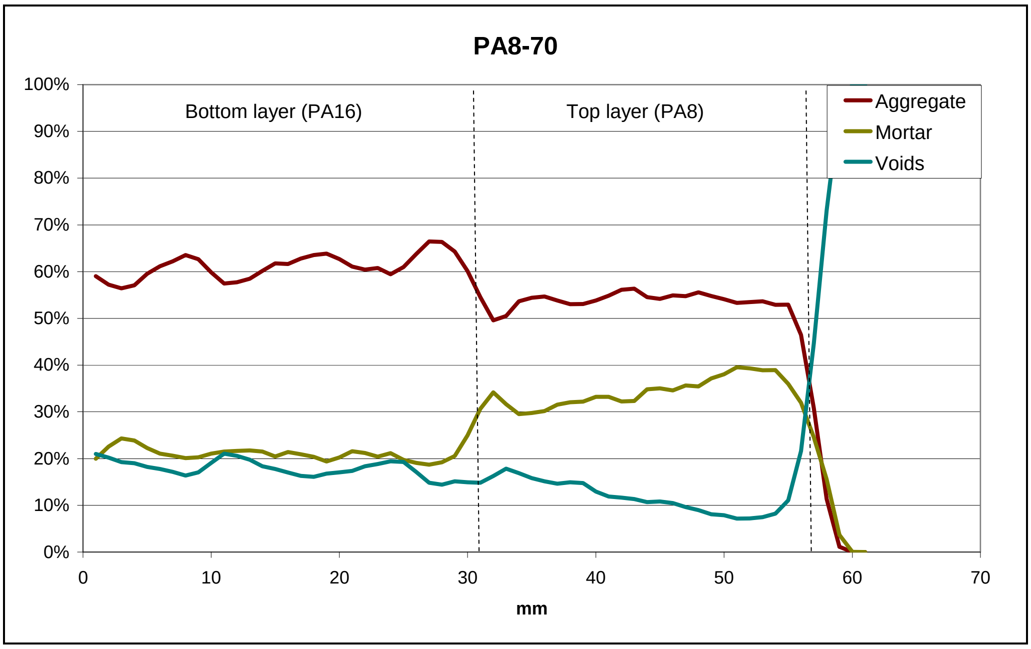


Figure 4.10. Result of a CT-scan of a core from the PA8-70 pavement, which was drilled in 2005.

---

[7] As there are no scans of drilled cores from when the pavements were new, interpretations of the results of the scans are based on assumptions of likely results of scans of new pavements.

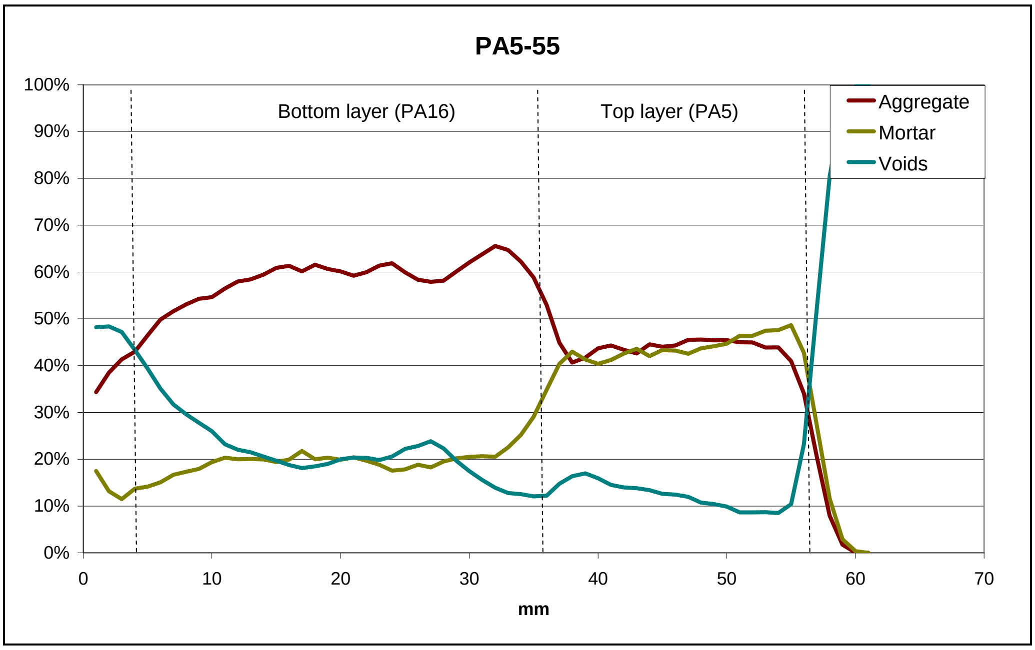


Figure 4.11. Result of a CT-scan of a core from the PA5-55 pavement, which was drilled in 2005.

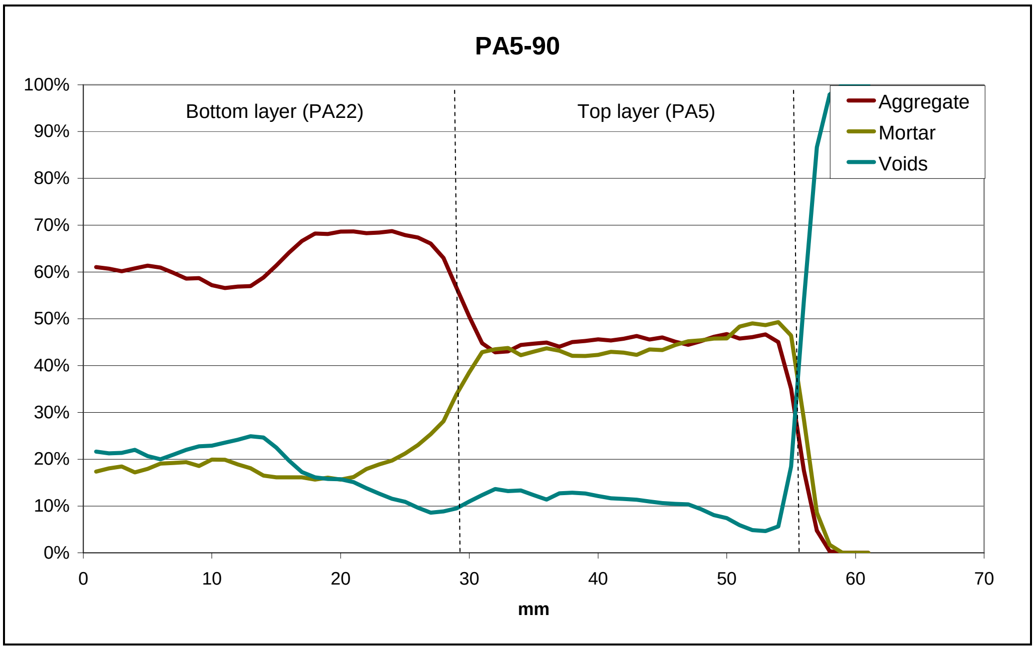


Figure 4.12. Result of a CT-scan of a core from the PA5-90 pavement, which was drilled in 2005.

A possible interpretation of the increase in the percentage aggregate at the top of the bottom layer is that the small aggregate from the top layer enters the large voids formed by the aggregate in the bottom layer. This could explain an increase in aggregate paired with a decrease in void. However, the small aggregate should be mixed with mortar, and this percentage could therefore also be expected to increase, if this explanation is correct. This does not appear to be the case.

Another explanation could be that the increase is caused by the compaction process when the bottom layer is laid. If this is the case, the same phenomenon could be expected for the top layer, which does not appear to be the case. However, the top layers of these drilled cores have been subject to traffic and weather for six years before the cores were drilled and scanned. This may have changed the top. To shed further light on this matter, it will be necessary to scan cores from new two-layer pavements and possibly also to follow the development of such pavements for a number of years.

4.4 Built-in voids

The built-in voids have been measured on cores drilled from the test pavements in 1999, 2001, 2003 and 2005 (Andersen 2005). Each year four cores have been drilled from each of the porous pavements. The percentages built-in voids are determined as an average value based on weight and geometric measurements of the cores. The uncertainty in the determination of the percentage built-in voids using this method exceeds one percent.

Cores have been drilled both in and between the wheel tracks, but no unambiguous differences have been found between these two positions. This is in accordance with the findings in the measurements of permeability. Results of the measurements of percentage built-in voids are shown in Table 4.3 and in Figure 4.13 and Figure 4.14.

*Table 4.3. Percentage built-in voids (V_L) measured on cores drilled from the test pavements. (*High uncertainty due to very thin layers in the cores) (Andersen 2005).*

	Layer	1999	2001	2003	2005
PA8-70	**PA8 (top)**	26.5 %	27.2 %	23.4 %	24.0 %
	PA16 (bottom)	22.8 %	24.0 %	25.3 %	26.5 %
PA5-55	**PA5 (top)**	26.6 %	22.7 %	25.7 %	31.3 %*
	PA16 (bottom)	25.2 %	24.1 %	25.5 %	28.0 %
PA5-90	**PA5 (top)**	23.7 %	19.9 %	22.4 %	22.6 %
	PA22 (bottom)	21.8 %	21.9 %	22.8 %	24.2 %

The measurements reveal no clear tendency in the development of the percentage built-in voids in the top layer, especially since the result of the 2005 measurement for the PA5-55 pavement is uncertain. As the permeability measurements clearly show that clogging takes place, it is remarkable that no decrease in the percentage built-in voids can be seen. This indicates that the percentage built-in air voids is not a good measure of clogging.

In the bottom layer there is a tendency towards an increase in the percentage built-in voids. That there is no decrease indicates that dust and dirt is not accumulated in this layer but rather washed away to the drainage system at the curb. Thus, the bottom layer serves its purpose. The apparent increase indicates that pavement material may in fact be washed away.

The CT-scans (see Section 4.3) indicate that the percentages built-in voids in 2005 are 22-24 in the bottom layers of all the three pavements and 22-23 in the top layers. However, the results of the scans cannot be compared directly to the results of the analyses presented in this section due to a lack of calibration between the two methods.

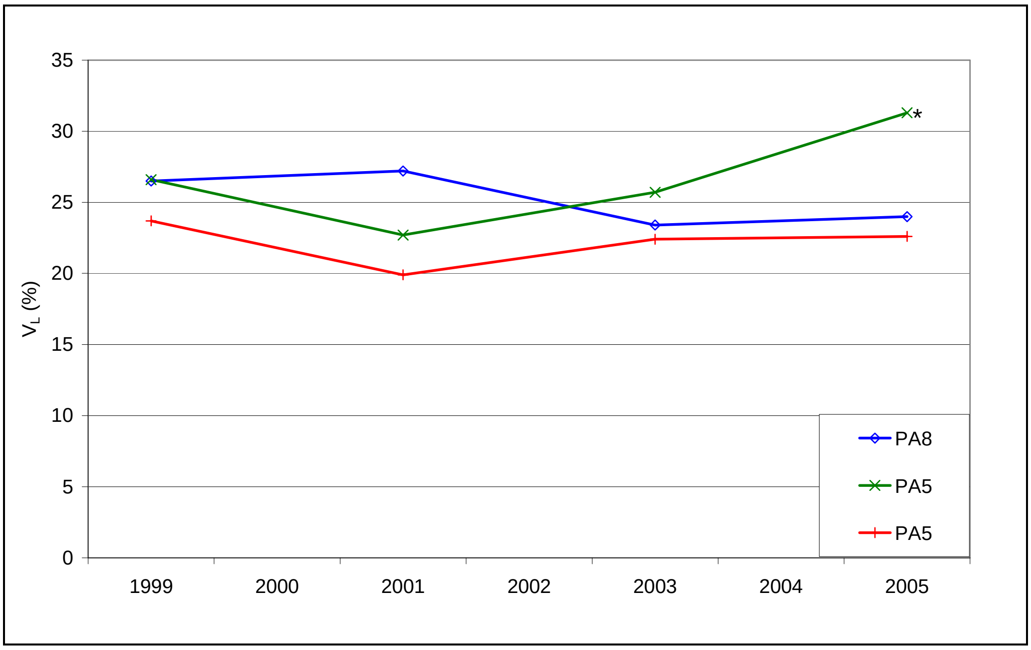


*Figure 4.13. Percentage built-in voids (VL) in the top layer of the test pavements. (*High uncertainty due to very thin layers in the cores). Data from Andersen (2005)*

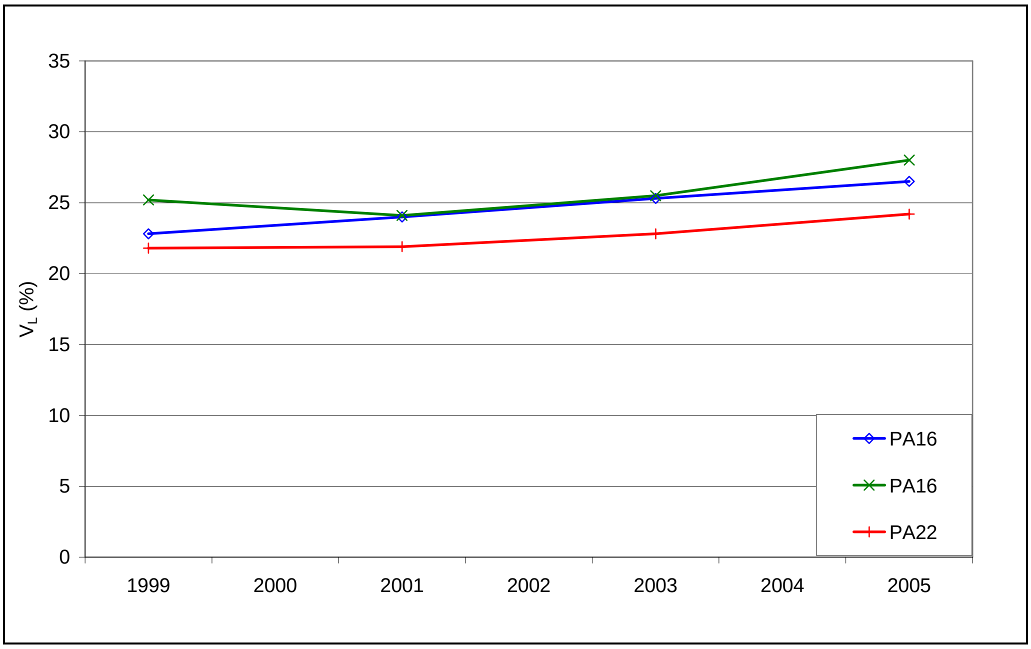


Figure 4.14. Percentage built-in voids (VL) in the bottom layer of the test pavements. Data from Andersen (2005).

4.5 Asphalt analyses

The composition of the asphalt has been analyzed from the cores, which have been drilled from Øster Søgade[8]. Bitumen is separated from stones and filler by using solvents, so that it is possible to measure the bitumen content in the cores. Grain-size curves for the stone and filler are determined by sifting the material through sieves with increasing fineness. Analyses of drilled cores will usually result in a higher content of finer materials than would be expected from the original asphalt mix. This is partly due to stones being cut through in the drilling process, and partly because drilling mud may settle in the pores of the cores and thus be registered as extra filler.

Table 4.4 and Figure 4.15, Figure 4.16 and Figure 4.17 present results from the sieve analysis of stone and filler material in the drilled cores. From 1999 to 2003 the filler content has increased by approximately two percent in the PA5 and PA8 and 1 percent in the PA16 and PA22. For material < 0.5 mm there has been an increase of 3-4 percent in the PA5 and PA8 and 1-2 percent in the PA16 and PA22.

Table 4.4. Sieve analysis data of drilled cores from Øster Søgade. (Analyses in 2005 were carried out at a different laboratory than in 1999-2003) (Andersen 2005).*

	Year	PA5	PA8	PA16	PA22
Filler	**1999**	6.0	5.9	4.8	5.6
	2001	7.6	7.1	5.7	5.6
	2003	8.6	8.2	6.5	6.4
	2005	7.5*	7.8*	6.0*	5.2*
< 0.5 mm	**1999**	7	7	6	6
	2001	11	10	8	7
	2003	12	11	8	8
	2005	10*	11*	8*	7*
< 2 mm	**1999**	10	8	7	7
	2001	20	14	10	8
	2003	20	14	9	8
	2005	18*	15*	9*	9*

[8] In 1999, tests were carried out on asphalt samples taken at the asphalt works when the asphalt was being prepared for laying. In 2005, analyses were done at a different laboratory than in 1999-2003. This increases the uncertainty of comparisons by 2-3 percent.

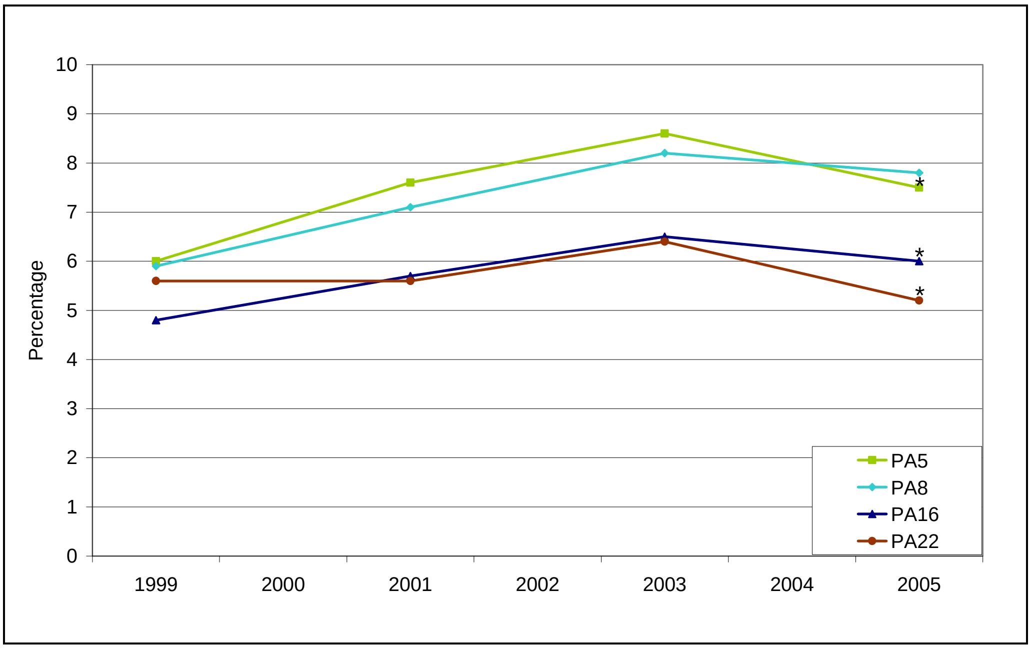


*Figure 4.15. Percentages filler in drilled cores from Øster Søgade. (*Analyses in 2005 were carried out at a different laboratory than in 1999-2003) (Andersen 2005).*

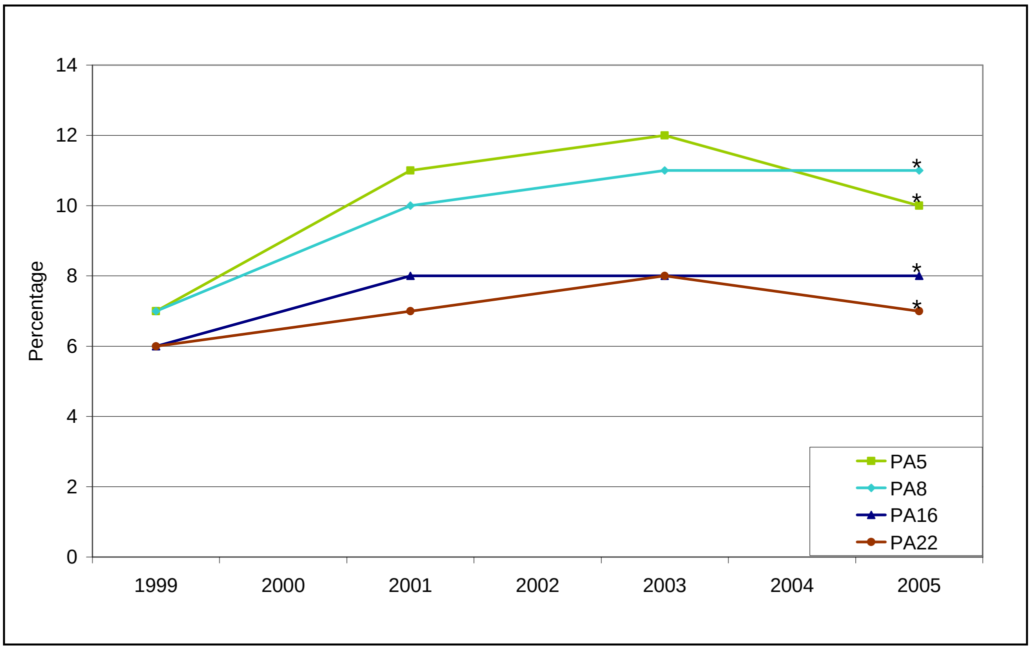


*Figure 4.16. Percentages stone material < 0.5 mm in drilled cores from Øster Søgade. (*Analyses in 2005 were carried out at a different laboratory than in 1999-2003) (Andersen 2005).*

The contents of material < 2 mm increases by 8-10 percent in the PA5 pavement. 2-3% may be attributed to cut stones; the rest is dirt, which has settled before drilling. In the PA8, the percentage material < 2 mm has increased by 5-6 percent. 1-2 percent of this is likely to be cut stones; the remainder is dirt.

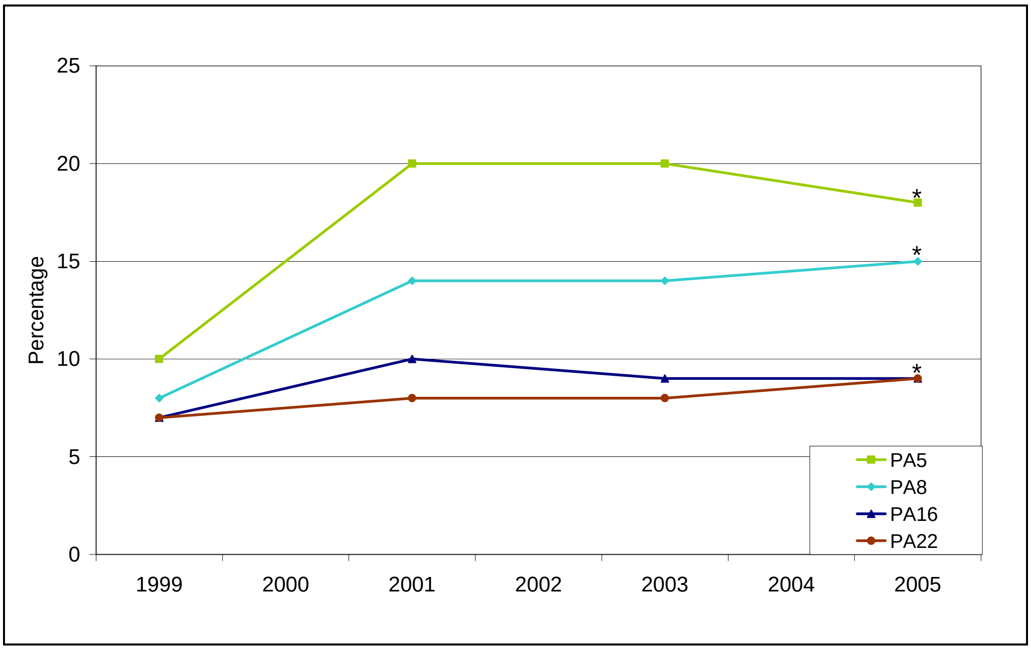


*Figure 4.17. Percentages stone material < 2 mm in drilled cores from Øster Søgade. (*Analyses in 2005 were carried out at a different laboratory than in 1999-2003) (Andersen 2005).*

Results of the measurements of bitumen percentages are shown in Table 4.5 and Figure 4.18. There are no apparent changes as the pavements age. The most apparent changes are from 1999 to 2001, but 1999 is not directly comparable to the other years because the data from 1999 are not from drilled cores.

Table 4.5. Bitumen percentages in pavements on Øster Søgade (Andersen 2005).

	Bitumen percentage			
	1999	**2001**	**2003**	**2005**
PA5	6.3	6.2	6.0	6.1
PA8	5.4	5.1	5.1	5.1
PA16	3.9	4.1	4.0	4.0
PA22	3.5	3.8	3.6	3.9

The bitumen has been tested for softening point (Ring & Ball – $T_{R\&B}$) and penetration. Unless bitumen is very soft, bitumen penetration is measured at 25°C. The penetration is measured as the settling in 5 seconds of a standardized needle with a load of 100 g in a bitumen specimen (Thagesen 1998). Penetration is expressed in 1/10 mm. The lower the penetration, the harder the bitumen. $T_{R\&B}$ is a measure of the temperature at which bitumen has a certain softness. The softer the bitumen, the lower is the $T_{R\&B}$ value, which is expressed in degrees Celsius.

The $T_{R\&B}$ and penetration measures for the bitumen in the three porous pavements – an SBS modified bitumen, type 50/100-75 (see Section 2.1) – are presented in Table 4.6. The $T_{R\&B}$ value remains more or less constant throughout the entire period, whereas the penetration decreases rapidly after the pavement is laid. This indicates a hardening of the bitumen which makes it more vulnerable to raveling.

Table 4.6. Bitumen consistency for the original bitumen and for bitumen from cores drilled in 1999, 2001, 2003 and 2005 (Andersen 2005).

	Pavement	$T_{R\&B}$ (°C)	Penetration (1/10 mm)
Original bitumen		81.0	83
1999	**PA5**	77.1	61
	PA8	78.5	65
	PA16	74.6	60
	PA22	70.8	61
2001	**PA5**	72.8	25
	PA8	71.5	30
	PA16	80.0	28
	PA22	–	–
2003	**PA5**	72.1	26
	PA8	78.8	16
	PA16	77.2	–
	PA22	70.0	–
2005	**PA5**	74.9	33
	PA8	76.7	27
	PA16	76.3	29
	PA22	74.5	38

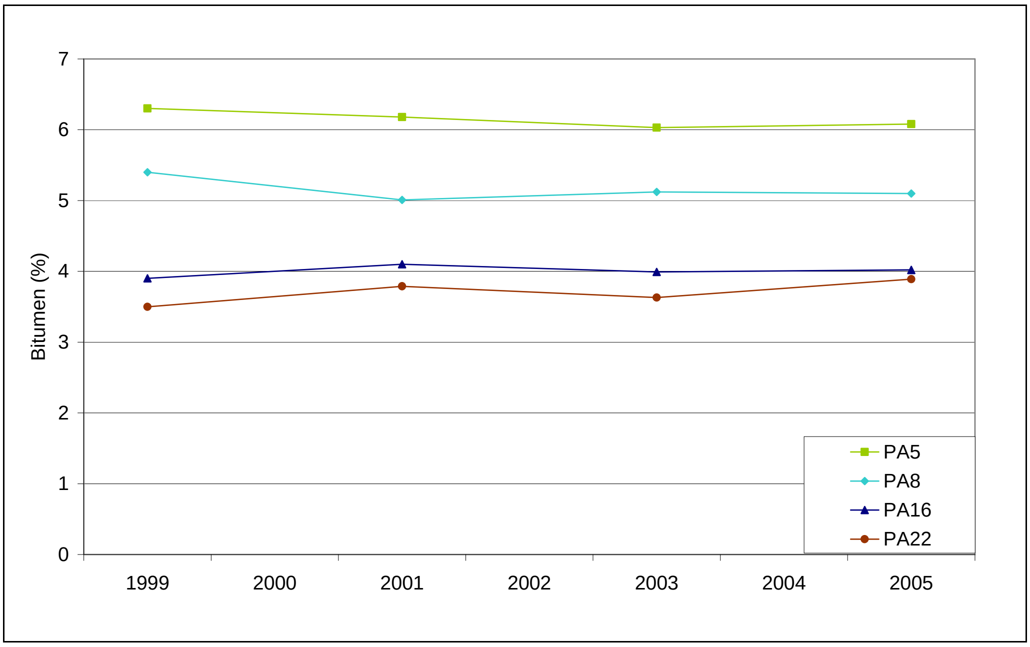


Figure 4.18. Bitumen percentages in the porous pavements on Øster Søgade. Data from Andersen (2005).

4.6 Thin and plane sections

Figure 4.19. Example of a cut of a drilled core for making a thin section. (Raaberg 2000).

In 1999, 2000, 2004 and 2005 cores have been drilled in order to perform thin and plane section analyses of the porous pavements on Øster Søgade. The thin sections are 20 µm thick slices (35 mm x 45 mm) of the pavement. Before doing a thin section, the relevant section of the core is placed in vacuum and impregnated with epoxy, usually with a fluorescent added. When the epoxy has hardened, the section is cut into thin slices which are polished down to the required thickness.

The thin sections are studied under a microscope and provide a very detailed picture of the structure of the pavement.

Through thin sections it is possible to find out where in the pavements clogging takes place, and to some extent also the origin of the clogging dirt. Information can also be obtained on the state of the pavement, including the adhesion between aggregate and binder, presence of fibers, distribution of filler and stone materials and possible cracks in the pavement. If an epoxy without a fluorescent is used, it is possible to detect the distribution of the polymer in the pavement.

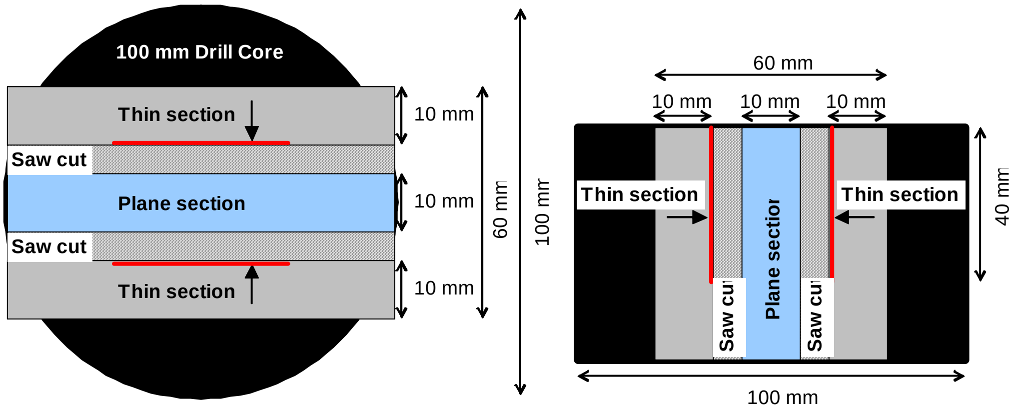


Figure 4.20. The preparation of thin and plane sections from a 100 mm drilled core. Top view (left) and side view (right) (Nielsen 2007b).

Plane sections are 10 mm thick vertical slices of a drilled core, which are filled with epoxy, cut in two and polished. In this way two plane sections are made from each drilled core. The plane sections are placed under ultraviolet light and photographed digitally. The pictures are analyzed using a picture analysis program. The plane sections provide information on the void content and on the size, shape and distribution of the built-in voids. Often it will also be possible to see dirt if the sections are placed under a microscope.

4.6.1 Plane sections – a look at clogging

Figure 4.21 to Figure 4.23 show plane sections of cores drilled from the porous pavements in September 1999 when the test sections were new. The aggregate and binder is shown in blue and the voids in white. There is a tendency towards larger voids in the top layer with 8 mm aggregate (PA8-70) than in the layer with 5 mm aggregate and in the bottom layer with 22 mm aggregate (PA5-90) compared to the layer with 16 mm aggregate.

Based on picture analyses the percentages built-in voids are determined for each of the three plane sections. The results are shown in Table 4.7. The difference between the results from the plane section analyses and the measurements of the cores are significant. One reason may be that the results from the plane sections are based on only one drilled core from each test pavement and thus are subject to some uncertainty.

This is supported by a great variation between the two plane sections which are made from the same core (Raaberg 2000). However, the systematic variation between the results of the two methods could indicate a more systematic difference between the two methods.

*Table 4.7. Percentages built-in voids in the new porous pavements determined through picture analysis of plane sections and through measuring of drilled cores (Andersen 2005; Raaberg 2000)***.**

	Layer	**Plane section (%)**	**Drilled core (%)**	**Difference (%)**
PA8-70	**PA8 (top)**	21.8	26.5	-4.7
	PA16 (bottom)	19.7	22.8	-3.1
PA5-55	**PA5 (top)**	21.8	26.6	-4.8
	PA16 (bottom)	22.4	26.6	-2.8
PA5-90	**PA5 (top)**	18.4	23.7	-5.3
	PA22 (bottom)	18.2	21.8	-3.6

Analysis of plane sections from porous pavements is still a fairly new procedure, so there is little experience with determining void percentages by this method. Due to the great uncertainty in determining void percentages from the plane sections, this has only been done in 1999, so no results are available for the later years. In 2003 and 2005, plane sections have only been used for illustration of the degree of clogging.

Figure 4.21 to Figure 4.23 show the new pavements with aggregate and voids standing out clearly and no indication of clogging. Figure 4.24 to Figure 4.26 show the pavements in 2007 with clear gray shades of dirt in the pores, especially at the very top of the pavements.

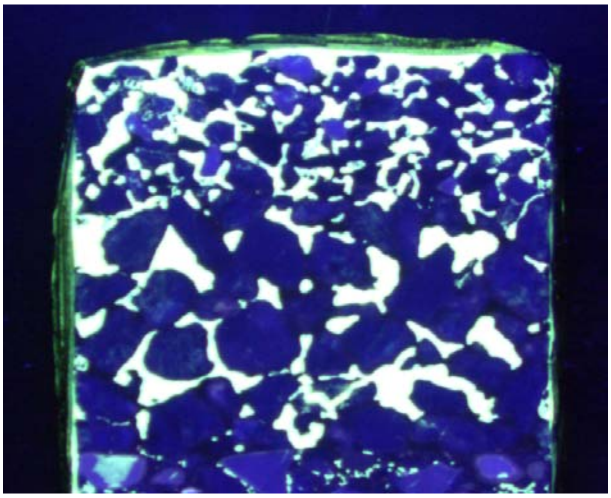


Figure 4.21. Plane section from 1999 of the PA8-70 pavement with the 8 mm porous top layer, the 16 mm porous bottom layer and the dense base course at the bottom (Bendtsen et al. 2002).

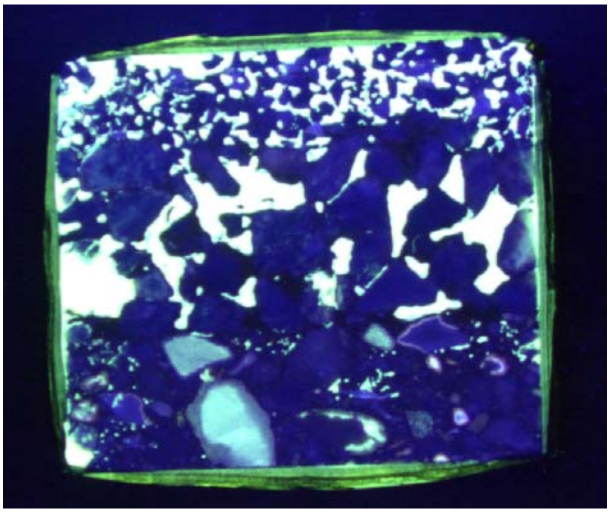


Figure 4.22. Plane section from 1999 of the PA5-55 pavement with the 5 mm porous top layer, the 16 mm porous bottom layer and the dense base course at the bottom (Bendtsen et al. 2002).

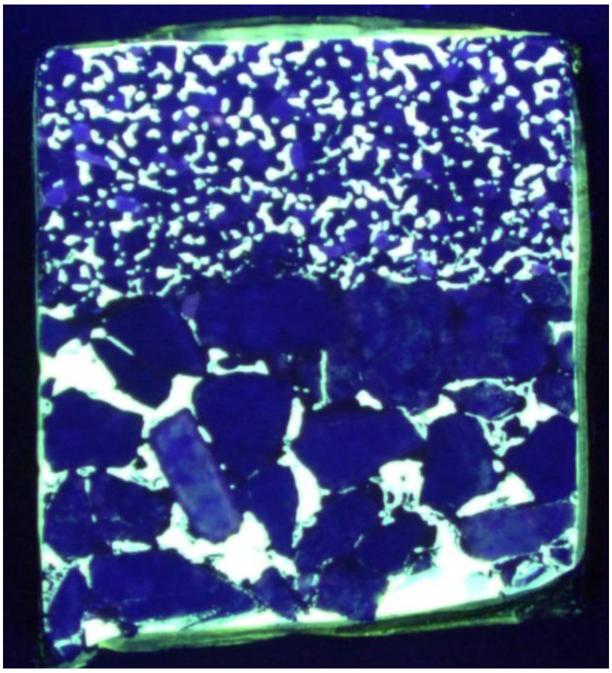


Figure 4.23. Plane section from 1999 of the PA5-90 pavement with the 5 mm porous top layer and the 22 mm porous bottom layer (Bendtsen et al. 2002).

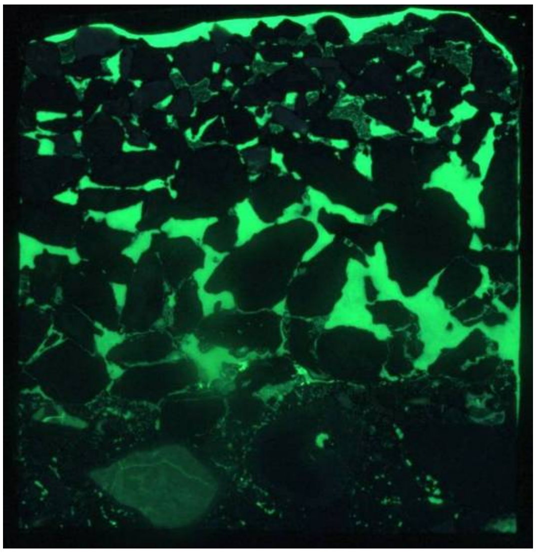


Figure 4.24. Plane section from 2007 of the PA8-70 pavement with base course. Dirt is clearly visible filling out voids in the top-layer of the pavement. Some dirt is also visible in the bottom layer (Raaberg & Neidel 2009).

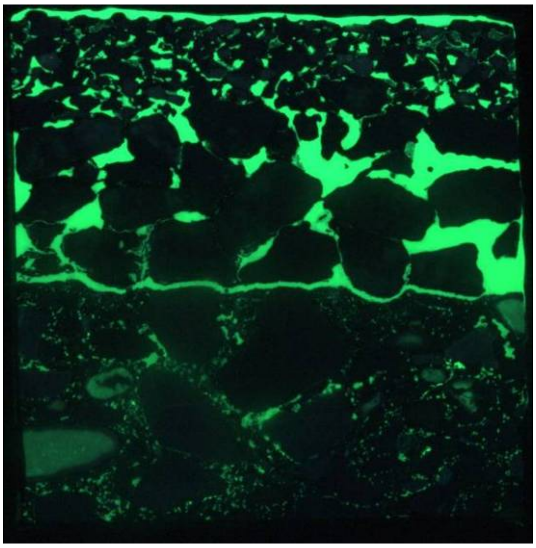


Figure 4.25. Plane section from 2007 of the PA5-55 pavement with base course. Dirt is clearly visible filling out voids in the top of the top-layer of the pavement. Some dirt is also visible further down in the pavement (Raaberg & Neidel 2009).

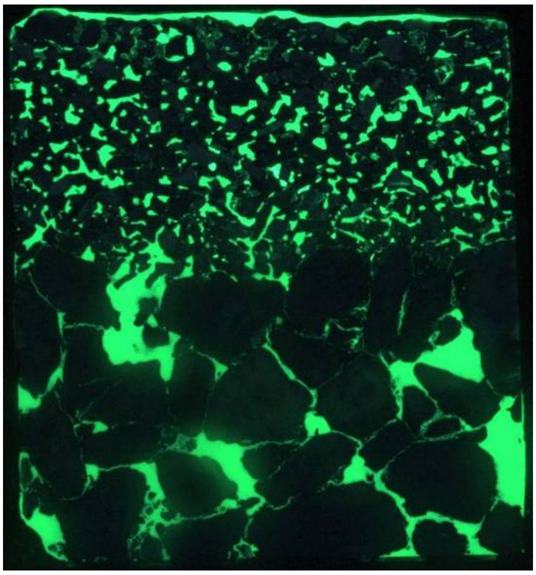


Figure 4.26. Plane section from 2007 of the PA5-90 pavement. Dirt is clearly visible filling out voids in the very top of the top-layer of the pavement. Some dirt is also visible further down in the pavement (Raaberg & Neidel 2009).

4.6.2 Thin sections – the state of the pavement

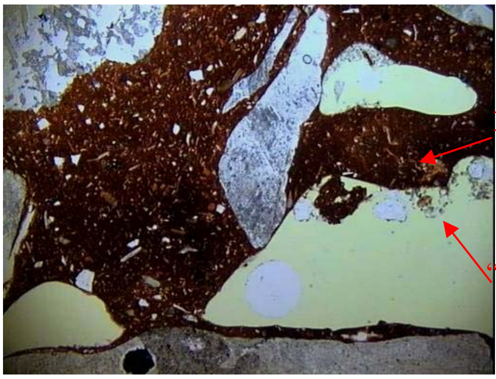


Figure 4.27. Thin section from 1999. A typical picture from the top layer: thick binder coatings and some “dirt” (Raaberg & Neidel 2009).

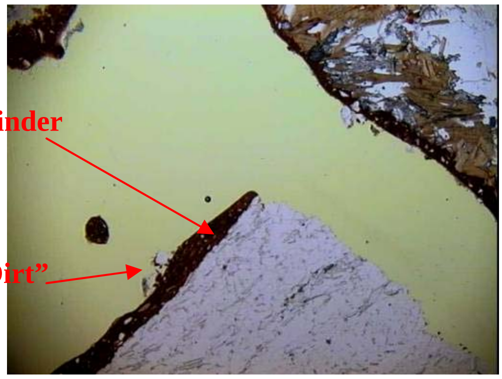


Figure 4.28. Thin section from 1999. Gray aggregate with no coating. A little “dirt” in the pores (Raaberg & Neidel 2009).

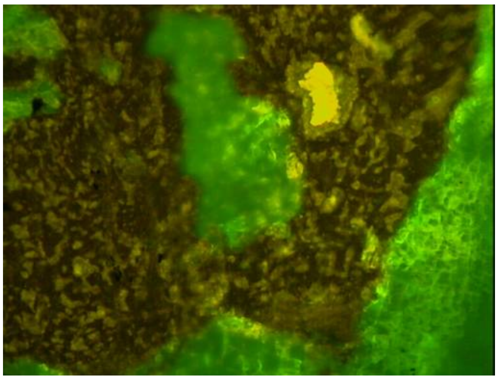
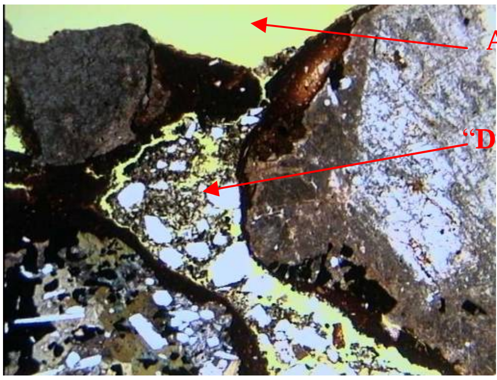


Figure 4.29. Thin section from 1999. Dispersal of polymer in the bitumen. The polymer is seen as lighter colored spots in the brown bitumen (Raaberg & Neidel 2009).

The first thin sections were done on drilled cores taken from all three porous pavements in September 1999, shortly after the pavements were laid. The results (Raaberg & Neidel 2009) show that:

- Generally there are thick binder coatings around the aggregate (Figure 4.27), but especially in the bottom layers there are aggregate surfaces with no coating (Figure 4.28).
- Even at this early stage, small amounts of “dirt” is found inside the pores of the pavements (Figure 4.27 and Figure 4.28).
- The dispersal of polymer in the bitumen is good (Figure 4.29).

In 2000, cores were drilled from the southern end of the PA8-70 pavement and the northern end of the PA5-90 pavement because noise measurements and visual inspection indicated clogging of the pavements at the ends close to the dense pavements. Thin sections of the cores are shown in Figure 4.30, Figure 4.31 and Figure 4.32.



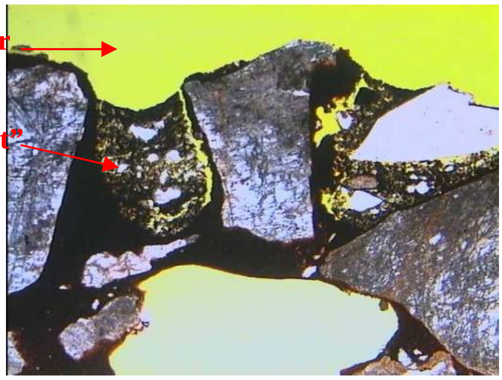


Figure 4.30. Thin section from 2000. Pore filled with "dirt" close to the surface of the northbound lane of the PA8-70 pavement (Raaberg & Neidel 2009).

Figure 4.31. Thin section from 2000. Pores filled with "dirt" at the surface of the southbound lane of the PA5-90 pavement (Raaberg & Neidel 2009).

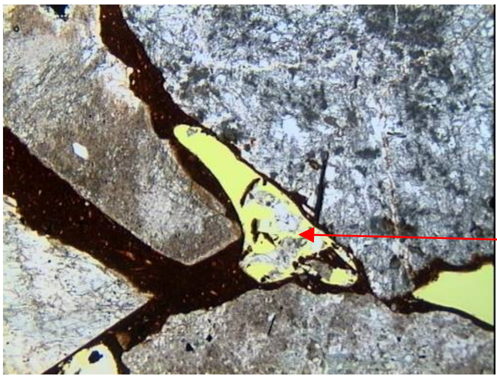


Figure 4.32. Thin section from 2000. Pore with "dirt" in the top layer of the northbound lane of the PA5-90 pavement (Raaberg & Neidel 2009).

As in 1999, the binder coatings are mostly thick, but there is also some aggregate surfaces with no binder. In the bottom layer of the pavements there is dirt in the pores to the same extent as in 1999, but in the lanes where vehicles drive from a dense pavement onto the porous pavements[9] there is extensive clogging of the pores in the top layer of the pavements. In the opposite lanes there is some dirt in the top layers.

Cores were drilled again in 2003; four years after the test sections were laid.
The thin sections now show extensive clogging of the top layers of all three porous pavements. Signs of degradation can be seen in both layers of porous asphalt on all three sections, and in one position on the PA8-70 section also in the base layer (Figure 4.35) (Raaberg & Neidel 2009). The degradation is in the forms of crushing of the aggregate (Figure 4.33 and Figure 4.34) and problems with the adhesion of the binder to the aggregate (Figure 4.33).

[9] Northbound on the PA8-70 pavement and southbound on the PA5-90 pavement.

Thin sections from cores drilled in 2005 repeat the picture from 2003 of clogged pores in the top of the pavement, crushed aggregate and problems with the adhesion of the binder to the aggregate in some areas. In others there are still thick coatings of binder on the aggregate. In addition to the above problems, lack of cohesion in the binder can be seen (Raaberg & Neidel 2009). An example of this is seen in Figure 4.36.

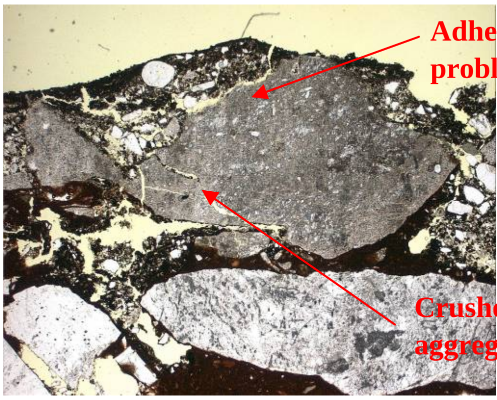


Figure 4.33. Thin section from 2003. Adhesion problems and crushed aggregate at the top of thePA8-70 pavement (Raaberg & Neidel 2009).

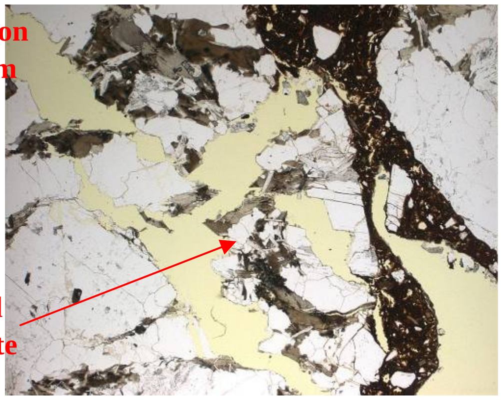


Figure 4.34. Thin section from 2003. Crushed aggregate in bottom layer of the PA5-90 pavement (Raaberg & Neidel 2009).

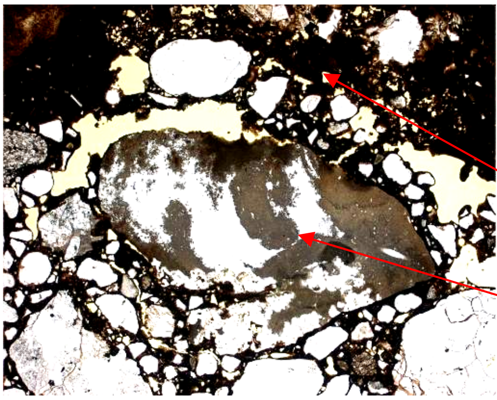


Figure 4.35. Thin section from 2003. Degeneration of the base layer beneath the PA8-70 pavement (Raaberg & Neidel 2009).

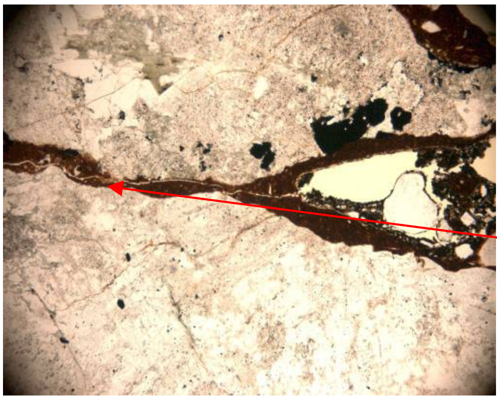


Figure 4.36. Thin section from 2005. Lack of cohesion (crack) in the binder between two stones (Raaberg & Neidel 2009).

Nielsen (2007a) performs a visual assessment of clogging based on thin sections from ten drilled cores from Øster Søgade in 2005. Based on a method presented in Nielsen (2007b), the extent of clogging is classified into three classes and presented in Table 4.8. The three classes are:

- No clogging (**<8**)
- Uncertain clogging (**8-16**)
- Serious clogging (**>16**)

Table 4.8. Visual assessment of clogging on Øster Søgade based on thin sections from cores drilled in 2005. Green: No clogging (<8). Yellow: Uncertain clogging (8-16). Red: Serious clogging (>16) (Nielsen 2007a).

Depth	**PA8-70**				**PA5-55**				**PA5-90**	
0-10 mm	14	18	20	18	18	18	23	23	15	21
10-20 mm	20	16	20	12	21	21	18	22	20	21
20-30 mm	17	13	14	15	11	11	6	7	17	19
30-40 mm	4	4	5	7	6	2	5	7	10	3

The assessment of clogging in Table 4.8 supports the indications in the CT-scans and plane sections that clogging primarily occurs in the top layer of the pavements. The top layers of the PA8-70 and PA5-90 pavements are both 25 mm thick. The top layer of the PA5-55 pavement is 20 mm thick. Thus, “serious clogging” only occurs at depths including the top layers, and “no clogging” only occurs at depths that do not include the top layers.

4.7 Summarizing pavement measurements

MPD values, which in this context have been used to describe surface texture, appear to be of questionable value as a measure of surface characteristics of porous pavements. If laser measurements of surface texture are to be used to describe the physical state of porous pavements, there is a need for applying other methods of assessing the data from such measurements.

The Becker’s tube method for measuring permeability gives clear results of the state of the pavements. The PA8-70 pavement maintains permeability longer than the two PA5 pavements, which in relation to clogging do not appear to be suitable unless a different cleaning strategy can produce better results. All three pavements eventually clog up, but the PA8 does retains some permeability almost throughout its structural lifetime.

The clogging starts at the ends of the test sections where vehicles enter the sections from a dense pavement. It thus appears that at least part of the clogging is due to material which is dragged onto the porous pavements by vehicles.

From the Becker's tube measurements it is clear that the cleaning strategy used in this project has not been sufficient to maintain the permeability of the pavements. Although the PA8-70 pavement retains some permeability throughout its structural lifetime, the permeability is gradually reduced. Thereby the first part of hypothesis no. 4 (see Chapter 1) has been proven wrong, and it can be rejected.

The fact that the results of the measurements are better for the PA8-70 pavement than for the two PA5 pavements even when the pavements were new and the percentage voids were the same indicates that the use of water for measuring permeability may not produce results which are fully representative for the permeability to air, as the flow resistance of air is less than that of water. This issue is worth looking further into, as it is being done in the Netherlands, where air is being used for measuring permeability.

The CT-scans indicate and the thin and plain sections show that clogging is mainly a problem in the top layers, whereas the bottom layers appear to maintain the ability to lead away water and dirt that may have entered that far into the pavements. It is therefore possible that better cleaning strategies may be better at maintaining the permeability and thereby also the noise reducing effect of the pavements.

CT-scanning is a new method for assessing drilled cores. It needs further testing and development if results are to be fully utilized. At present it cannot replace thin and plane sections as a means of assessing the state of pavements, but it may be a supplement as a scan produces results an entire drilled core whereas the thin and plane sections only show a very small part of a core. Thus, with further development the scans may produce results which are less detailed but more representative for a pavement than the highly detailed but very local results from thin and plane sections.

Hypothesis no. 7 states that the lifetime of the porous pavements is the same as that of ordinary dense pavements on urban roads. This is disproved by the extensive raveling, which eventually led to sealing of the two PA5 pavements and necessitated a change of top layer also on the PA8-70 pavement after 8 years.

The results of the bitumen tests show hardening of the binder. In the thin sections this can be seen to have led to deterioration of the pavements with adhesion problems and cracks in the binder. Together with crushing of the aggregate, which is also seen in the thin sections, this has caused the extensive raveling. Improvements in these pavement characteristics are necessary if the lifetime of porous pavements are to be increased.

5. Acoustical measurements

A variety of acoustical measurements have been carried out throughout the project period. These include:

- Measurements done according to the Statistical Pass-By (SPB) method (ISO 11819-1 1997). From 1999 to 2006 these measurements were carried out by the same measuring team from DELTA Danish Electronics, Light and Acoustics. As presented in Chapter 3, SPB measurements are initially done at three points for each of the three porous pavements and the reference pavement. From 2003 onward this was reduced one point at each pavement.[10]
- Controlled Pass-By measurements with selected vehicles at speeds in the interval 40-60 km/h. The measuring method is the same as used in the SPB method, but for a controlled selection of vehicles rather than a random selection of those driving on the road. These measurements are carried out by DELTA Danish Electronics, Light and Acoustics in 2001.
- Measurements at 1.2 and 5 m to see the influence of elevation on the noise levels. These measurements are carried out by DELTA Danish Electronics, Light and Acoustics.
- Measurements according to the Close Proximity (CPX) method (ISO 11819-2 2000). The measurements are carried out by M+P Consulting Engineers from the Netherlands in 1999. In 2007 measurements were done by the Danish Road Institute.
- Measurement of sound absorbance on site using the extended surface method, which has later been standardized (ISO 13472-1 2002) and using the Dutch α-in-situ method, where an impedance tube is placed on the road surface. The extended surface measurements are carried out by DELTA Danish Electronics, Light and Acoustics in 2000 and 2001 and the α-in-situ measurements by M+P Consulting Engineers in 1999.
- Sound absorption measurements on Marshall specimen and drilled cores using an impedance tube and the transfer-function method (ISO 10534-2 1998), see Section 2.2.

The aim of using this variety of measuring techniques is to obtain a detailed description of the acoustical properties of the test pavements. It has also been an aim to see if there are other measuring methods than the expensive SPB method which can be used to assess the noise reducing properties of porous pavements. This could be in order to check the compliance with tender specifications or to follow the properties over the lifetime of a pavement.

[10] PA8-70a, PA5-55b, PA5-90c and DAC8a. In 2004 the PA8-70 pavement was measured at all three measuring points and the reference pavement at points a and b.

In this context, only the SPB measurements are reported as these are the only measurements which have been carried out throughout the project. The results of all other acoustical measurements are reported by Bendtsen, Larsen and Greibe (2002)

5.1 Important parameters

A number of parameters relating to traffic, the road and its surroundings influence the noise levels which are measured close to the road:

2. **Traffic**
    - Traffic level
    - Distribution on vehicle categories
    - Speed
    - Driving pattern – accelerations and decelerations
    - Vehicle characteristics on the specific road including choice of tires

3. **The road**
    - Noise characteristics of the pavement
    - Pavement temperature during measurements
    - Wet or dry road

4. **Surroundings**
    - Terrain between the road and the microphone
    - Distance between the road and the microphone
    - Microphone height
    - Reflections from nearby buildings

In this project where the pavement noise characteristics are the central point of attention, it is important to keep all other parameters constant for all measurements on both the porous and the reference pavements. This is the background for the selection of the SPB method as the central acoustical measurement method used every year in this project.

5.1.1 Traffic levels and vehicle categories

The traffic level and its distribution on vehicle categories are important to the noise level. In the analyses L_{AFmax} values are used. L_{AFmax} is the maximum noise level measured with the time constant “Fast” for an average vehicle in the relevant measuring position. L_{AFmax} values have been measured for passenger cars (pass), light goods vehicles (LGV) including all-terrain vehicles, heavy vehicles with two axels (HGV-2), and heavy vehicles with more than two axels (HGV-m). Based on these measurements noise has been calculated for a vehicle corresponding to the average vehicle-type distribution on urban roads. This is in this project defined as 80 % pass, 10 % LGV, 7.5 % HGV-2 and 2.5 % HGV-m. Motorcycles are not included as very few have been observed during measurements.

5.1.2 Driving pattern

The test road has been selected so that most vehicles drive at steady speed without accelerations or decelerations. The measuring points are located at least 100 meters from the signalized intersections at each end of the road so that accelerations from these intersections do not influence the measurements. It has been assessed that the two slight curves on the test road (see Figure 3.4) do not influence the driving pattern significantly. Accelerating vehicles – for instance because they have turned onto the test road from a side road – are excluded from the measurements.

5.1.3 Vehicle characteristics

Noise emissions from individual vehicles vary depending on the vehicles' age, type, tire type and maintenance. In each vehicle category a sufficient number of vehicles have been measured so that a representative average is achieved. Vehicles with obvious defects – such as defect silencers – or with studded tires, loud music etc. are excluded from the measurements.

5.1.4 Pavement temperature

From previous measurements and from literature it is known that there is a correlation between tire-road noise and temperature so that noise levels increase at lower temperatures. All noise measurements have been done in fine weather during the summer period, so it is assessed that variations in temperature do not influence the results. Therefore these have not been corrected to a standard temperature.

5.1.5 Surroundings

The terrain between the carriageway and the microphone is hard (asphalt pavements or concrete paving stones) in all measuring positions. However, part of the sound propagation from the vehicles to the microphone takes place over the porous pavements, which have a sound absorbing effect. This effect is part of the noise reducing effect
of using porous pavements, and it is therefore included in the noise measurements. The effect may vary somewhat at the various measuring positions due to the layout of the road, and it may also vary between the north and the southbound lanes.

All measurements have been done with the microphone placed 1.2 meters above terrain directly on the facade of the buildings which are located on the eastern side of Øster Søgade. There are no buildings on the western side of the road, so conditions regarding reflections are the same at all measuring positions.

5.1.6 Meteorology

Measurements are done close to the carriageway at distances between 9 and 11 meters. Wind and temperature conditions are therefore of minimal importance to the sound propagation. Along the western side of Øster Søgade are a number of large chestnut trees. During measurements it is ensured that wind rattling the leaves does not produce noise levels which may influence results. All measurements are done on dry roads, at least 48 hours after the latest rain fall to secure that no rain water remained in the pores of the pavement.

5.2 SPB measurements

Apart from some small deviations described below, the noise measurements have been carried out according to the Statistical Pass-By Method (ISO 11819-1 1997). The SPB method is designed for measuring noise from various pavements with great accuracy. The method lays down calculation of a Statistical Pass-By Index (SPBI) according to:

$$SPBI = 10 \times \log\left(\sum W_x \times 10^{\frac{L_{veh,x}}{10}} \right)$$

$L_{veh,\,x}$ is the noise level from vehicles in category x nominated to a distance of 7.5 meters and a speed of 50 km/h. W_x is the weight assigned to the vehicle category. SPBI is a measure of the noise level.

The HGVs on Øster Søgade drive slower than the 50 km/h specified in ISO 11819-1, and because there is a large element of uncertainty involved in extrapolating noise levels from heavy vehicles at such low speeds, the calculated SPBI are modified as shown in Table 5.1 and accordingly labeled SPBI'.

Table 5.1. Reference speeds and weights used for the vehicle categories in ISO 11819-1(1997) and in calculating SPBI'.

		Light vehicles		**HGVs**	
		Passenger cars	**LGVs**	**HGV-2**	**HGV-m**
ISO 11819-1	**Weight W_x**	0.9		0.075	0.025
	Reference speed	50 km/h			
SPBI'	**Weight W_x**	0.8	0.1	0.075	0.025
	Reference speed	50 km/h		45 km/h	40 km/h

The sound pressure level per 1/3 octave band is registered for vehicles passing in normal traffic at the time where the A-weighted sound pressure level with time weighting "Fast" is highest (L_{AFmax}). Through linear regression of the sound pressure level on the logarithm of the speed the noise level at the reference speed is determined for each vehicle category (see Figure 5.1).

A noise reduction expressed as SPBI' corresponds to an equivalent reduction given as $L_{Aeq,T}$, which is usually used for assessing road traffic noise. $L_{Aeq,T}$ measurements are not used in this project as they do not give as exact results as those achieved with the SPB method.

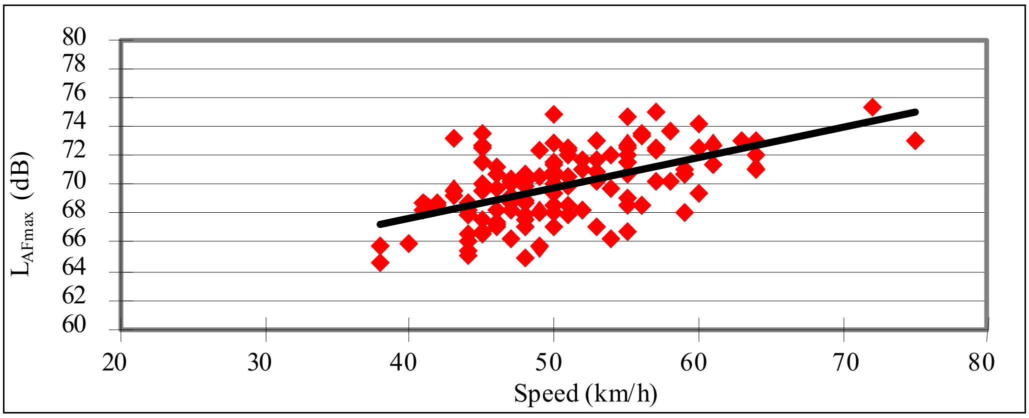


Figure 5.1. Example of results of measurements of noise from 128 passenger cars in a measuring point and the regression line for the noise level as a function of the logarithm of the speed. The value of the regression at 50 km/h is 70.0 dB (DELTA 1999c).

5.2.1 Measuring conditions

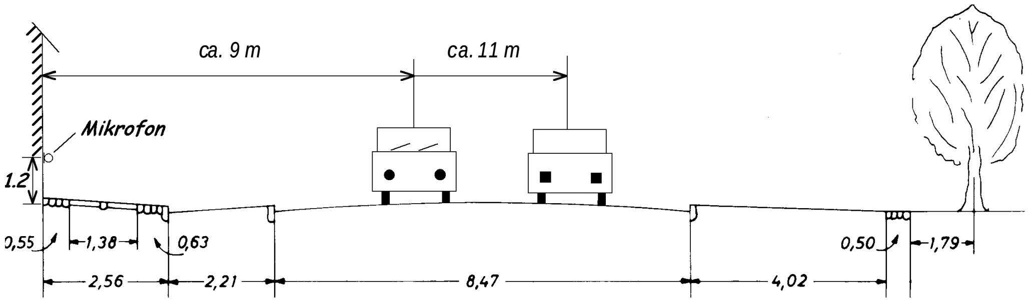


Figure 5.2. Cross section of Øster Søgade with microphone position and typical distances (DELTA 1999c).

In order to control the effect of reflections from the buildings on the eastern side of Øster Søgade the microphones are placed on a board directly on the facade of the buildings as shown on Figure 5.2 and Figure 5.3. Consequently 6 dB was subtracted from the measured sound pressure levels to compensate for the reflections from the board. Thereby the resulting noise levels are A-weighted “free field” maximum levels.

The distance (d) from the road center to the measuring positions have been measured in all twelve positions. All results are normalized to a standard distance of 7.5 meters by subtracting 20×log(d/7.5) from the measured noise level (Road Directorate 1998). In doing so it was presumed that the acoustical centre of the vehicles is located 1 meter from the road center (see Figure 5.2).

Vehicle speed was measured with radar (see Figure 5.4). At most measuring positions the radar was located so close to the carriageway that it was not necessary to correct the registered speed for the angle between the radar beam and the direction of driving. At some measuring positions the speed was corrected by 2 or 3 km/h.

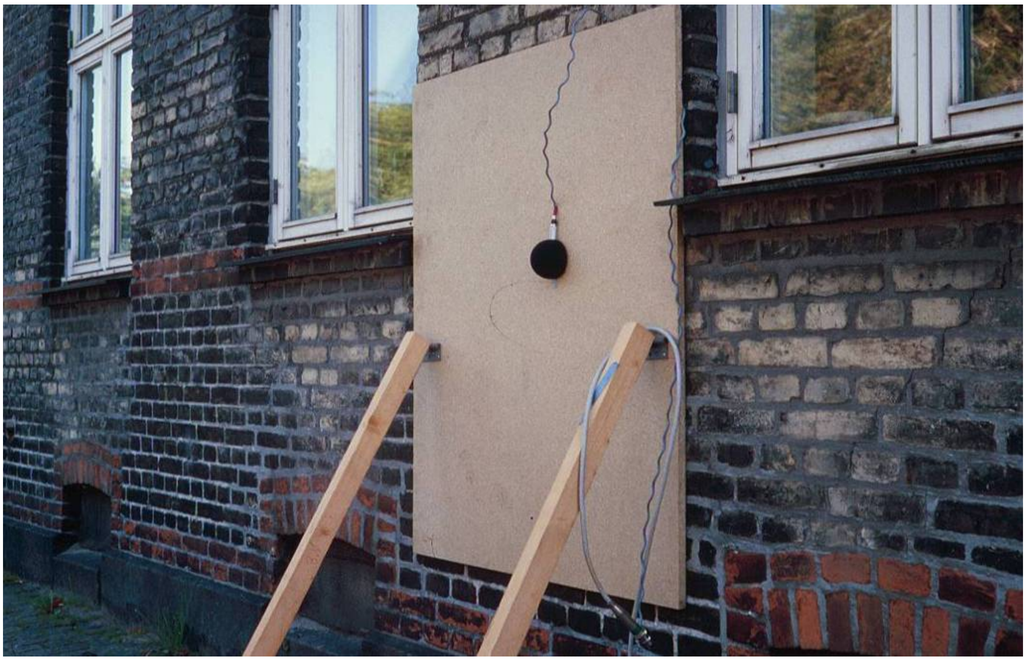


Figure 5.3. Microphone placed on a board on a facade.

Figure 5.4. The vehicle speed is registered by radar as seen in the lower right hand corner.

During measurements the radar emits a slight acoustical signal which tells the person performing the measurement whether a vehicle drives at constant speed, is accelerating or decelerating. Only measurements at constant speed are accepted. For each vehicle which is included in the measurements the maximum noise level, frequency specter, vehicle type, driving direction and speed is recorded.

5.2.2 Number of vehicles

The number of vehicles included in the measurements on each section is shown in Table 5.2. For budgetary reasons the number of measuring points and therefore also the number of vehicles included has been reduced as the project has proceeded.

Table 5.2. The number of vehicles included in the measurements at all measuring points in each year (Bendtsen & Kragh 2007; DELTA 1999c; Kragh 2005; Kragh 2006).

	Measured	Measured at points	Passenger cars	LGV	HGV-2	HGV-m	Total
Old pavement	**March**	All except PA5-55a, DAC8a	1162	609	361	98	2230
1999	**Sept**	All	1659	647	195	65	2566
2000	**Jun/Jul**	All	1442	542	349	80	2413
2001	**Jun/Aug**	All	1425	508	164	36	2133
2002	**June**	All except PA8-70b, DAC8b	1129	451	219	133	1932
2003	**May**	PA8-70a, PA55b, PA5-90b, DAC8a	575	201	99	13	888
2004	**Aug/Sep**	PA8-70a-c, PA55b, PA5-90b, DAC8a-b	783	293	120	56	1252
2005	**June**	PA8-70a, PA55b, PA5-90b, DAC8a	579	198	93	43	913
2006	**June**	PA8-70a, PA55b, PA5-90b, DAC8a	659	214	80	30	983
2007	**April**	PA8-70a, PA55b, PA5-90b, DAC8a	412	76	20	7	515

At all individual measuring points except PA8-70c in year 5 the number of light vehicles – passenger cars and LGVs together – exceeds 100, which is specified in ISO 11819-1. In many cases the number of heavy vehicles on the road has been so small that it has not been possible to do measurements on the required number of these vehicles within a realistic time span (2-3 hours). This is especially the case for the multi-axle HGVs of which there are very few on Øster Søgade. In 2007 no multi-axle HGVs were measured at positions PA5-55b and PA5-90b, and only 4 and 4 were measured at positions PA8-70a and DAC8a.

Therefore, it has not been possible to calculate SPBI' for 2007. For this reason noise levels for passenger cars L_{vehP} is also presented for comparison.

5.2.3 Statistical uncertainty

The statistical uncertainty of the measuring results is determined as defined by Lydteknisk Institut (1988). The uncertainty is half the width of a 90 % confidence interval, corresponding to a 95 % confidence level in a one sided test. This uncertainty in the values of SPBI' is determined for all measuring positions on a test section together. The uncertainty is shown in Table 5.3. For passenger cars it is generally 0.1 dB, and for SPBI' it is between 0.5 and 0.8 dB. The higher level for the SPBI' is due to high levels of uncertainty for the heavy vehicles, of which there are few included in the measurements.

Table 5.3. Statistical uncertainty in dB for passenger cars and SPBI' determined for the three measuring points on each test section together (Bendtsen & Kragh 2007; DELTA 1999c; Kragh 2005; Kragh 2006).

	PA8-70		PA5-55		PA5-90		DAC8 (ref.)	
	Pass	**SPBI'**	**Pass**	**SPBI'**	**Pass**	**SPBI'**	**Pass**	**SPBI'**
Old pavement	0.1 dB	0.1 dB	0.1 dB	0.1 dB	0.1 dB	0.1 dB	0.1 dB	0.1 dB
1999	0.1 dB	0.6 dB	0.1 dB	0.6 dB	0.1 dB	0.6 dB	0.1 dB	0.6 dB
2000	0.1 dB	0.6 dB	0.2 dB	0.8 dB	0.1 dB	0.6 dB	0.1 dB	0.6 dB
2001	0.1 dB	0.8 dB	0.1 dB	0.6 dB	0.1 dB	0.6 dB	0.1 dB	0.6 dB
2002	0.1 dB	0.5 dB	0.1 dB	0.6 dB	0.1 dB	0.6 dB	0.1 dB	0.5 dB
2003	0.2 dB	0.6 dB	0.1 dB	0.7 dB	0.1 dB	0.7 dB	0.1 dB	0.6 dB
2004	0.1 dB	0.5 dB	0.1 dB	0.5 dB	0.1 dB	0.6 dB	0.1 dB	0.5 dB
2005	0.1 dB	0.6 dB	0.1 dB	0.6 dB	0.1 dB	0.6 dB	0.1 dB	0.5 dB
2006	0.1 dB	0.5 dB	0.1 dB	0.6 dB	0.1 dB	0.6 dB	0.1 dB	0.5 dB
2007	0.2 dB	–	0.1 dB	–	0.1 dB	–	0.2 dB	–

The uncertainty of the instruments used for the measurements is assessed to be at least .5 dB. To this is added a contribution from small day-to-day variations in road surface temperature, driving pattern etc. Therefore, the difference in registered noise levels for two road sections should be at least .8 dB in order to conclude that there is a difference between the two sections (Kragh 2005).

5.2.4 Special conditions

In summer 2001 major pipeline work on Dag Hammerskjölds Allé at the northern end of Øster Søgade caused Øster Søgade to be closed to southbound traffic. Measurements of the northbound traffic were carried out in June 2001. In order to measure noise from the southbound lane, the northbound traffic was transferred to the southbound lane for a few days in August 2001. Thus, in 2001 noise for the two lanes were measured on separate days at all positions.

On the DAC8 reference section the drivers going north in the southbound lane found themselves driving towards a barrier across the road at the intersection (see Figure 5.5). This may have influenced the driving pattern in this direction.

Speeds recorded during the noise measurements support this (Kragh 2005). The speeds recorded at the DAC8 section during the noise measurements in August 2001 were lower than at any other of the annual measuring campaigns. Similar reduced speed levels were not seen at the sections with porous pavements.

Figure 5.5. During the measurements in 2001 traffic on Øster Søgade was one-way.

5.3 Noise levels on the old pavement

One reason for measuring noise levels at the old worn down pavement on Øster Søgade was to make sure that there at no measuring point are problems with uneven driving patterns and accelerations, which could cause increased noise levels. In the "before"-measurements, SPBI has been calculated according to ISO 11819-1 without the modification described in Section 5.2. Thus, the noise levels before and after the rebuilding are not directly comparable.

SPBI is shown in Figure 5.6 and noise from passenger cars is shown in Figure 5.7. For practical reasons it was not possible to measure noise at positions PA5-55a and DAC8a before the road works started.

The variation in Figure 5.6 between the 10 measuring points is from 73.1 to 75.8 dB with a mean level of 74.2 dB. At most measuring points noise levels are of the same level, within ±1 dB. At position PA5-55c the SPBI level is 1.6 dB higher than the average level.

The project group judges the varying noise levels to primarily be caused by cracks and holes in the pavement and not by uneven driving patterns along the test road. This is supported by the texture measurements on the old pavement which showed MPD levels of 0.3 to 1.0 mm. This variation indicates an uneven surface with cracks, raveling and holes.

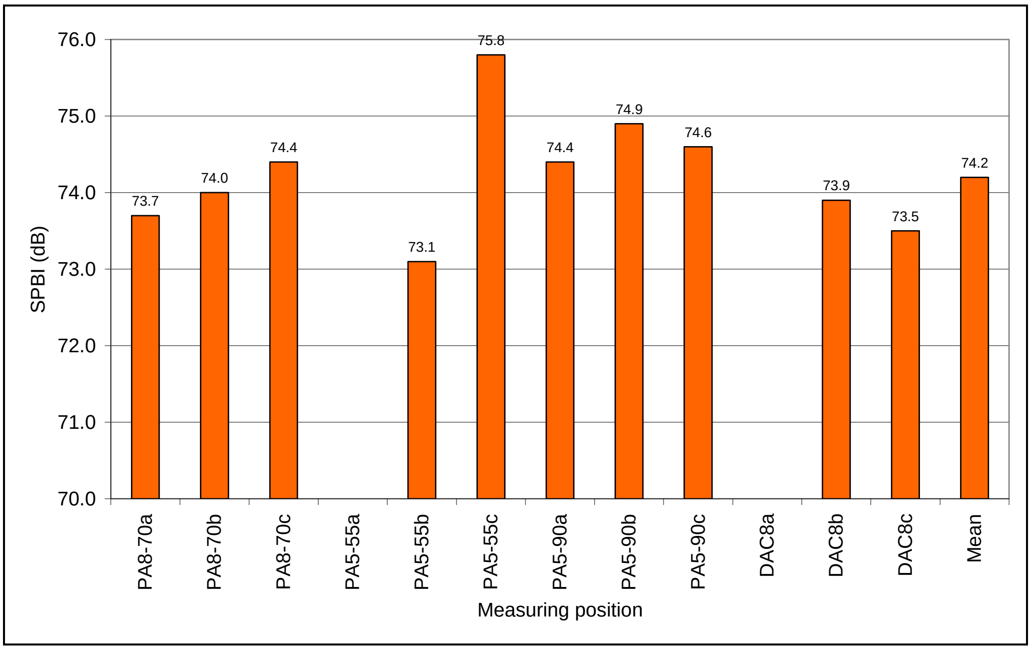


Figure 5.6. SPBI (mixed traffic) for each measuring position before the rebuilding of Øster Søgade in 1999 (DELTA 1999c).

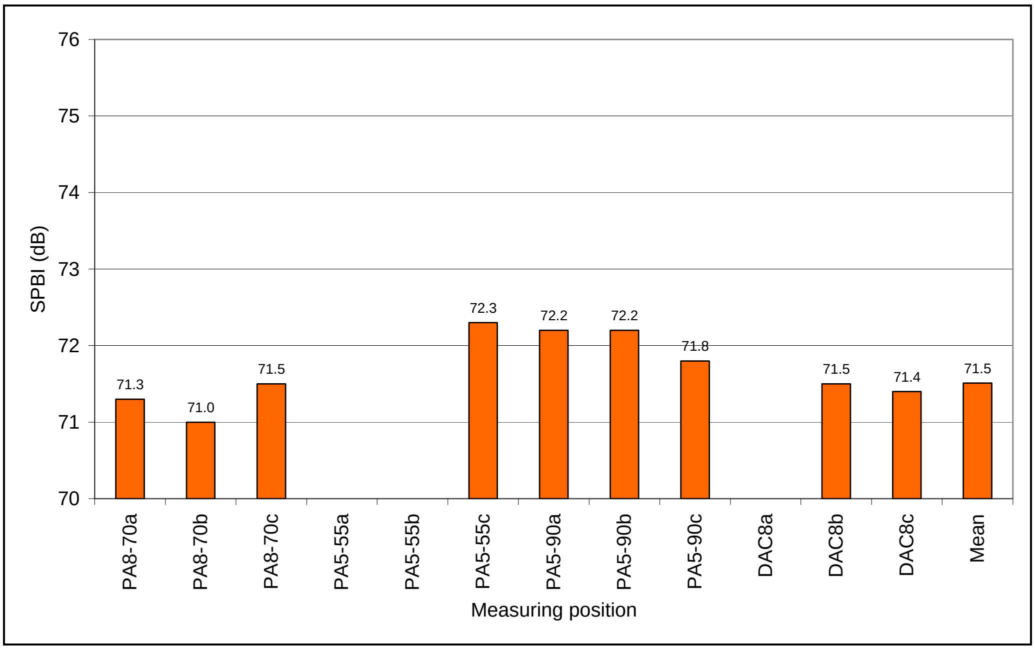


Figure 5.7. LvehP (passenger cars) for each measuring position before the rebuilding of Øster Søgade in 1999 (DELTA 1999c).

5.4 Noise levels at the test sections

Figure 5.8 and Figure 5.9 show the SPBI' results of the noise measurements on the test sections from 1999 to 2006. Figure 5.10 and Figure 5.11 show the noise levels of passenger cars throughout the entire test period from 1999 to 2007. The values from each section are based on measurements from between one and all three measuring points at the section (see Table 5.2).

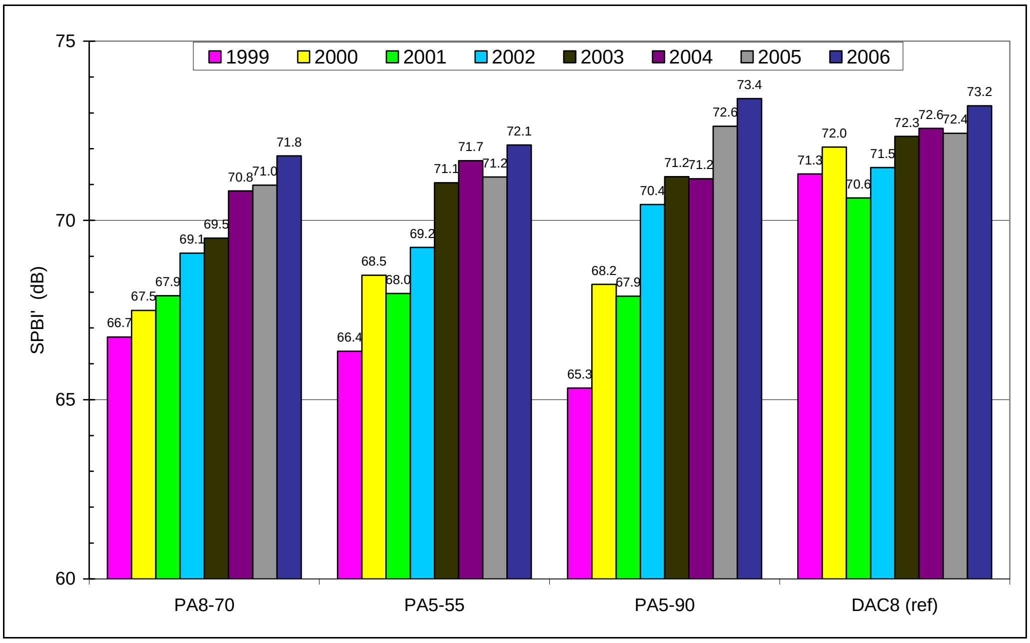


Figure 5.8. SPBI' (mixed traffic) for each of the four test sections (Kragh 2006).

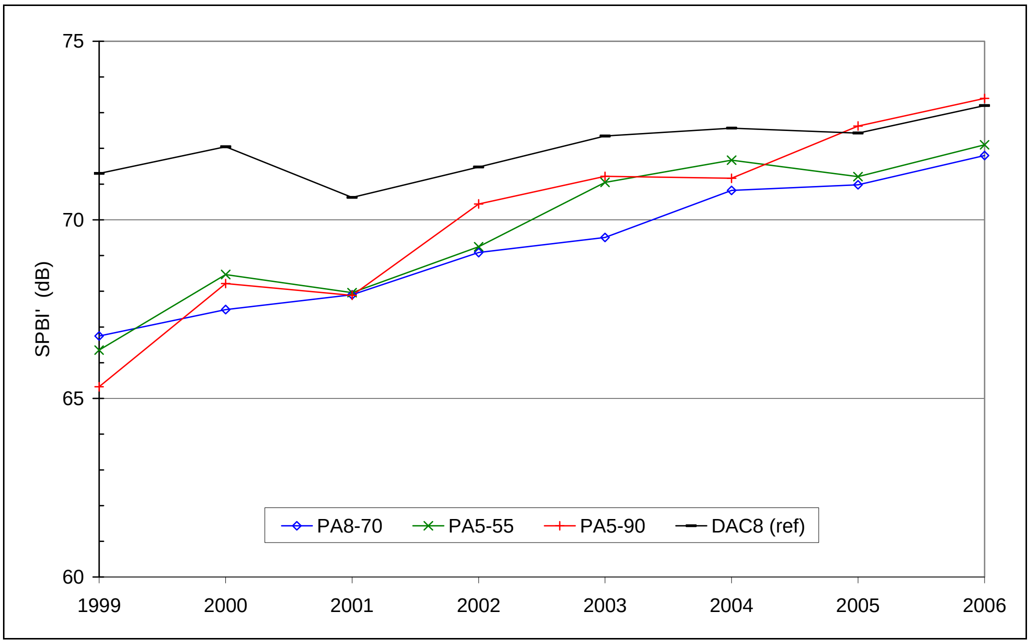


Figure 5.9. SPBI' (mixed traffic) for each of the four test sections (Kragh 2006).

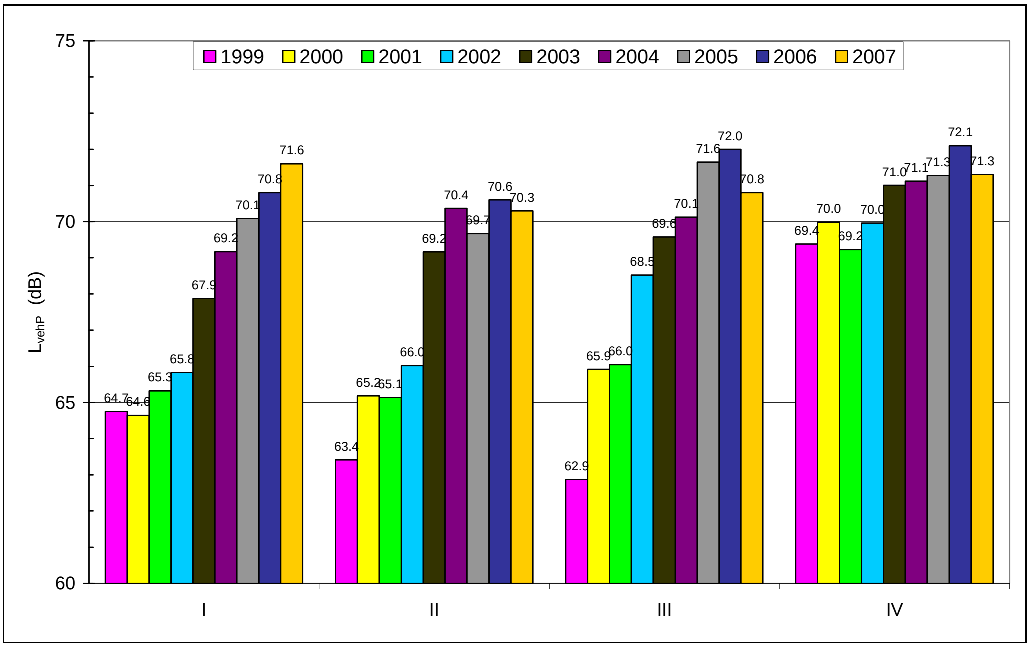


Figure 5.10. LvehP (passenger cars) for each of the four test sections at a reference speed of 50 km/h (Bendtsen & Kragh 2007; Kragh 2006).

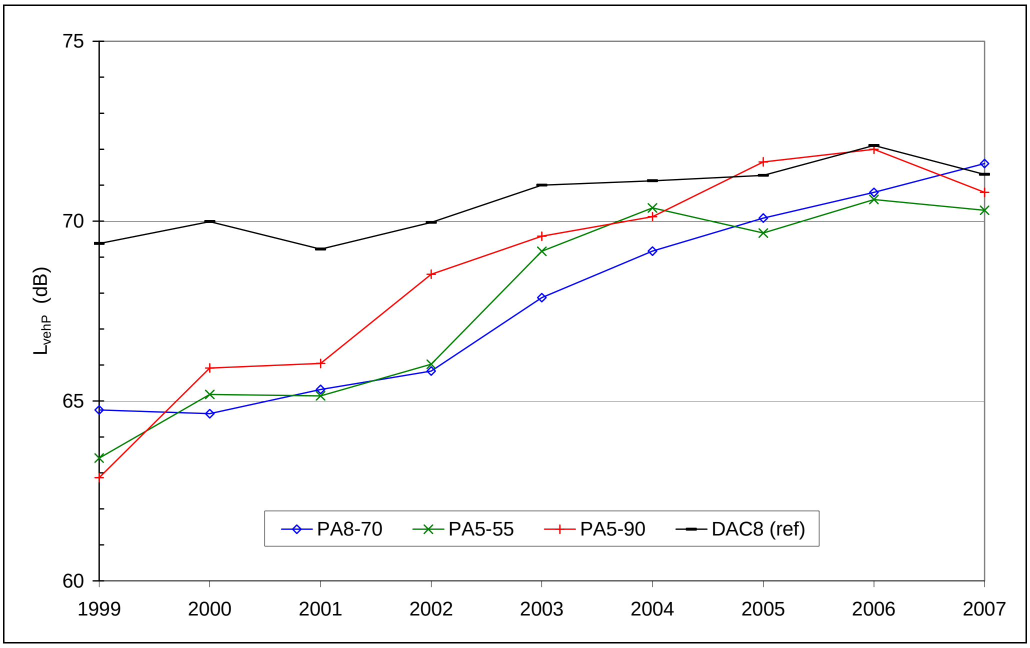


Figure 5.11. LvehP (passenger cars) for each of the four test sections at a reference speed of 50 km/h (Bendtsen & Kragh 2007; Kragh 2006).

5.4.1 Reference pavement

The noise levels at the DAC8 reference pavement generally increase over time. The dip in levels in 2001 is likely to be due to change in driving patterns due to road works (see Section 5.2). The SPBI' levels increase by 0.27 dB/year on average from 1999 to 2006. The L_{vehP} levels increase by 0.24 dB on average from 1999 to 2007 or, if an average of the 2006 and 2007 levels are used as value for 2007, by 0.29 dB.

In any case, the increase in noise levels at the DAC8 pavement on Øster Søgade is significantly higher than the average 0.1 dB for reported by Kragh (2008) for dense asphalt concrete pavements.

After seven and eight years the noise levels from passenger cars (72.1 dB and 71.3 dB) are close to the 71.8 dB level for passenger cars on a DAC11 at 50 km/h in the Danish version of the Nord2000 noise prediction method. The Nord2000 level is based on a series of measurements on DAC11 pavements with an average age of 8 years.

5.4.2 Porous pavements

The very low noise levels at the new PA5-55 and PA5-90 pavements increase by 2-3 dB during the first year and then increase gradually by a total of 5 dB over the following 6 years. The sealing of the two PA5 pavements (see Section 2.7) was performed in September 2005, after the noise measurements for that year were carried out. From 2005 to 2006 noise levels at these pavements increase by between 0.4 and 0.9 dB. Although both the visual inspection (see Section 2.7) and the MPD measurements (see Section 4.1) indicate a smoother surface after the sealing, this does not result in a decrease in the A-weighted noise levels.

At the PA8-70 pavement noise levels increase gradually throughout the whole period, SPBI' by 5 dB till 2006 and L_{vehP} by 7 dB till 2007. The significant increase in noise levels, which is seen on the PA5 pavements is not seen on this pavement. In 2007 L_{vehP} at the PA8-70 pavement is at the same level as at the reference pavement.

5.4.3 Noise reduction relative to the reference pavement

Figure 5.12 and Figure 5.13 shows the noise reduction throughout the test period for each of the porous pavements compared to the reference pavement at the same age. The two pavements with 5 mm aggregate provide very high noise reductions of 5 and 6 dB when they are new, but already after one year the noise reducing potential of the PA8-70 pavement is higher than that of the pavements with 5 mm aggregate. In 2007, where the PA8-70 pavement is the noisiest of the four pavements, there are clear signs of raveling of the pavement. Contrary to the two PA5 pavements the PA8-70 pavement was not sealed in 2005 to prevent further raveling (see Section 2.7).

The PA8-70 pavement has the highest average lifetime (1999-2006) noise reduction of 2.7 dB (SPBI'). On the PA5-55 pavement the average noise reduction is 2.2 dB and on the PA5-90 pavement it is 2.0 dB. For passenger cars the average lifetime (1999-2007) noise reduction is 2.8 dB for the PA8-70 and the PA5-55 pavements. For the PA5-90 pavement it is 2.0 dB.

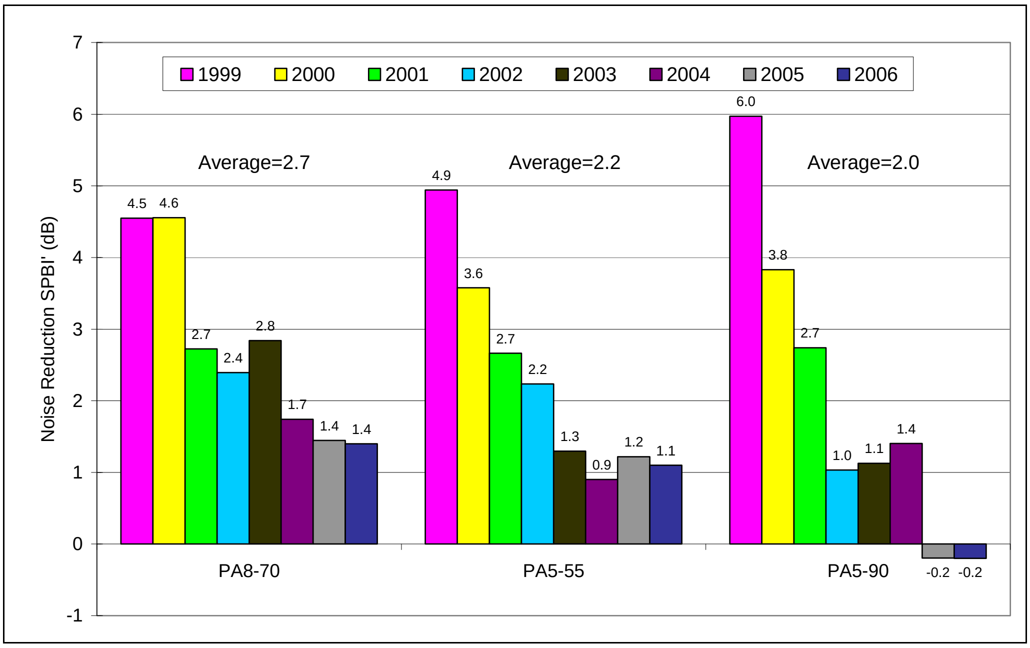


Figure 5.12. Noise reducing effect of the porous pavements defined as the difference in SPBI' (mixed traffic) between the porous pavements and the reference pavement at the same age (Kragh 2006).

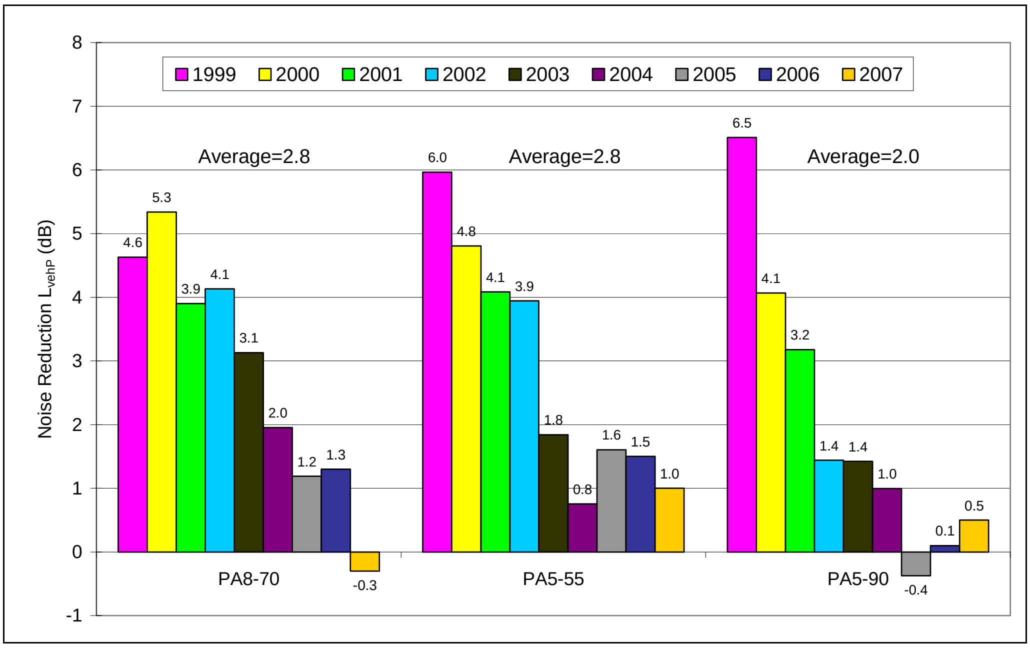


Figure 5.13. Noise reducing effect of the porous pavements defined as the difference in LvehP (passenger cars) between the porous pavements and the reference pavement at the same age at a speed of 50 km/h (Bendtsen & Kragh 2007; Kragh 2006).

5.5 Frequency spectra analyses

The noise has been measured in ⅓-octave band frequency spectra. The uncertainty of the measurement results is lowest for passenger cars (see Table 5.3). Therefore the frequency spectra analyses are based on these results.

A-weighted frequency spectra for both SPBI’ (mixed traffic) and L_{vehP} (passenger cars) for all years for each pavement can be seen in Appendix 3 and for all pavements for each year in Appendix 5. In Appendix 4 differences in frequency spectra between the porous pavements and the reference pavement are shown for all years pavement by pavement, and in Appendix 6 the differences are shown for all pavements year by year.

5.5.1 Evaluation criteria

According to Kuijpers (2001), radial vibrations of the tire carcass and profile elements along with pipe resonances in the channels formed in the tire footprint dominate noise generation at frequencies below 1 kHz. At frequencies above 1 kHz, noise generation is dominated by tangential vibrations of the tire profile elements, stick-slip between tire and pavement, air pumping and Helmholtz resonances (Figure 5.14). The effect of these mechanisms may vary with speed. This is indicated by speed exponents.

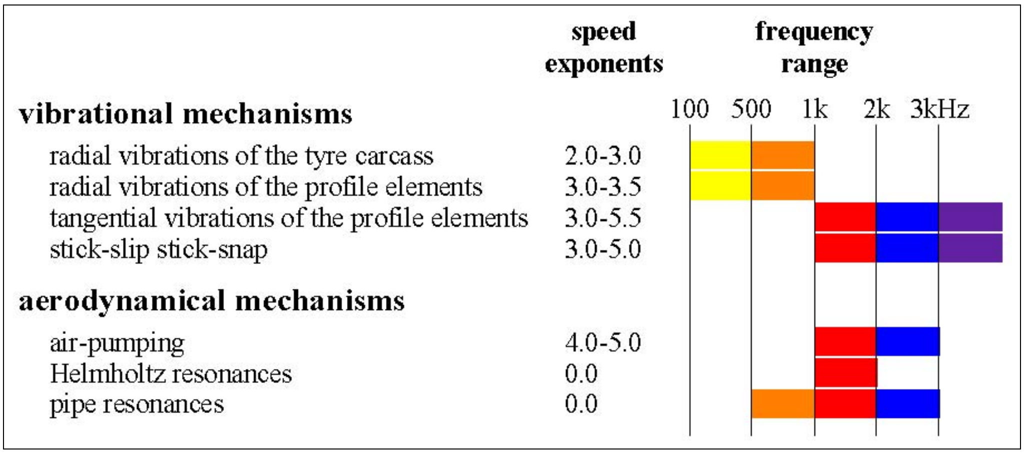


Figure 5.14. Overview of frequency ranges for tire/road noise generation mechanisms (Kuijpers 2001).

The noise generated from vibrations in the tire depends on the texture of the road. The more even the road, the less vibrations and therefore less noise. The vibration generated noise is typically in the frequency range from 500 to 1500 Hz.

The aerodynamic noise generating mechanisms depend on the ability of the air close to or in the thread of a tire to be displaced as the tire roles and as the thread is compacted and expanded when coming into and out of contact with the road surface. he aerodynamic noise is typically in the frequency range above 1000 Hz.

Porous pavements have a capacity for absorbing noise, typically at frequencies between 200 and 1000 Hz and with a clearly distinguishable frequency of maximum absorption.

In the following, comparisons of all the four pavements at various ages are performed. This is followed by more detailed analyses of the development over time of the specters of each of the four pavements. The results of the measurements of the physical condition of the pavements in Chapter 4 are used to interpret the spectral results.

5.5.2 Comparison of all four pavements

Figure 5.15 shows the spectra for the four test pavements when they were new in 1999. The reference pavement has a typical spectrum for dense asphalt concrete pavements with a minimum at 1000 Hz.

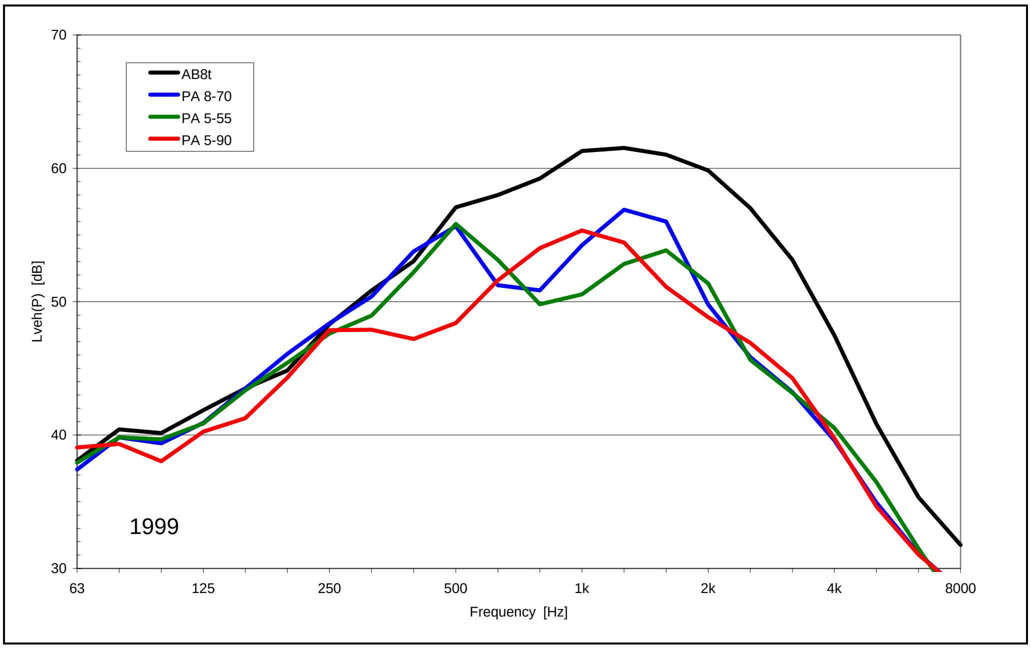


Figure 5.15. A-weighted ⅓-octave band frequency spectra of noise from passenger cars for each of the four test sections in 1999 at a reference speed of 50 km/h (Kragh 2006).

The L_{vehP} levels for the porous pavements are lower than those for the reference pavement at the dominating frequencies. For the PA5-90 pavement the levels are lower at all frequencies above 250 Hz. The PA5-55 and the PA8-70 pavements are lower at frequencies above 400 Hz. The porous pavements all have characteristic dips in the frequency spectra due to the sound absorbing effect of the pavements, the PA5-90 at 400 Hz, the PA8-70 at 630-800 Hz and the PA5-55 at 800-1000 Hz. This indicates that increased thickness of a porous pavement results in the dips in the frequency spectra – and the sound absorption – occurring at a lower frequency. Table 5.4 shows that there is a reasonable correlation between the occurrence of the frequency dips and absorption maxima measured on drill cores (see Section 2.2).

All three porous pavements have significantly lower noise levels at frequencies above 1 kHz. This indicates that the aerodynamic noise is reduced because of the built in air voids which result in open surface textures and communicating pores.

Table 5.4. Absorption maxima measured on drill cores and frequency dips measured for passenger cars in real traffic in 1999.

	Frequency of absorption maximum measured on drill cores (Table 2.5)	Dip in frequency spectra measured in real traffic (SPB measurements)
PA8-70	500-630 Hz	630-800 Hz
PA5-55	500-630 Hz	800-1000 Hz
PA5-90	315 Hz	400 Hz

Figure 5.16 shows the frequency spectra when the pavements were one year old in 2000. There are still indications of the dips in the frequency spectra, although these are far less pronounced than in 1999. This indicates a beginning clogging of the pores, which reduces the noise absorbing effect. There is an indication that noise levels at the porous pavements are increasing relative to the reference pavement at frequencies below 250-315 Hz. According to Kuijpers (2001), this indicates an increase in radial vibrations in the tires.

At frequencies above 1000 Hz the porous pavements are still significantly less noisy than the reference pavement. This indicates that in spite of the beginning clogging of the porous pavements, the surface texture is still open and thus reduces aerodynamic noise.

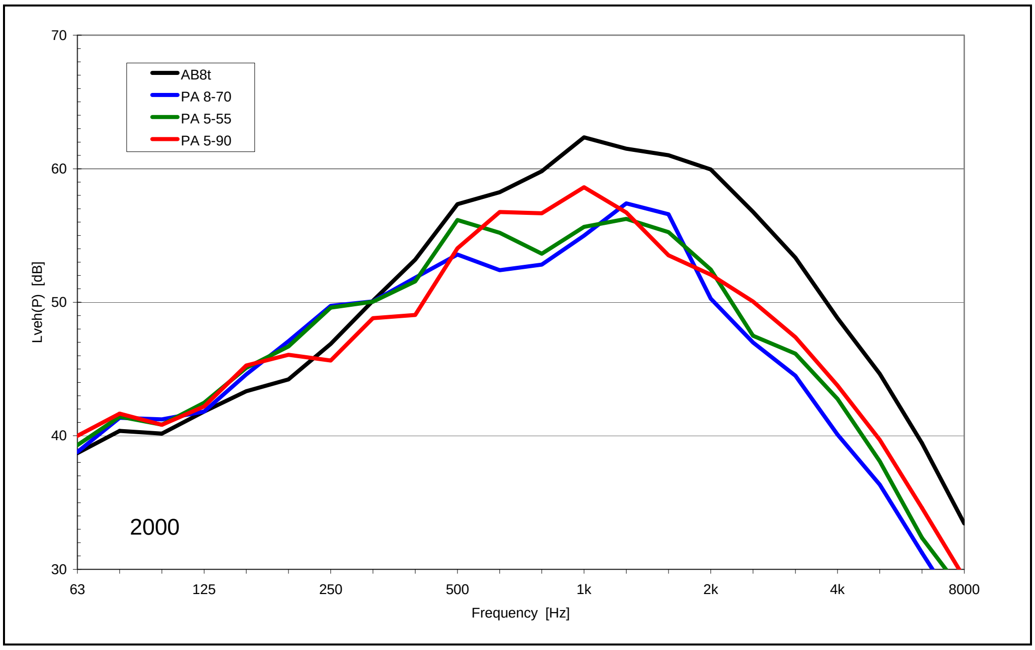


Figure 5.16. A-weighted ⅓-octave band frequency spectra of noise from passenger cars for each of the four test sections in 2000 at a reference speed of 50 km/h (Kragh 2006).

The spectra from 2003 of the four year old pavements are shown in Figure 5.17. The dips in the frequency spectra have disappeared, indicating that the porous structure of the pavements has been disturbed by clogging in the upper layers of the pavements.

This is in agreement with the results of the thin sections of the drill cores (see Section 4.6), which show extensive clogging, and with the measurements of permeability (see Section 4.2), which showed significantly reduced permeability, especially for the two PA5 pavements.

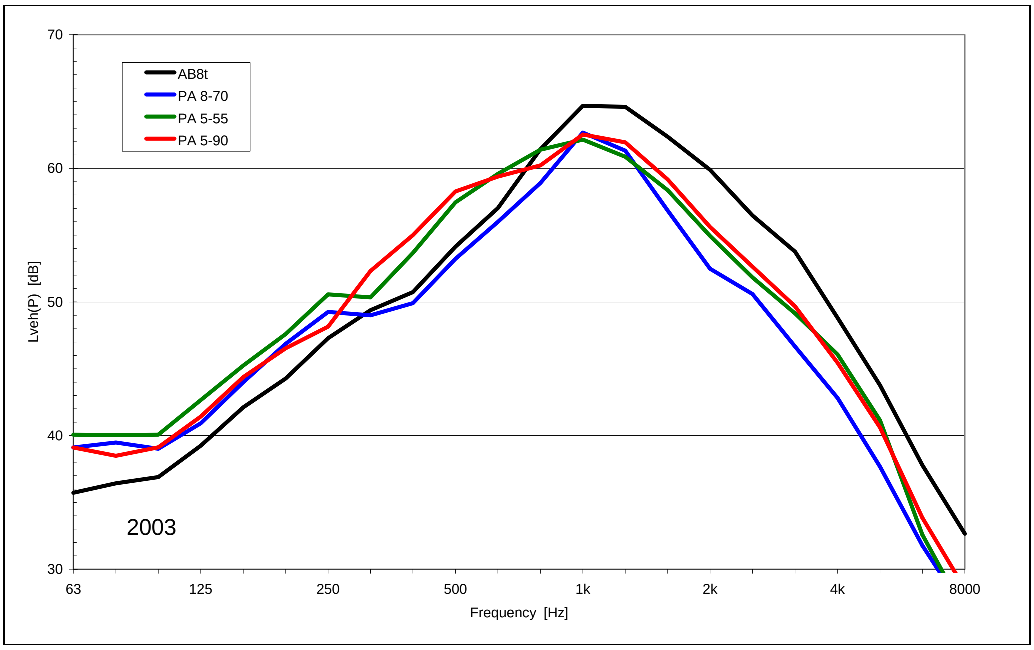


Figure 5.17. A-weighted ⅓-octave band frequency spectra of noise from passenger cars for each of the four test sections in 2003 at a reference speed of 50 km/h (Kragh 2006).

Noise levels have increased at frequencies above 1 kHz, and it is clear that the PA8-70 pavement now performs best at these frequencies. The increase indicates an increase of the aerodynamic noise, which is consistent with the results of the permeability measurements and the thin sections. These measurements also show the PA8-70 pavement to maintain the best permeability of the three test pavements.

At frequencies below 1000 Hz, which are dominated by vibration-generated noise, for the two PA5 pavements and below 315 Hz for the PA8-70 pavement noise levels are higher at the porous pavements than at the reference pavement. This indicates an increase in the roughness of the pavement texture of the porous pavements. The measurements of the mean profile depth of the pavements do indicate slight increases in MPD values (see Section 4.1).

The spectra after eight years from 2007, when the porous pavements were worn down with raveling are shown in Figure 5.18. All three porous pavements are noisier than the reference pavement at frequencies below 1 kHz. This is in agreement with the observations of extensive raveling.

Above 1 kHz the porous pavements still produce lower noise levels than the reference pavement. This indicates that although the pavements are completely clogged – the two PA5 pavements have even had the surface sealed – there is still an open (not porous) structure, which reduces aerodynamic noise.

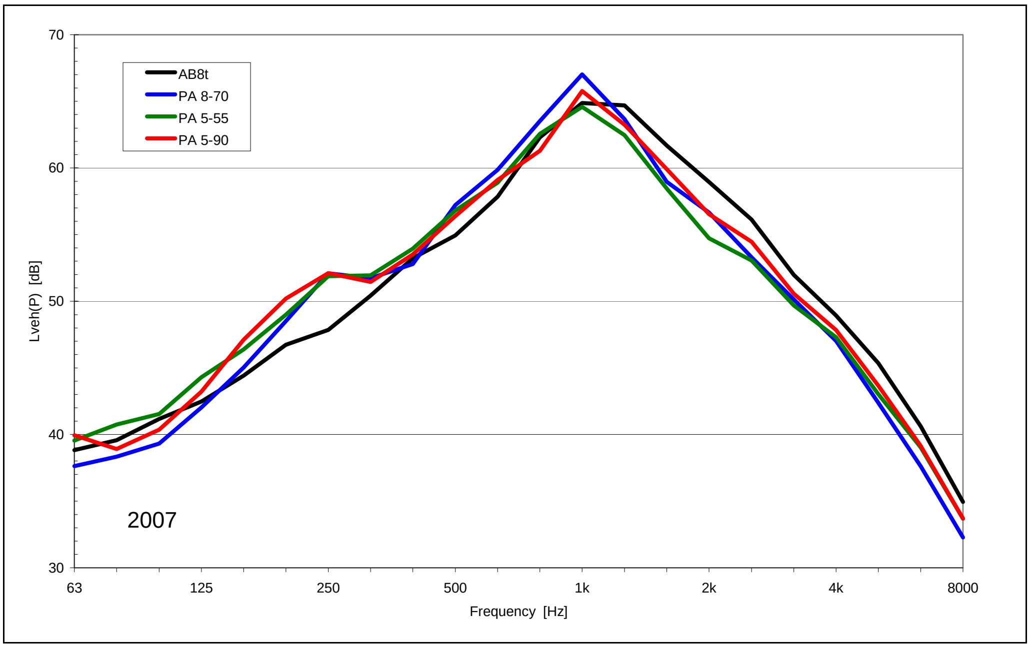


Figure 5.18. A-weighted ⅓-octave band frequency spectra of noise from passenger cars for each of the four test sections in 2007 at a reference speed of 50 km/h.

5.5.3 Each pavement year by year

The spectra for each year for the DAC8 reference pavement for passenger cars can be seen in Figure 5.19. The increase in noise over the eight years primarily occurs in the frequency range from 500 to 1500 Hz. This indicates that it is the pavement surface texture that gets rougher and increases the tire vibrations, thus generating noise. The MPD value increases from 0.3 mm to 0.7 mm from the new pavement was in 1999 to 2007 (see Figure 4.5).

Figure 5.20 show spectra for each year for the PA8-70 pavement. The PA8-70 pavement shows a tendency towards increasing noise levels over time at frequencies higher than 500 Hz. The tendency is clearest at frequencies between 500 and 1250 Hz. In this specific frequency range there are two reasons for the increase in noise. The new pavement has a significant frequency dip at 630-800 Hz, which disappears over the first years as clogging occurs. In the following years raveling starts, thus making the surface rougher. This also increases noise in this frequency range.

The PA8-70 pavement was not sealed in 2005 to prevent raveling (see Section 2.7). The noise around 1 kHz increases steadily from 2004 to 2007 indicating that raveling is ongoing in this period. At the higher frequencies noise gradually increases over the years as the pavement tends to clog. This increase seems to stop in 2004, indicating that the pavement is now clogged.

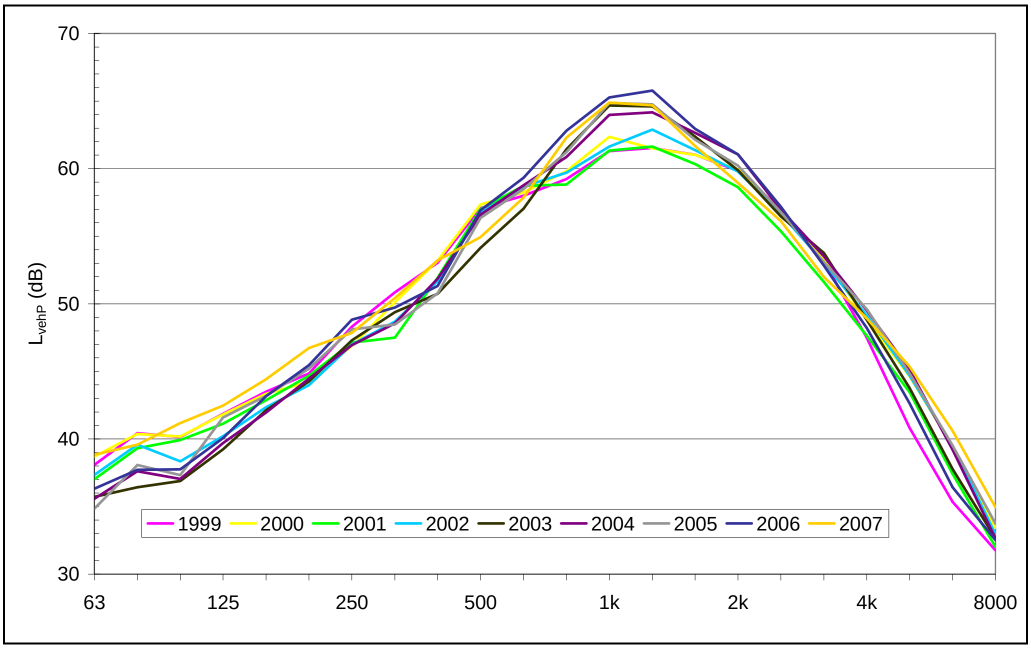


Figure 5.19. A-weighted ⅓-octave band frequency spectra for LvehP (passenger cars) for each year for the DAC8 reference pavement at a reference speed of 50 km/h (Kragh 2006).

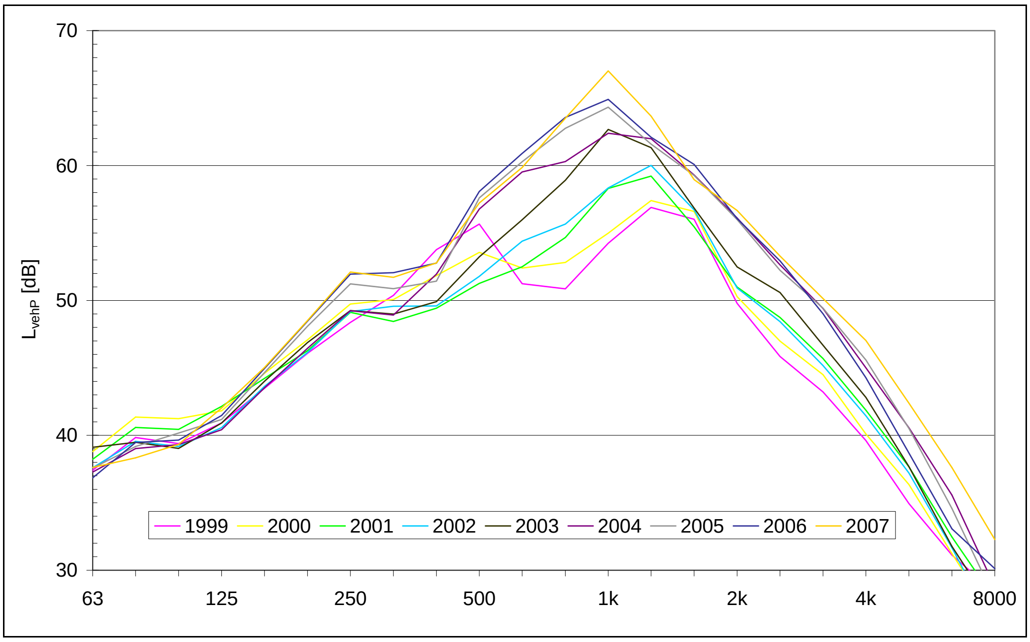


Figure 20. A-weighted ⅓-octave band frequency spectra for LvehP (passenger cars) for each year for the PA8-70 pavement at a reference speed of 50 km/h (Kragh 2006).

Figure 5.21 shows the difference between the year-by-year ⅓-octave band frequency spectra of L_{vehP} for the PA8-70 pavement and the reference pavement. The level of the reference pavement is subtracted from the level of the porous pavement from the same year. Similar spectra for all the porous pavements can be seen in Appendix 4.

The spectra for 1999 to 2001 – perhaps even 2002 – show a first absorption maximum at 500 to 800 Hz. In the later years this maximum has disappeared. There is a tendency that the frequency above which the porous pavement is noise reducing compared with the DAC8 reference pavement increases over time.

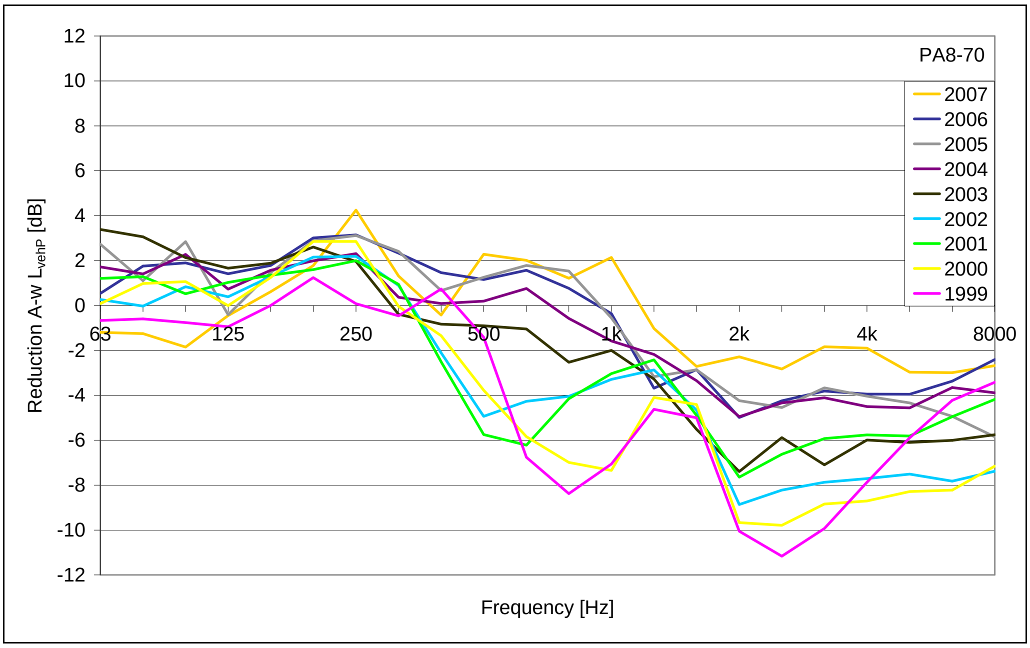


Figure 5.21. Difference in A-weighted ⅓-octave band frequency spectra for LvehP (passenger cars) between the PA8-70 pavement and the DAC8 reference pavement at a reference speed of 50 km/h. The values for the reference pavement are subtracted from the values for the porous pavement from the same year.

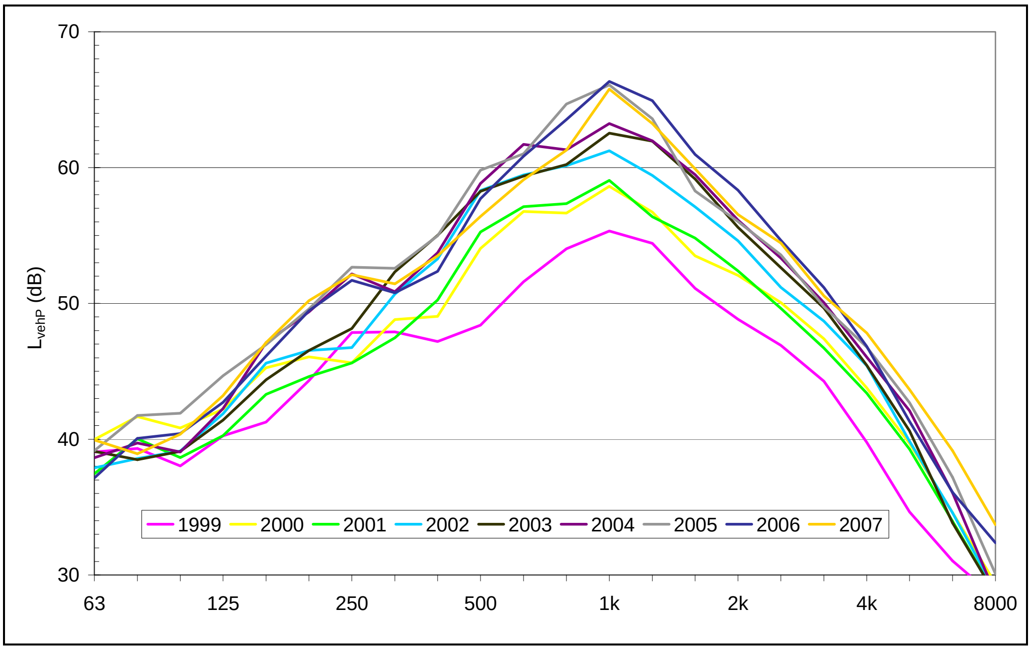


Figure 5.22. A-weighted ⅓-octave band frequency spectra for LvehP (passenger cars) for each year for the PA5-90 pavement at a reference speed of 50 km/h (Kragh 2006).

Figure 5.22 shows spectra for each year for the PA5-90 pavement. This pavement generally shows the same tendencies as the PA8-70 pavement, with one difference. The PA5-90 pavement was sealed after the noise measurements in 2005 to stop raveling. After this the increase in noise around 1 kHz stopped, whereas it continued on the unsealed PA8-70 pavement. This indicates that the sealing of the pavement did indeed stop the raveling. Similar tendencies are seen for the PA5-55 pavement (see Appendix 3 and Appendix 4).

5.6 Summary of the acoustical measurements

The results of the noise measurements from 1999, when the test pavements were new, clearly show that the porous pavements have high noise reducing capacities compared with the DAC pavement. Thereby hypothesis 1[11] is accepted as true.

Hypothesis 2[11] states that the porous pavement with the smallest aggregate size gives the highest noise reduction. This was true when the pavements were new, but already after one year the PA8 pavement is more noise reducing. This is most likely due to clogging of the two PA5 pavements, so if a cleaning strategy can be found, which can keep open the pores of the very fine porous pavements, these may remain more noise reducing than pavements with larger aggregate.

The thick PA5-90 pavement is the most noise reducing when the pavements were new. This may be used to validate hypothesis 3[11]. However, already after one year – and on average throughout the test period – the PA5-90 pavement is the least noise reducing of the three test pavements. This is due to differences in clogging of the three test pavements and has nothing to do with the thickness of the pavements, but still – seen over a longer period of time – this hypothesis cannot be validated based on the data from this project.

Hypothesis 4[11] was already rejected in Chapter 4 because the cleaning could not maintain the porosity of the pavements. The noise results further support a rejection of this hypothesis as the noise reducing capacity of the porous pavements clearly deteriorates throughout the test period.

The frequency spectra show that the noise reduction on the porous pavements mainly is at frequencies higher than 1 kHz. This indicates that the noise reduction mainly is due to a reduction of aerodynamic noise. The difference in vibrational noise between the porous pavements and the reference pavement is small, with a tendency that the porous pavements move from being slightly less noisy at low frequencies than the reference pavement, when the pavements are new to being slightly noisier already after one year.

[11] See page 18.

6. Pavement characteristics and noise

This chapter presents analyses of correlation between measures of the physical state of the test pavements and noise emissions (L_{vehP}). As the percentages built-in voids do not change significantly during the test period, focus will be on texture (MPD) and permeability. Relationships between texture and noise will focus on the northbound lane, as there are no results for the southbound prior to 2002.

The relation between pavement texture and noise emissions from passenger cars is shown in Figure 6.1. As it is seen in Figure 4.3 and Figure 4.4 the very high MPD values for the porous pavements in 1999 differ significantly from the later results and may be considered to be 'outliers' that can be excluded from the analyses. The values for 2007 for the two PA5 pavements may also be excluded, as these two pavements were sealed in September 2005. The relationship without these values is shown in Figure 6.2. As it is seen from the R^2-values of the regression models in the figure, there is a good correlation between MPD and noise.

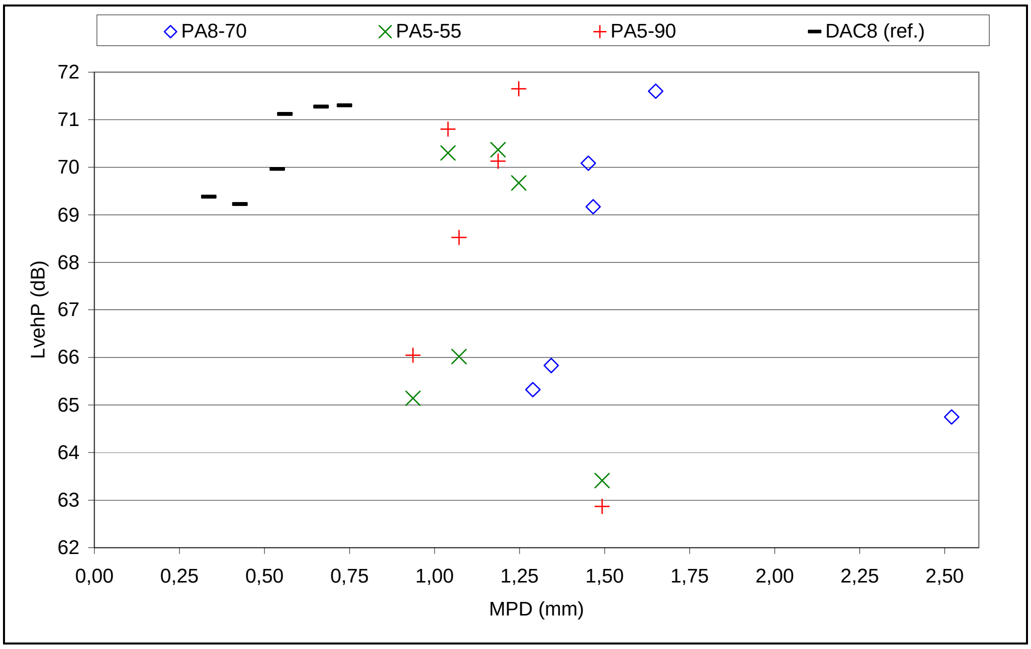


Figure 6.1. .Relationship between pavement texture (MPD – average of left and right wheel track) and noise emissions from passenger cars (LvehP) for the north bound lane for each pavement.

The comparable slopes of the trend lines for the three porous pavements indicate that this may be a characteristic of porous pavements. This, however, should be confirmed by further results before any conclusions are drawn. There is a difference of 1.3 dB in the values of the constants of the regression models for the two PA5 pavements. This may be due to the different thickness of the pavements, but it may also be caused by a difference, which is not accounted for by the data in this survey.

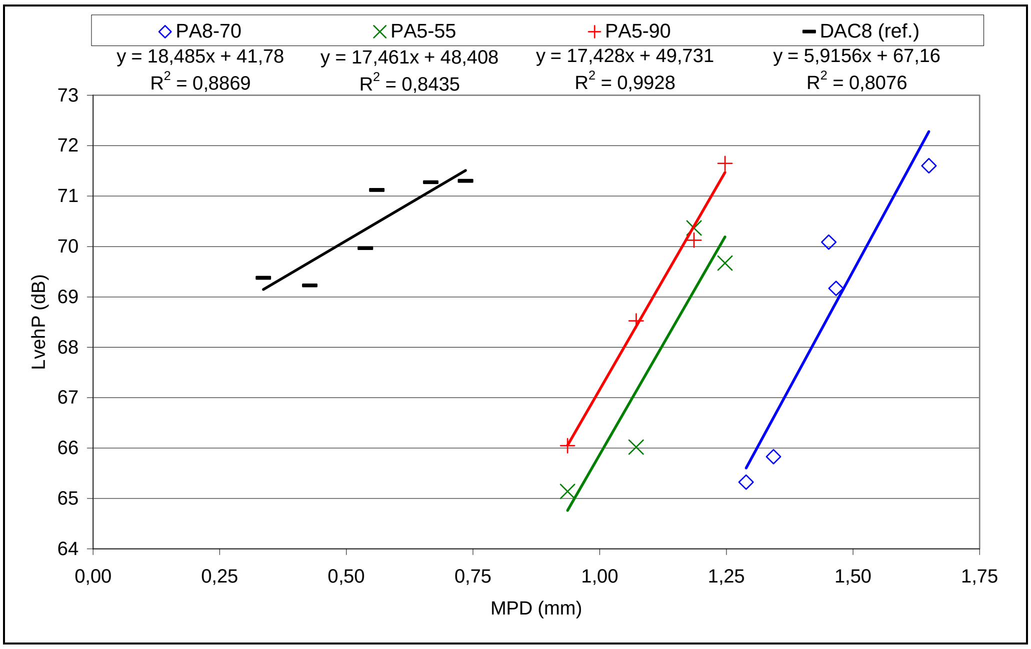


Figure 6.2. Relationship between pavement texture (MPD – average of left and right wheel track) and noise emissions from passenger cars (LvehP) for the north bound lane for each pavement. Data from 1999 is excluded for all three porous pavements, and data from 2007 is excluded for the two PA5 pavements.

Figure 6.3 shows the relationship between the permeability of the porous pavements measured with the Becker's tube method and noise emissions from passenger cars. As seen in the figure and also indicated by the R^2-values, the correlation is quite good for a logarithmic regression for the PA8-70 pavement, and poor for especially the PA5-55 pavement.

If the relationship is seen for the north- and southbound lanes separately (Figure 6.4 and Figure 6.5), the correlations for the northbound lane are better than for the southbound for all three pavements. In fact a comparison of the standard error of the estimate (2.09) of the regression model for the PA5-55 pavement in Figure 6.5 with the standard deviation (2.74) of the noise levels for the pavement shows that the model does not improve estimates of noise levels noticeably. For all other pavements and directions the standard errors of estimate are much lower than the standard deviations. This indicates that especially for the PA5-55 pavement southbound there are one or more confounding parameters for determining the noise emissions, which have not been accounted for.

A closer look at the distribution of the individual data points for the 5 mm porous pavement in Figure 6.5 indicates that the apparent correlation between permeability and noise emission should be viewed with some caution as the majority of the data points are spread out at a permeability measure of 75 seconds per ten cm of water.

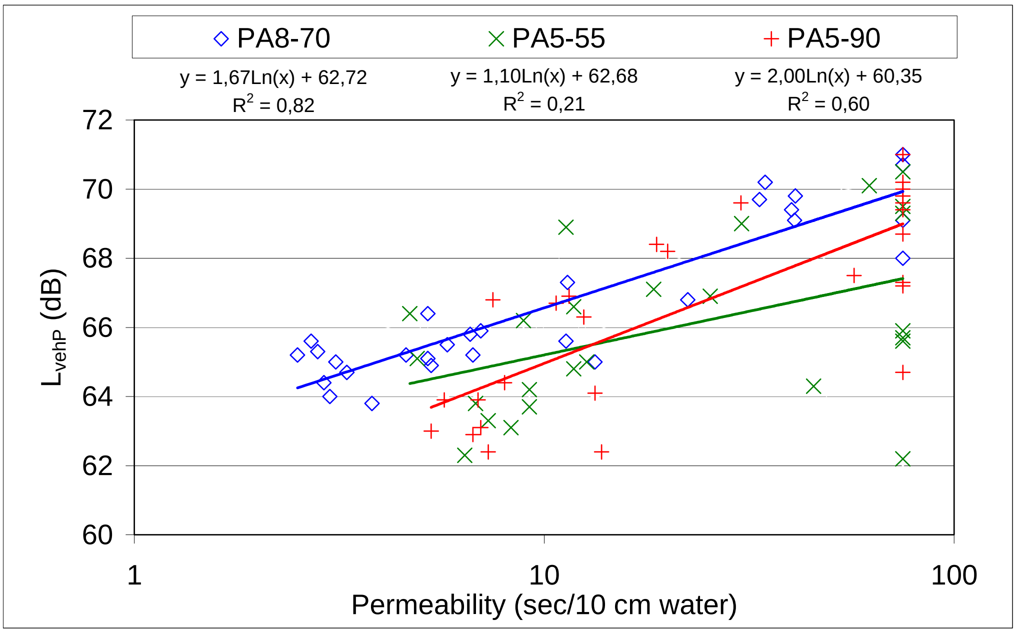


Figure 6.3. Relationship between pavement permeability – measured with the Becker's tube method – and noise emissions from passenger cars for the north- and southbound lanes together for each porous pavement.

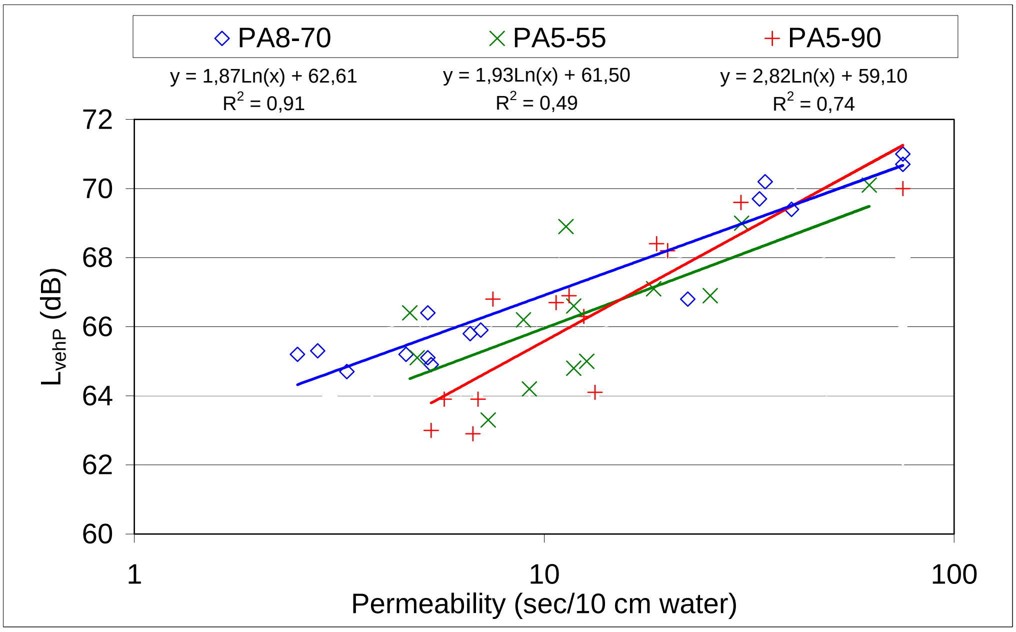


Figure 6.4. Relationship between pavement permeability – measured with the Becker's tube method – and noise emissions from passenger cars for the northbound lanes for each porous pavement.

From Figure 4.7 and Figure 4.8 it is clear that the PA5 pavements lost their permeability after just a couple of years in the southbound lane, whereas the PA8-70 pavement southbound and all three pavements northbound remained permeable for four or more years. Therefore, the apparent correlations between permeability and noise levels, which are seen in Figure 6.3-Figure 6.5 may in fact contain a correlation with other pavement characteristics (for example surface structure), which changes over time. This is supported by Figure 6.6, which indicates a correlation between the age labels of the data points and the noise levels.

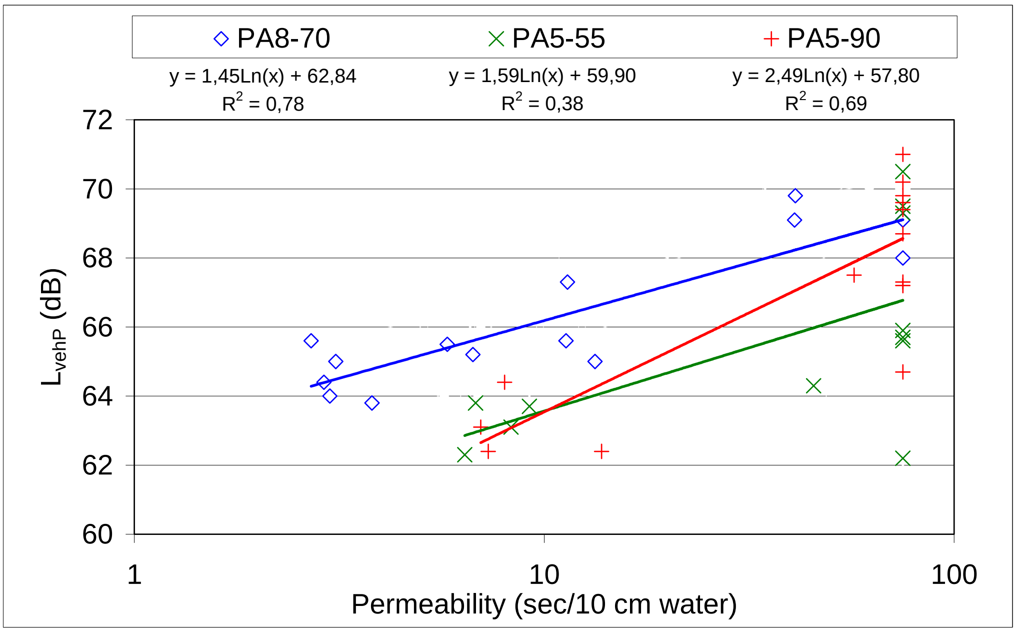


Figure 6.5. Relationship between pavement permeability – measured with the Becker's tube method – and noise emissions from passenger cars for the southbound lanes for each porous pavement.

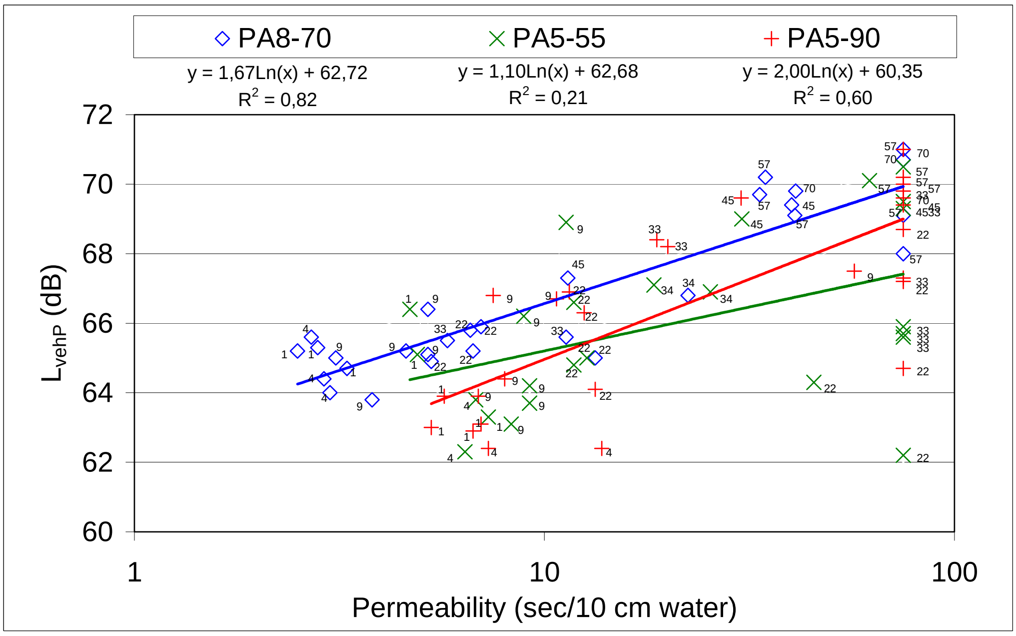


Figure 6.6. Relationship between pavement permeability and noise emissions from passenger cars for all three porous pavements in both directions. Each data point has been labeled with the month of the measurement.

A closer analysis of the data does indicate that the age of the pavement – or rather one or more pavement characteristics for which age is a proxy – is also an important parameter and thus a confounder to the correlation between permeability and noise. It is clear from Figure 4.5 that MPD increases over time. Thus this may be one pavement characteristic for which age is a proxy.

A multiple regression analysis with permeability[12] (perm), MPD[13], pavement thickness (thick) and top-layer aggregate size as independent variables for predicting L_{vehP} produces a model with an R^2 of 0.67. The standard error of the estimate of the model is 1.34, which is lower than the standard deviation of the dependent variable L_{vehP} (2.22), so the model does give a better estimate of the noise levels than if one simply calculates the average value.

All independent variables except the permeability are significant, but the coefficient for aggregate size is negative so that noise increases with decreasing aggregate size. The explanation for this unlikely outcome may very well be that there is a high correlation between aggregate size and MPD (0.84). Aggregate size is therefore not used as explanatory variable. A new regression with permeability, MPD and pavement thickness results in the following model with a standard error of the estimate of 1.59:

$$L_{vehP} = 53.93 + 1.20 * \ln(perm) + 5{,}51 * MPD + 0{,}04 * thick \qquad (R^2{=}0{,}52)$$
$$(p{=}0{,}000)(p{=}0{,}000) \quad (p{=}0{,}000) \quad (p{=}0{,}016)$$

As mentioned above there are no texture measurements for the southbound lane prior to 2002, so the MPD values used in the above regressions are from the northbound lane. These may not be valid, so regression is also done for the northbound lane alone. This results in a model with higher R^2 (0.847) and a standard error of 0.8944. However, pavement thickness is no longer significant. The resulting model without pavement thickness (SE: 0.905) is:

$$L_{vehP} = 58.07 + 2.09 * \ln(perm) + 2.77 * MPD \qquad (R^2{=}0{,}834)$$
$$(p{=}0{,}000)(p{=}0{,}000) \quad (p{=}0{,}021)$$

The R^2 value is fairly high, but it appears that there are still one or more parameters for determining L_{vehP}, which are not accounted for in the data. Figure 6.7 shows the results of the model.

[12] Data for permeability is the natural logarithm of the drainage times for 10 cm of water found in the Becker's tube measurements.

[13] Excluding the 'outliers' from 1999 on all three porous pavements and also the measurements from 2007 on the sealed sections with PA5.

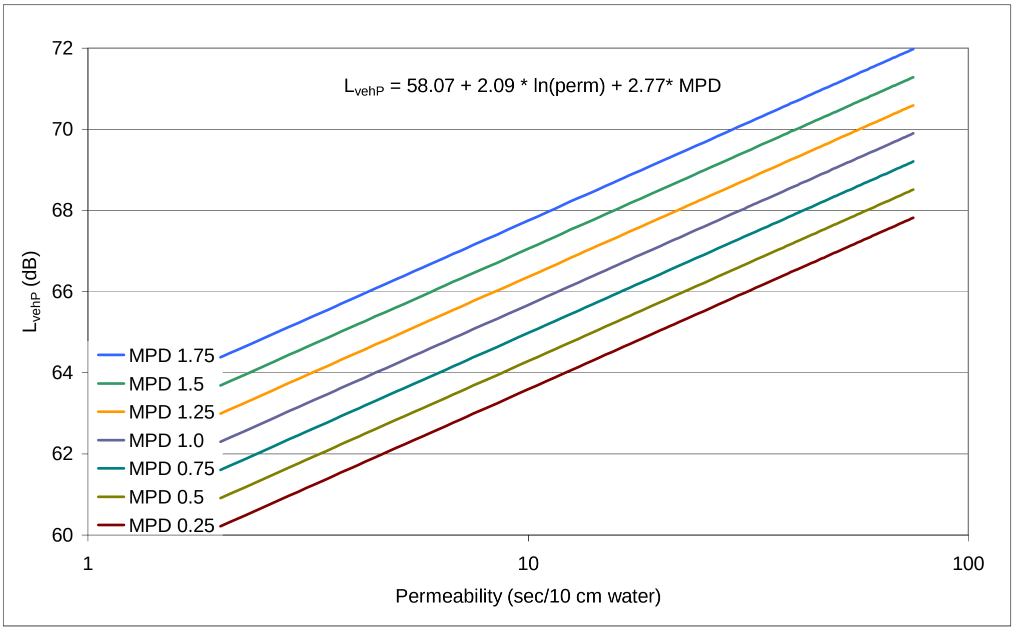


Figure 6.7. Noise emissions from passenger cars (LvehP) as a function of pavement permeability and texture (MPD) for all three porous pavements in the northbound lane.

7. Conclusions

Three types of two-layer porous pavements have been tested on an urban road with a speed limit of 50 km/h. Annual measurements including noise, permeability, texture (MPD - mean profile depth) and air voids have been performed from the pavements were new in 1999 and until the top layers were worn down in 2007. High noise reductions of 4.5 to 6.0 dB – relative to a dense asphalt concrete reference pavement with 8 mm maximum aggregate size of the same age – were achieved from mixed traffic when the pavements were new.

7.1.1 Noise reduction

The noise reduction was mainly due to the following three factors:

4. The medium frequency noise generated from vibrations in the tire was reduced by using small maximum aggregate size of 5 mm (PA5-55 and PA5-90) and 8 mm (PA8-70). The frequency spectra show indicate reduced vibration generated noise when the pavements were new. As they age raveling occurs, first on the two PA5 pavements. These two pavements were sealed in 2005. This stopped the raveling process. Significant raveling was first observed on the PA8-70 pavement in 2007.
5. The high frequency aerodynamic noise was reduced by using high percentages built-in air voids of 23.7 to 26.6 percent to create high porosity in the pavements. When the pavements were new, there were high reductions of noise at frequencies above 1 kHz. The pores started to clog in the upper part of the top layer, which resulted in increasing high frequency noise. The PA8-70 pavement maintained the highest noise reducing capacity as the pavements aged.
6. The noise absorbing capacity of the pavements was optimized by the high percentage built-in air voids combined with thick pavement layers with communicating pores. High noise absorption was seen as noise level dips at frequencies between 400 and 800 Hz when the pavements were new. After two years these dips disappeared because of clogging of the upper part of the top layers. This “closed off” the connection to the porous structure in the pavements.

7.1.2 Surface characteristics

The MPD-results of the laser measurements indicate that raveling occurs and that the pavements turn rougher and thereby noisier as they age. There is a strong correlation between MPD and noise levels on the individual test pavements.

The Becker's tube measurements of permeability show that the PA8-70 pavement retains its permeability longer than the two PA5 pavements, which clog up after 3-4 years. At this time the noise reducing effect compared to the reference pavement is close to only 1 dB. The PA5 pavements do not appear to be suitable on urban roads as means of noise reduction unless a different cleaning strategy can produce better results at maintaining their porosity and thereby their acoustical lifetime.

On the PA8-70 pavement the correlation between permeability and noise emissions is quite high. There is also a fair correlation for the PA5-90 pavement, whereas it is poor for the PA5-55 pavement. A regression with permeability and MPD as independent variable for predicting L_{vehP} produces a model with a fair ability to predict noise levels, but there appears to still be one or more parameters, which influence the noise, which are not accounted for in the data.

On both PA5 and PA8 pavements the clogging starts where vehicles drive onto the porous pavements from dense pavements. This indicates that at least part of the clogging is due to material, which is dragged onto the porous pavements by vehicles. Thus, it is likely that longer sections of porous pavements will maintain their porosity and thereby their noise reducing effect longer than the short test sections in this project.

Although the Becker's tube method for measuring permeability gives clear results on the degree of clogging of the pavements, it should be considered whether a measure of clogging which is based on air flow will produce results that better reproduce the ability of the pavements to reduce aerodynamic noise.

It is clear from the CT-scans and the thin and plane sections of drilled cores that the clogging takes place in the top layers. The bottom layers appear to maintain their porosity and thereby the ability to lead away water and dirt. It is therefore possible that better cleaning strategies may be better at maintaining the permeability and thereby also the noise reducing effect of the porous pavements.

Bitumen tests show hardening of the binder in the porous pavements. In the thin and plane sections this can be seen to have lead to deterioration of the pavements with adhesion problems and cracks in the binder. This, together with crushing of the aggregate, has lead to extensive raveling which necessitated sealing of the pavements.
As SBS-modified bitumen is used for the porous pavements in this project, other means of reducing raveling must be developed if the structural lifetime of porous pavements is to be increased.

7.1.3 Hypotheses

The following seven hypotheses regarding the functionality of the porous test pavements were defined when the project was started:

1. New two-layer porous pavements have high noise reducing capacities on urban roads compared to dense asphalt concrete. Noise levels at the new porous pavements were between 4.5 dB and 6.0 dB lower than those at the reference pavement for mixed traffic and 4.6 to 6.5 dB lower for passenger cars. Thus, this hypothesis accepted as true.
2. The two-layer porous pavement with the smallest aggregate size has the best noise reduction. When the pavements were new, this was certainly the case, but seen over the whole test period the PA8-70 pavement has the highest noise reducing capacity with an average noise reduction over the eight year period of 2.7 dB for mixed traffic compared to 2.0 and 2.2 dB for the two PA5 pavements. Thus, this hypothesis is rejected. It may be true, if a cleaning strategy can be found, which can maintain the porosity of the PA5 pavements.
3. The thickest of the two-layer porous pavements has the best noise reduction. This was certainly true, when the pavements were new, but already after one year and throughout the remaining test period the PA5-90 pavement is the least noise reducing of the three porous pavements.
4. Using yearly high pressure cleaning of the pavements will maintain their porosity and high acoustical absorption and for these reasons they will keep their high noise reducing capacities in their entire lifetime on urban roads. As there are no test sections to compare with, which were not cleaned, it cannot be concluded whether the cleaning has had an effect on the clogging, but the full porosity and noise reducing capacities were not maintained throughout the test period. Therefore this hypothesis is rejected.
5. Roads in urban areas with fine graded porous pavements have the same traffic safety quality (same risk levels) as ordinary roads. This matter has not been treated in this report, but based on observations by the project group and on Greibe (2000), Greibe (2002) and Bendtsen, Larsen & Greibe (2002) this hypothesis is accepted as true.
6. There are no special problems with winter maintenance connected to using fine graded porous pavements in urban areas. This has not been treated in this report. Winter maintenance on Øster Søgade has been no different than on similar roads in Copenhagen, and the municipality has observed no special problems on the road. Thus, this hypothesis is accepted as true for this project.
7. The lifetime of two-layer porous pavements is the same as that of ordinary dense pavements on urban roads. As the top layers of the test pavements had to be sealed after six years and renewed after eight years due to serious raveling, this hypothesis is rejected.

7.1.4 Continuation

In June 2007, the top layers of the worn down pavements were milled off and replaced by new porous top layers with 8 mm maximum aggregate size. It is an objective to continue a measurement program on the new top layers.

Appendix

Appendix 1 – Permeability measurements.

Appendix 2 – CT-scan of pavements.

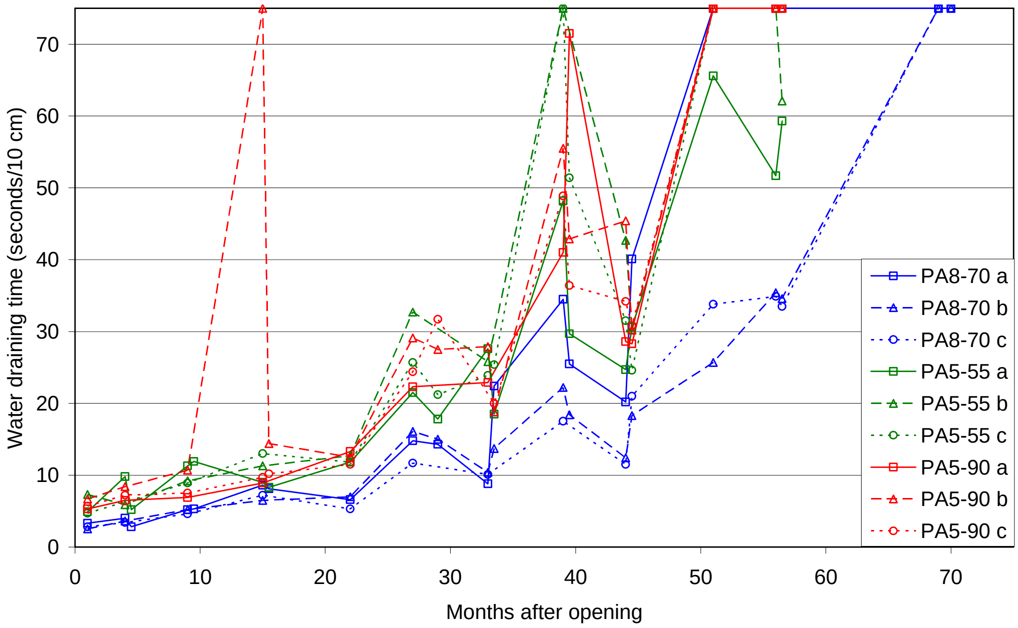
Appendix 3 – Frequency spectra pavement by pavement.

Appendix 4 – Differences in frequency spectra between the porous pavements and the reference pavement – pavement by pavement.

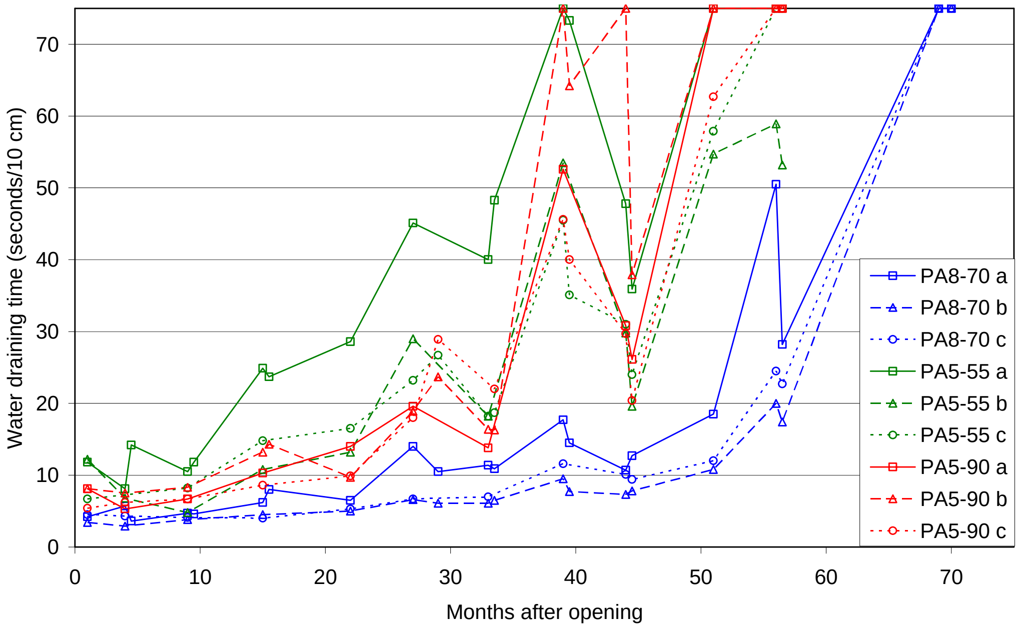
Appendix 5 – Frequency spectra year by year.

Appendix 6 – Differences in frequency spectra between the porous pavements and the reference pavement – year by year.

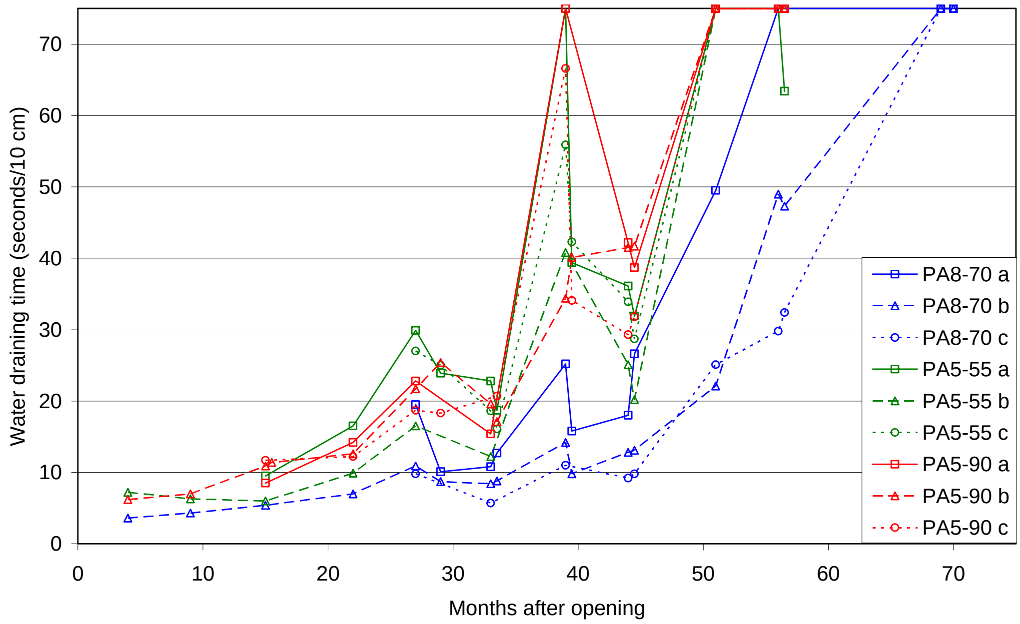
Appendix 1
– Permeability measurements



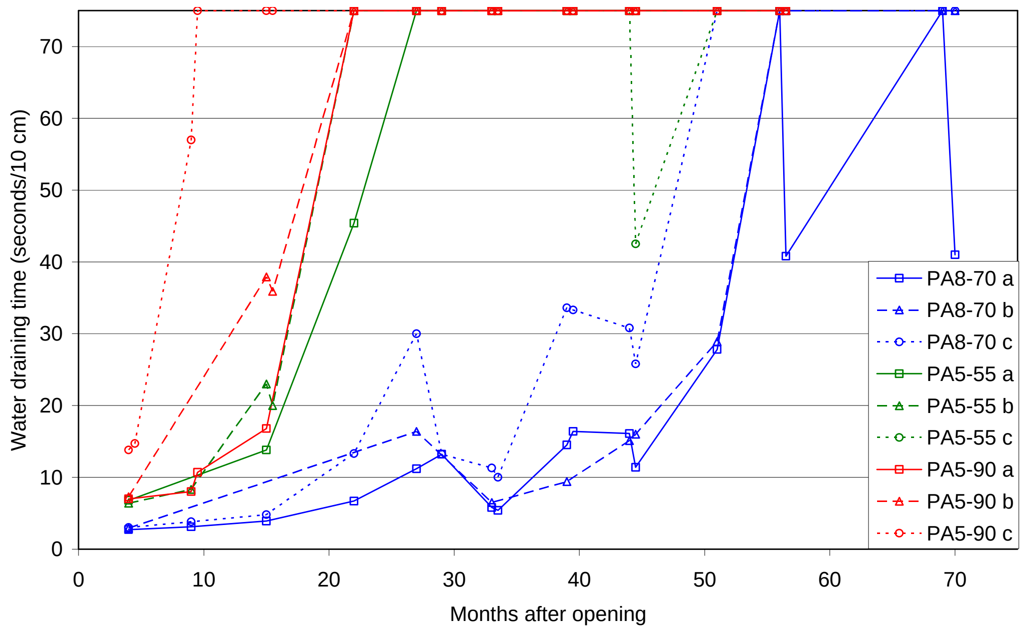
Northbound lane, right wheel track.



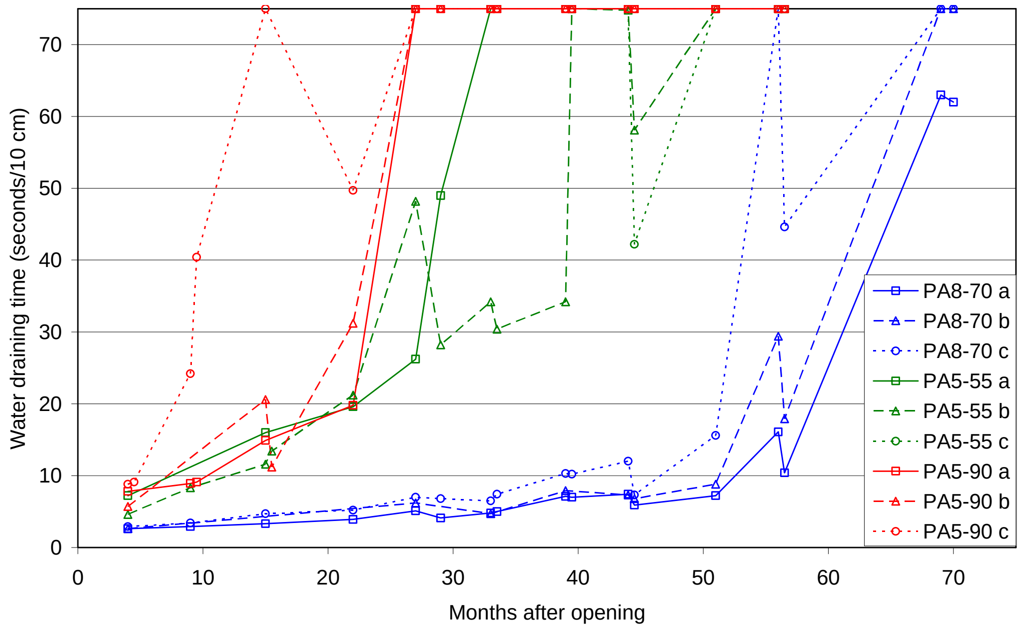
Northbound lane, between wheel tracks.



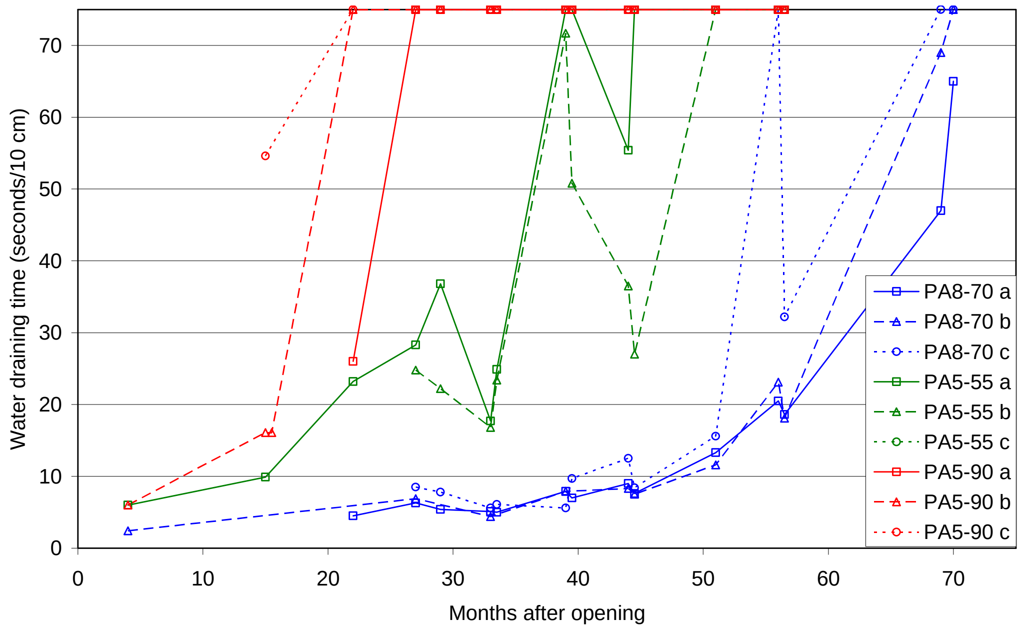
Northbound lane, left wheel track.



Southbound lane, right wheel track.



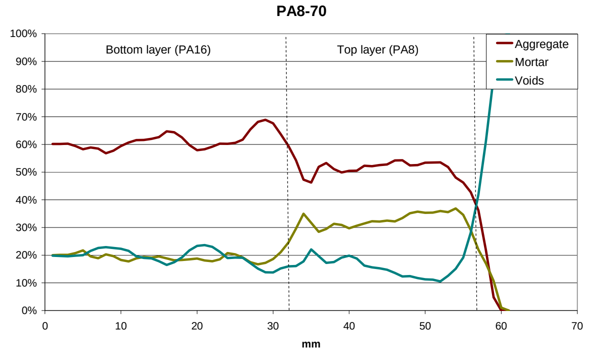
Southbound lane, between wheel tracks.

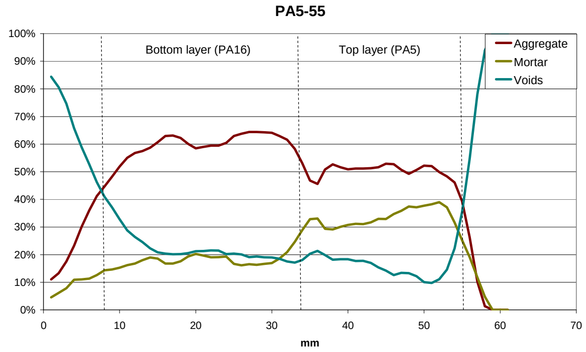


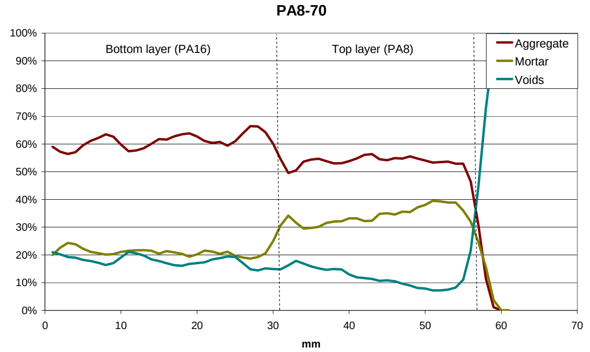
Southbound lane, left wheel track.

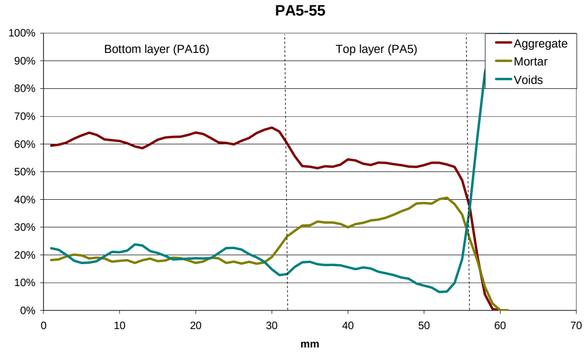
Appendix 2

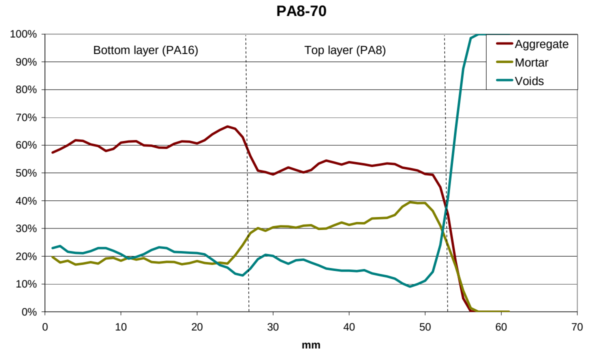
– CT-scan of pavements

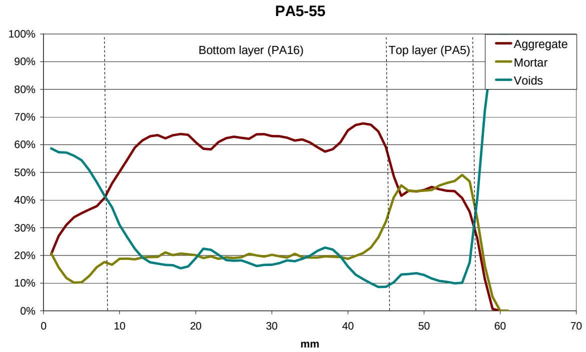


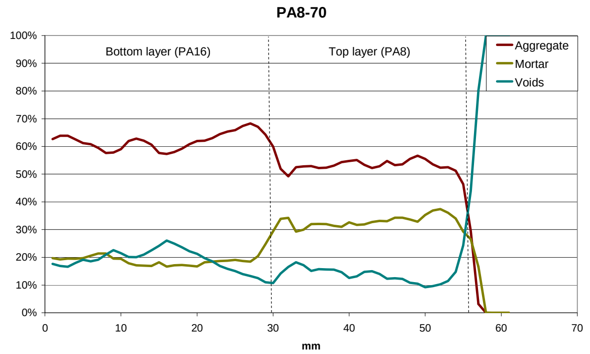


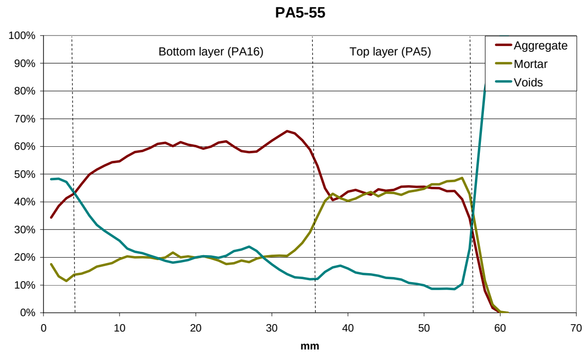


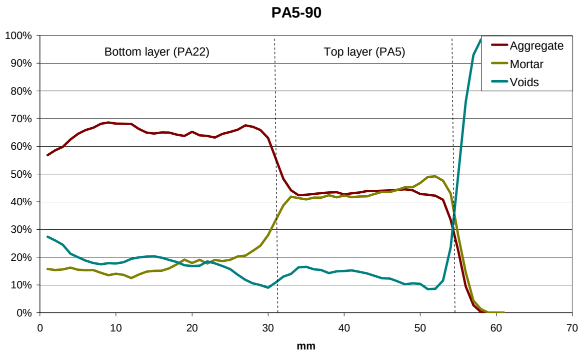


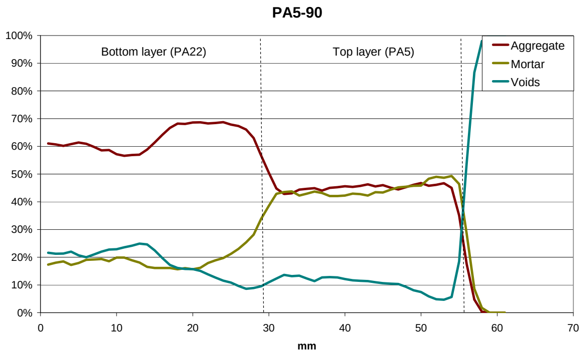








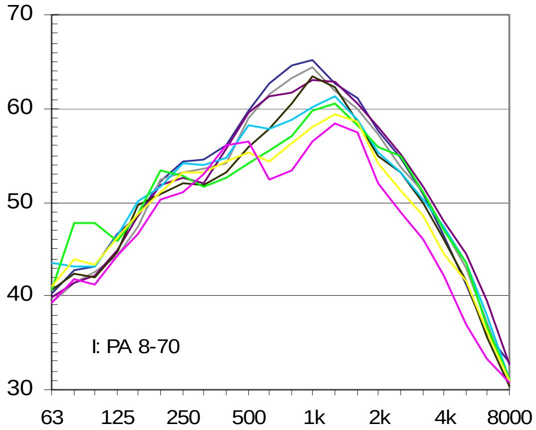

PA5-90
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Bottom layer (PA22)
Top layer (PA5)
Aggregate
Mortar
Voids
0
10
20
30
40
50
60
70
mm

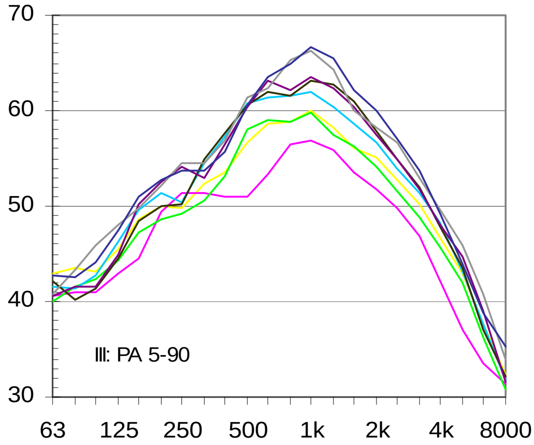

PA5-90
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Bottom layer (PA22)
Top layer (PA5)
Aggregate
Mortar
Voids
0
10
20
30
40
50
60
70
mm

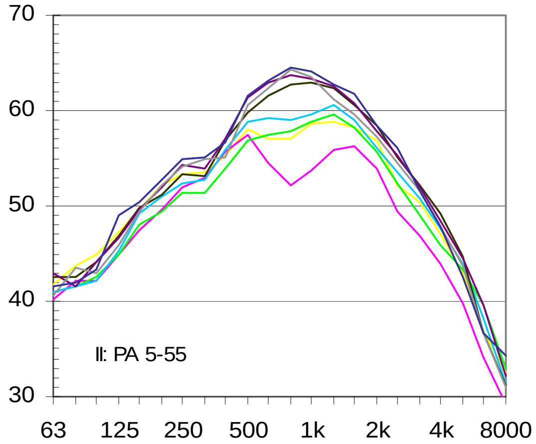
Appendix 3

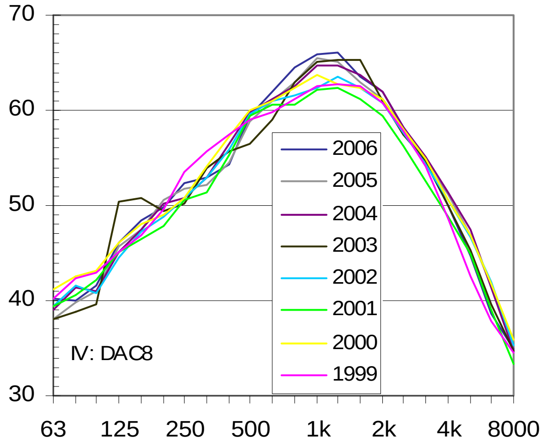
– Frequency spectra of SPBI’ and L_{vehP}, pavement by pavement

SPBI’

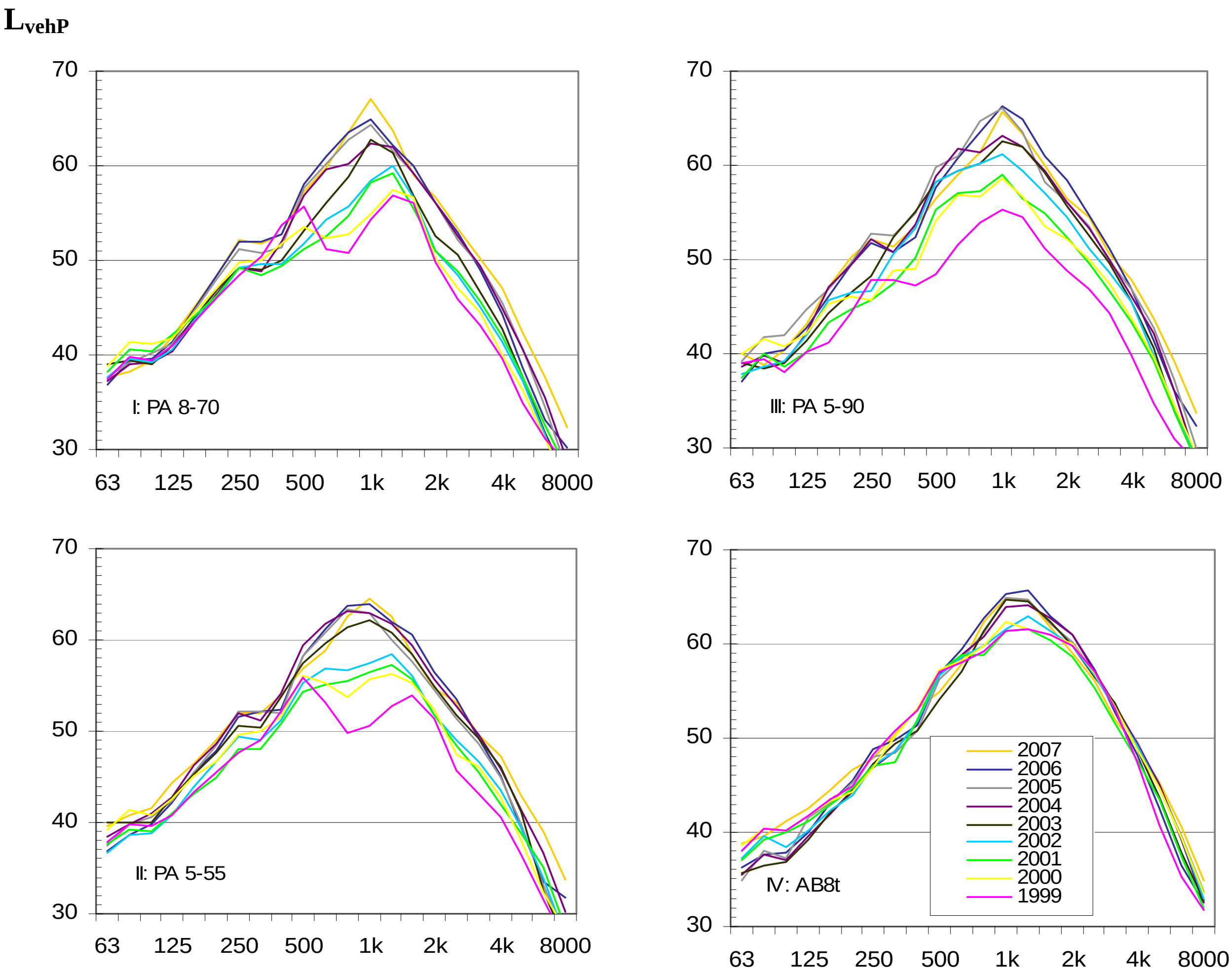








(Kragh 2006)

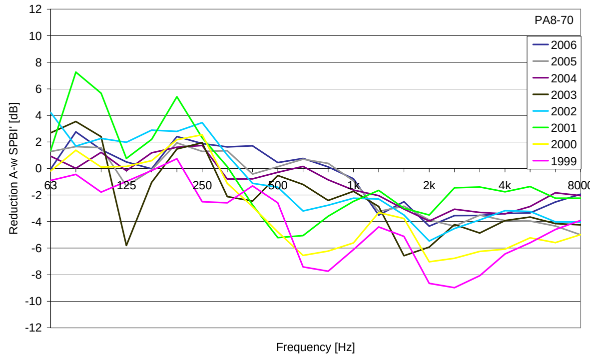

LvehP
70
60
50
40
30
63
125
250
500
1k
2k
4k
8000
I: PA 8-70
III: PA 5-90
II: PA 5-55
IV: AB8t
2007
2006
2005
2004
2003
2002
2001
2000
1999

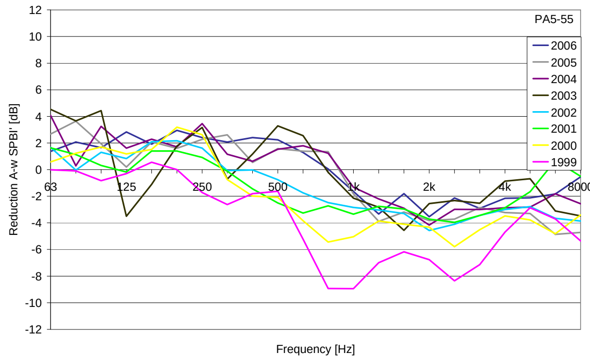
(Kragh 2006)

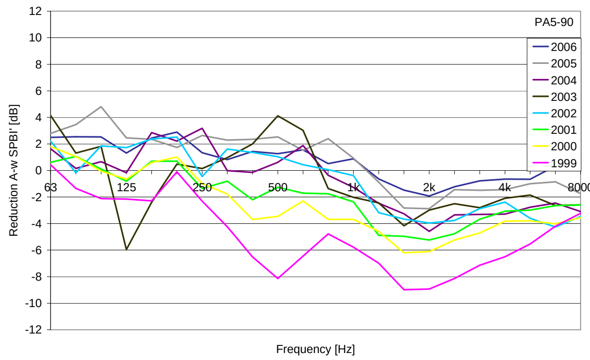
Appendix 4

– Differences in frequency spectra between porous pavements and reference pavement – pavement by pavement

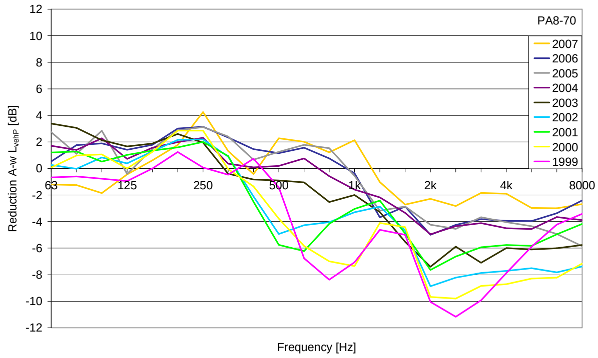
SBPI’

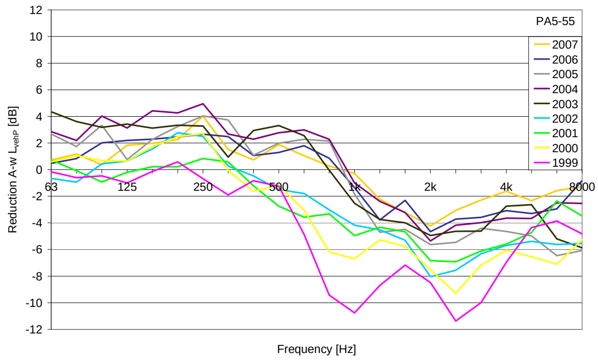


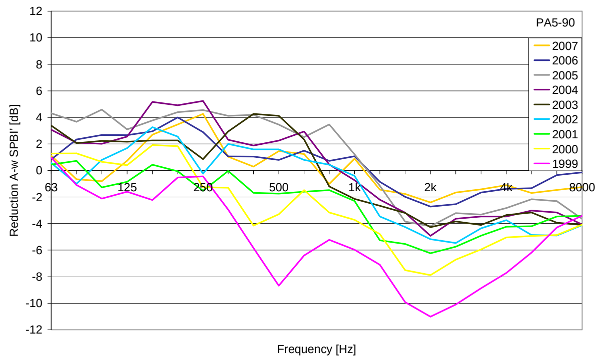




L_{vehP}





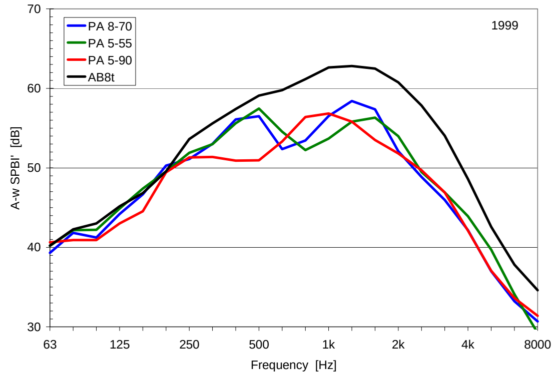


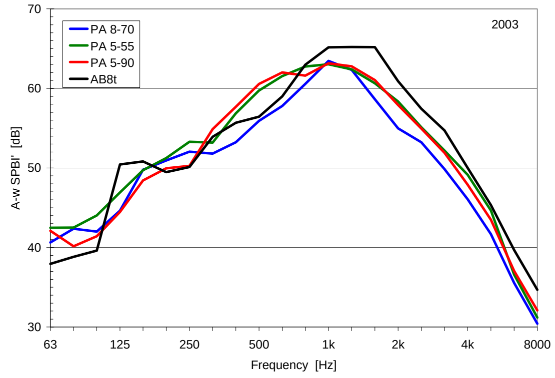
The ⅓-octave are found by subtracting the value for the reference pavement from the value for the porous pavement (Kragh 2006)

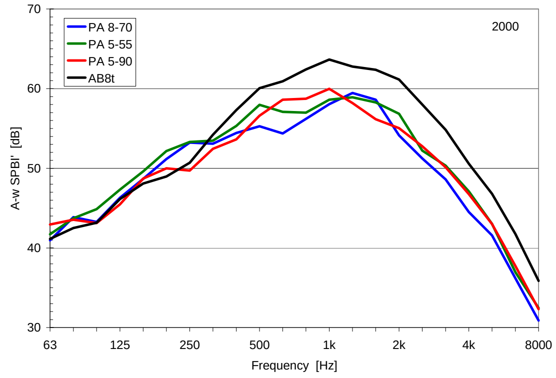
Appendix 5

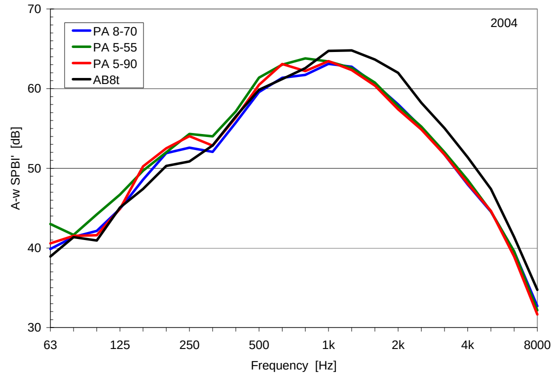
– Frequency spectra year by year

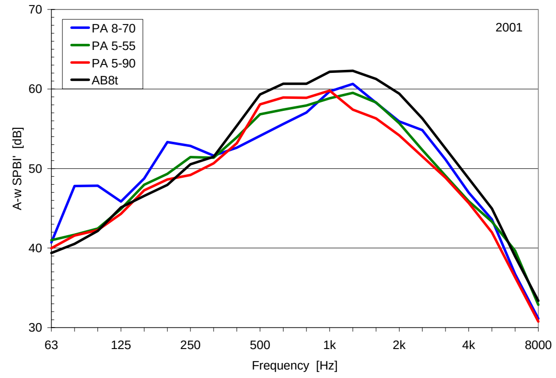
SPBI’

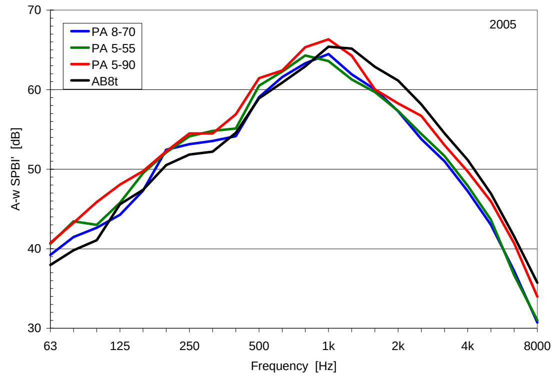


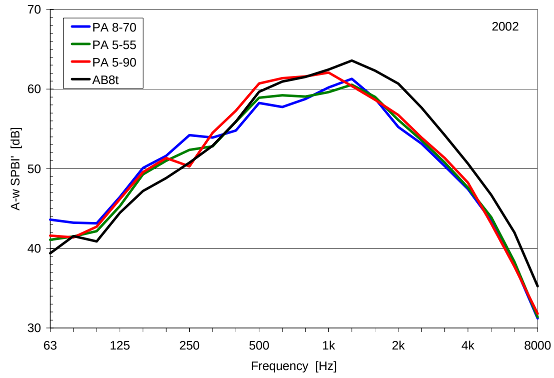


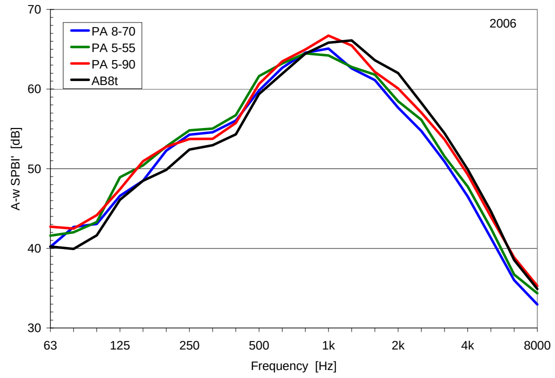




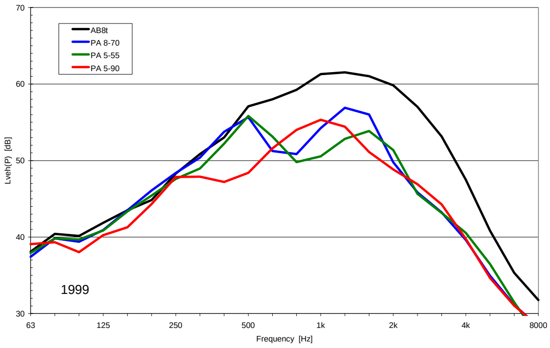


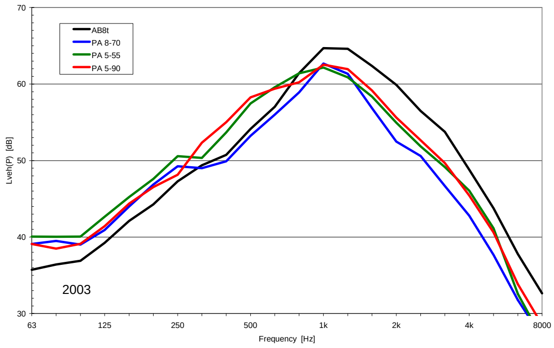


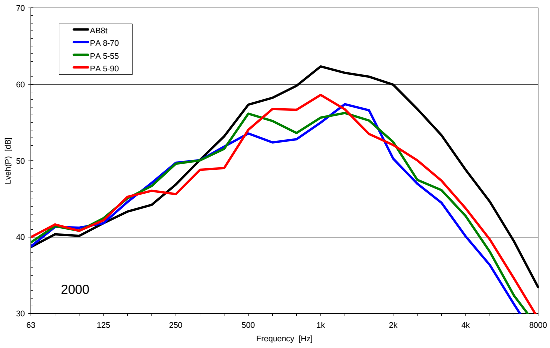


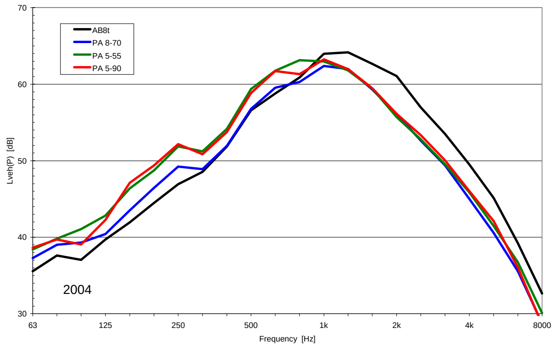


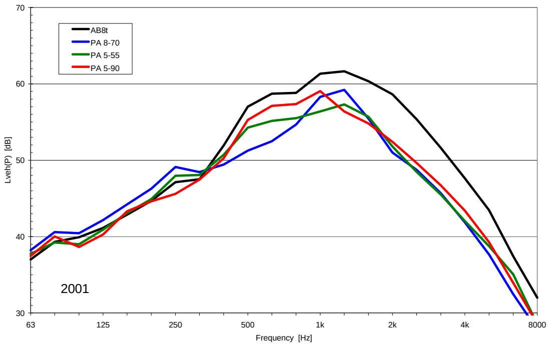
L_{vehP}

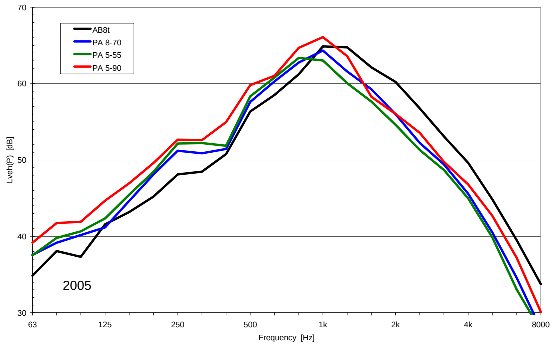

AB8t
PA 8-70
PA 5-55
PA 5-90
1999
70
60
50
40
30
Lveh(P) [dB]
63
125
250
500
1k
2k
4k
8000
Frequency [Hz]

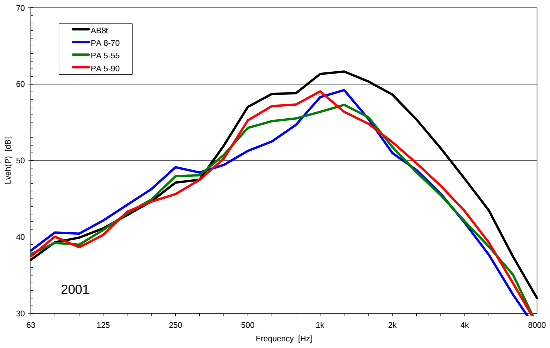

AB8t
PA 8-70
PA 5-55
PA 5-90
2003
70
60
50
40
30
Lveh(P) [dB]
63
125
250
500
1k
2k
4k
8000
Frequency [Hz]

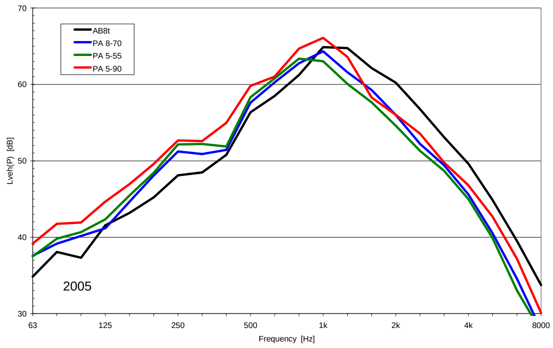

AB8t
PA 8-70
PA 5-55
PA 5-90
2000
70
60
50
40
30
Lveh(P) [dB]
63
125
250
500
1k
2k
4k
8000
Frequency [Hz]

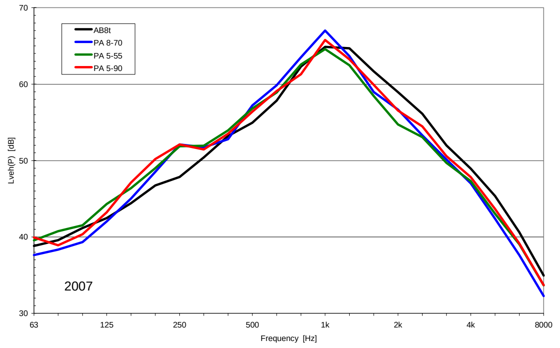

AB8t
PA 8-70
PA 5-55
PA 5-90
2004
70
60
50
40
30
Lveh(P) [dB]
63
125
250
500
1k
2k
4k
8000
Frequency [Hz]


AB8t
PA 8-70
PA 5-55
PA 5-90
2001
70
60
50
40
30
Lveh(P) [dB]
63
125
250
500
1k
2k
4k
8000
Frequency [Hz]


AB8t
PA 8-70
PA 5-55
PA 5-90
2005
70
60
50
40
30
Lveh(P) [dB]
63
125
250
500
1k
2k
4k
8000
Frequency [Hz]


AB8t
PA 8-70
PA 5-55
PA 5-90
2001
70
60
50
40
30
Lveh(P) [dB]
63
125
250
500
1k
2k
4k
8000
Frequency [Hz]


AB8t
PA 8-70
PA 5-55
PA 5-90
2005
70
60
50
40
30
Lveh(P) [dB]
63
125
250
500
1k
2k
4k
8000
Frequency [Hz]



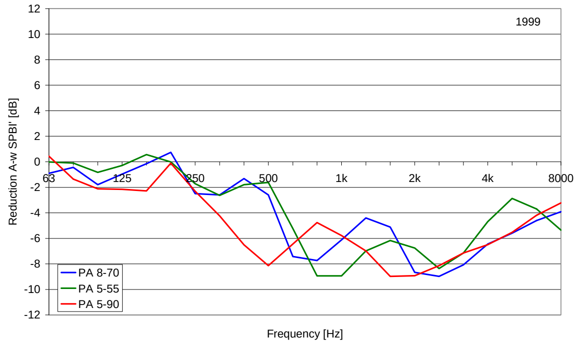
70
60
50
40
30
Lveh(P) [dB]
AB8t
PA 8-70
PA 5-55
PA 5-90
2007
63
125
250
500
1k
2k
4k
8000
Frequency [Hz]

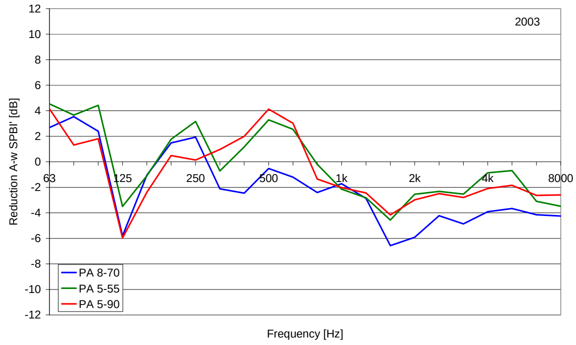
(Kragh 2006)

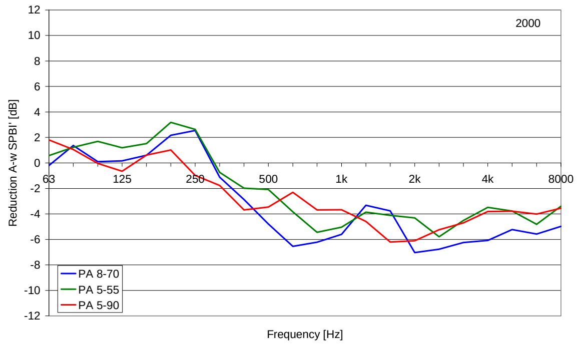
Appendix 6

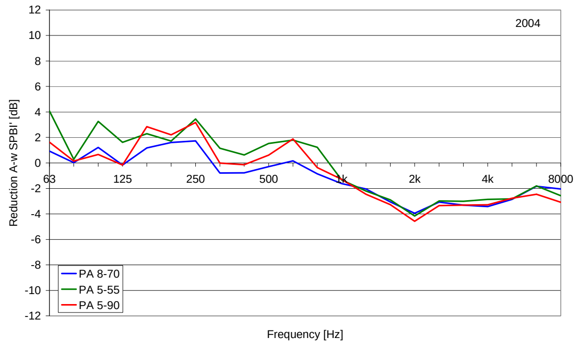
– Differences in frequency spectra between porous pavements and reference pavement – year by year

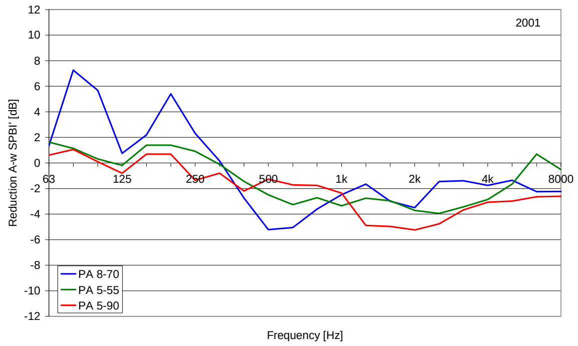
SPBI’

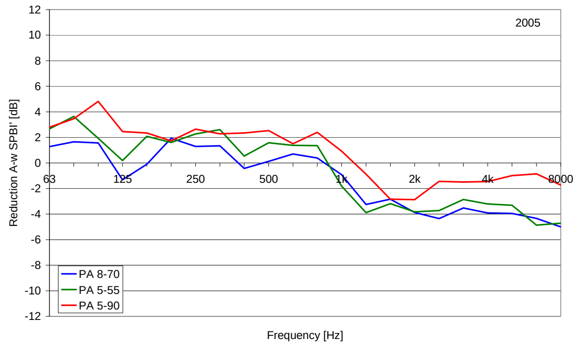


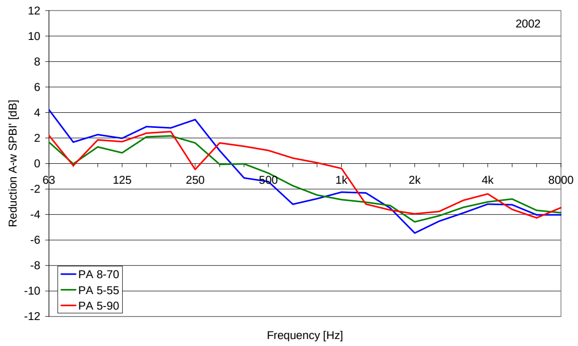


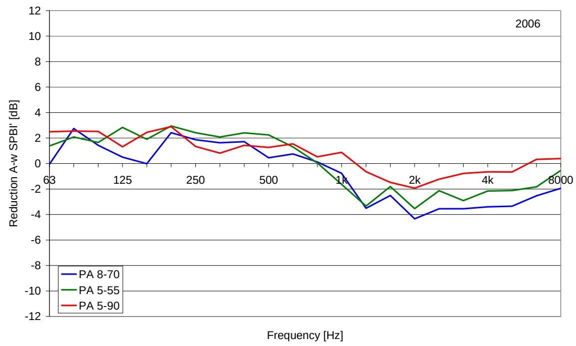




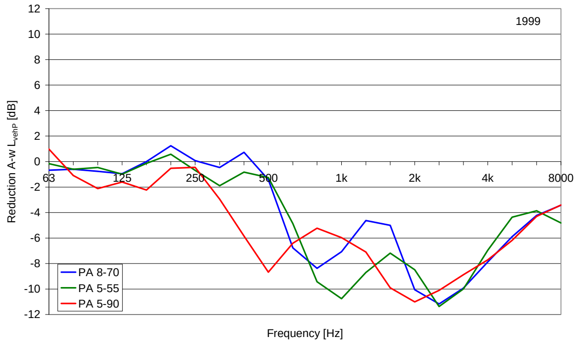


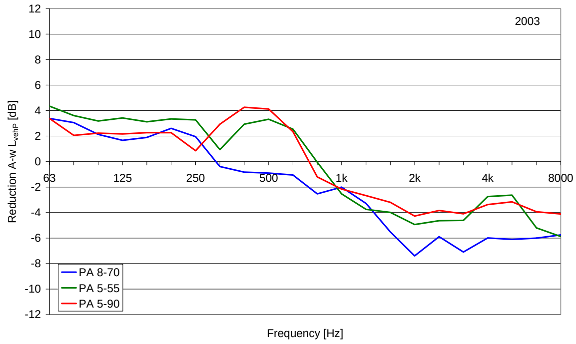


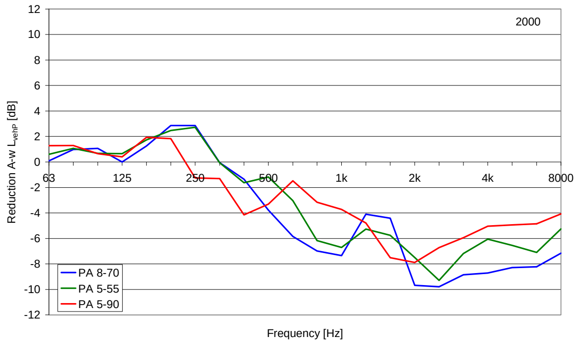


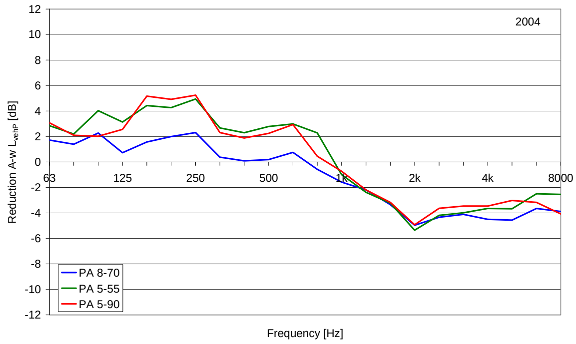


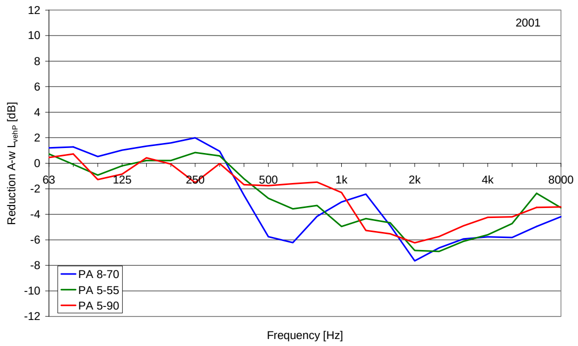
L_{vehP}

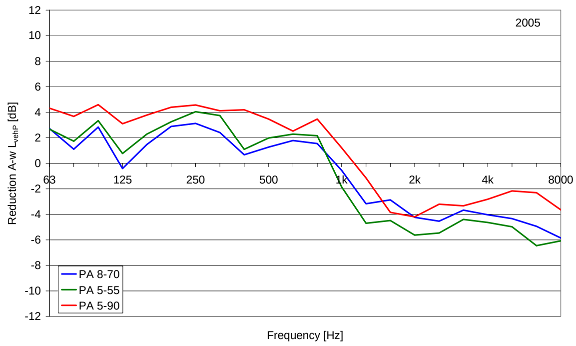

1999
Reduction A-w L_{vehP} [dB]
Frequency [Hz]
63 125 250 500 1k 2k 4k 8000
PA 8-70
PA 5-55
PA 5-90

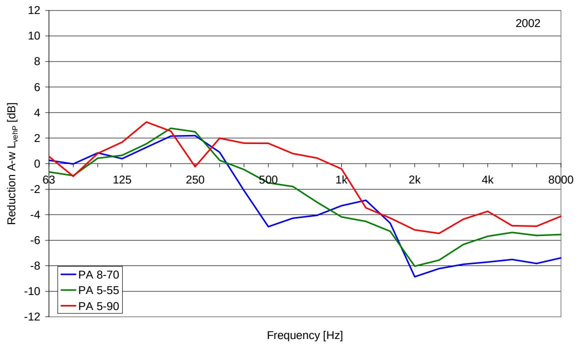

2003
Reduction A-w L_{vehP} [dB]
Frequency [Hz]
63 125 250 500 1k 2k 4k 8000
PA 8-70
PA 5-55
PA 5-90

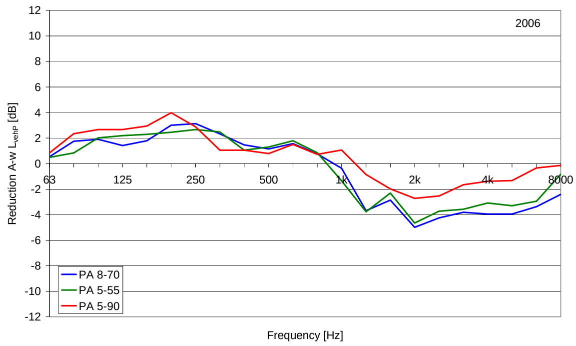

2000
Reduction A-w L_{vehP} [dB]
Frequency [Hz]
63 125 250 500 1k 2k 4k 8000
PA 8-70
PA 5-55
PA 5-90

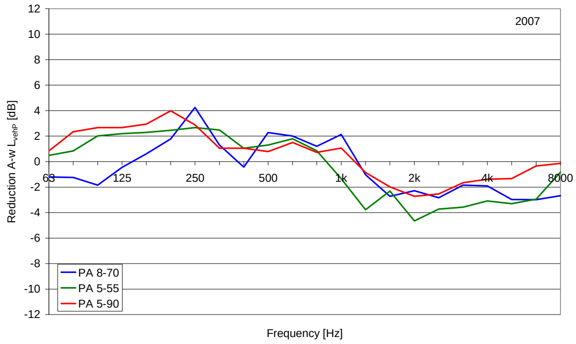

2004
Reduction A-w L_{vehP} [dB]
Frequency [Hz]
63 125 250 500 1k 2k 4k 8000
PA 8-70
PA 5-55
PA 5-90


2001
Reduction A-w L_{vehP} [dB]
Frequency [Hz]
63 125 250 500 1k 2k 4k 8000
PA 8-70
PA 5-55
PA 5-90


2005
Reduction A-w L_{vehP} [dB]
Frequency [Hz]
63 125 250 500 1k 2k 4k 8000
PA 8-70
PA 5-55
PA 5-90


2002
Reduction A-w L_{vehP} [dB]
Frequency [Hz]
63 125 250 500 1k 2k 4k 8000
PA 8-70
PA 5-55
PA 5-90


2006
Reduction A-w L_{vehP} [dB]
Frequency [Hz]
63 125 250 500 1k 2k 4k 8000
PA 8-70
PA 5-55
PA 5-90



The ⅓-octave values are found by subtracting the value for the reference pavement from the value for the porous pavement (Kragh 2006).

References

Andersen, J. B. 2001, "To-lags drænasfalt belægningsteknologi og specifikationer," in *Vejforum 2001 Program og Indlæg*, VEJ-EU, Roskilde.

Andersen, J. B. 2-lags drænasfalt - Øster Søgade. NCC Road. [2005-05-02]. 2005. Ref Type: Data File

Bendtsen, H. 1996, *Forsøg med støjreducerende vejbelægninger*, Road Directorate, Copenhagen, Statusrapport 45.

Bendtsen, H. 1998a, "Drainage asphalt and noise reduction over a long period," in *Euro-noise 98. Designing for Silence. Prediction, Measurement and Evaluation of Noise and Vibration. Munich 1998. Proceedings. Volume 1*, vol. Munich H. Fastl & J. Scheuren, eds., German Acoustical Society, Oldenburg, pp. 235-240.

Bendtsen, H. 1998b, *Erfaringer med støjreducerende vejbelægninger i Holland. Rejserapport fra et studiebesøg i Den Bosch, Holland*, Road Directorate, Copenhagen, Notat Note 56.

Bendtsen, H. 1999, *Belægningsteknologi, støj og to-lags drænasfalt i Holland. Noter fra en studietur i maj 1999*, Road Directorate, Copenhagen, Notat Note 64.

Bendtsen, H. & Kragh, J. 2007, *Replacement of Porous Top-Layer - Process and noise effect*, Road Directorate, Hedehusene, Technical note 58.

Bendtsen, H., Larsen, L. E., & Greibe, P. 2002, *Udvikling af støjreducerende vejbelægninger til bygader*, Danmarks TransportForskning, Kgs. Lyngby, Rapport 4.

Bendtsen, H., Nielsen, C. B., Raaberg, J., & Macdonald, R. A. 2002, *Clogging of porous bituminous surfacings – an investigation in Copenhagen*, Road Directorate, Danish Road Institute, Roskilde, VI Report VI Report 120.

Bendtsen, H. & Nielsen, E. 2008, *DRI-DWW Thin Layer Project - Final Report*, Road Directorate - Danish Road Institute, Hedehusene, Report 159.

DELTA 1999a, *Lydabsorptionskoefficient af asfaltprøver, Øster Søgade august 1999*, DELTA, Lyngby, AV 1756/99.

DELTA 1999b, *Lydabsorptionskoefficient af porøse asfaltprøver*, DELTA, Lyngby, AV 1402/99.

DELTA 1999c, *Trafikstøj ved fire forsøgsbelægninger på Øster Søgade*, DELTA, Lyngby, AV 1908/99.

Greibe, P. 2000, *Trafik og hastigheder på Øster Søgade. Før- og eftermålinger*, Road Directorate, Copenhagen, Arbejdsnotat.

Greibe, P. 2002, "Porous asphalt and traffic safety", in *Ninth International Conference on Asphalt Pavements*, Road Directorate, Copenhagen.

Hansen, E. d. P. & Hansen, K. K. 2000, *Investigations of Tile Drainpipes*, Department of Structural Engineering and Materials, Technical University of Denmark, Lyngby, Series 1, no. 26.

ISO 10534-2 1998, *Acoustics — Determination of sound absorption coefficient and impedance in impedance tubes – Part 2: Transfer-function method* International Organization for Standardization.

ISO 11819-1 1997, *Acoustics — Measurement of the influence of road surfaces on traffic noise – Part 1: The statistical pass-by method* International Organization for Standardization.

ISO 11819-2 2000, *Acoustics - Measurement of the influence of road surfaces on traffic noise - Part 2: The close-proximity method* International Organization for Standardization.

ISO 13472-1 2002, *Acoustics - Measurement of sound absorption properties of road surfaces in situ - Part 1: Extended surface method* International Organization for Standardization.

ISO 13473-1 1997, *Characterization of pavement texture by use of surface profiles - Part 1: Determination of Mean Profile Depth* International Organization for Standardization.

ISO 5128 1980, *Acoustics - Measurement of noise inside motor vehicles* International Organization for Standardization.

Kragh, J. 2005, *Traffic noise at two-layer porous asphalt - Øster Søgade, Year No, 6*, Road Directorate, Danish Road Institute, Hedehusene, Technical note Technical note no. 7.

Kragh, J. 2006, *Traffic noise at two-layer porous asphalt - Øster Søgade, Year No. 7*, Road Directorate, Danish Road Institute, Hedehusene, Technical note Technical note 46.

Kragh, J. 2008, *Road Surfacings - Noise reduction time history*, Road Directorate - Danish Road Institute, Hedehusene, Report 161.

Kuijpers, A. H. W. M. 2001, *Further analysis of the Sperenberg data*, M+P Raadgevende ingenieurs bv., 's-Hertogenbosch, M+P.MVM.99.3.1.

Larsen, L. E. & Bendtsen, H. 1 A.D.a, "Costs and perceived noise reduction of porous asphalt pavements", in *internoise 2001*, R. Boone, ed., Nederlands Akoestisch Genootschap, The Hague, pp. 1859-1864.

Larsen, L. E. & Bendtsen, H. 2001b, "Perception of noise reduction by porous asphalt", in *euro-noise 2001*, D. T. Tsahalis, ed., Laboratory of Fluid Mechanics and Energy, University of Patras, Patras.

Larsen, L. E. & Bendtsen, H. 2 A.D., "Noise reduction with porous asphalt - costs and perceived effect", in *Ninth International Conference on Asphalt Pavements*, Road Directorate, Copenhagen, Denmark.

Leest, A. J. v., Crielaard, J. J., Gruie, H. J. A. J., Gorkum, F. v., Heerkens, J. C. P., Nugteren, H. P., & Fafie, J. J. 1997, "Guidelines for determining the cleaning effects of porous asphalt," in *European Conference on Porous Asphalt, Vol. I, Madrid, March 12-14, 1997*, Asociación Española de la Carretera, Madrid, pp. 635-647.

Lefebvre, G. 1993, *Porous Asphalt* PIARC Technical Committee on Flexible Roads & PIARC Technical Committee on Surface Characteristics.

Lund, B. 1997, *Friction Test. Comparative testing with 3 different equipments carried out during the summer 1996*, Road Directorate, Danish Road Institute, Roskilde, 82.

Lydteknisk Institut 1988, *Støjsvage belægninger. Pilotprojekt*, Lydteknisk Institut, Lyngby, Technical report LI 360/88.

Ministry of Transport & Environmental Protection Agency 1998, *Begrænsning af trafikstøj*, Environmental Protection Agency, Copenhagen, Miljønyt 30.

Nielsen, C. B. 2007a, *Clogging of porous pavements - Assessment of test sections*, Road Directorate, Danish Road Institute, Hedehusene, Technical note Technical note 54.

Nielsen, C. B. 2007b, *Microstructure of porous pavements - Experimental procedures*, Road Directorate, Danish Road Institute, Hedehusene, Technical note Technical note 47.

Nielsen, C. B., Bendtsen, H., Andersen, B., & Larsen, H. J. E. 2005, *Noise reducing pavements in Japan - study tour report*, Road Directorate, Hedehusene, Danish Road Institute Technical note Technical note 31.

Phønix Asphalt Laboratory 1999a, *Specifikation. Produkt: AB 8t Granit, Ubelyst, Special*, Phønix Asfalt, Vejen.

Phønix Asphalt Laboratory 1999b, *Specifikation. Produkt: DA 16 Bundlag, Ubelyst*, Phønix Asfalt, Vejen.

Phønix Asphalt Laboratory 1999c, *Specifikation. Produkt: DA 22 Bundlag, Ubelyst*, Phønix Asfalt, Vejen.

Phønix Asphalt Laboratory 1999d, *Specifikation. Produkt: DA 5 Toplag, Ubelyst*, Phønix Asfalt, Vejen.

Phønix Asphalt Laboratory 1999e, *Specifikation. Produkt: DA 8 Toplag, Ubelyst*, Phønix Asfalt, Vejen.

Raaberg, J. 2000, *Tynd- og planslib af borekærner fra Øster Søgade i København 1999/2000*, Road Directorate, Danish Road Institute, Roskilde, Internal note 80.

Raaberg, J. & Neidel, A. 2009, *Øster Søgade. 8 år med 2-lag drænasfalt*, Road Directorate, Hedehusene, Rapport 168.

Road Directorate 1998, *Beregningsmodel for vejtrafikstøj*, Road Directorate, Copenhagen, 178.

S293 2001, *Branchestandard for polymermodificeret bitumen og specialbindemiddel. 2. udgave, 1-7-2001* Standardization Committee S293, Danish Standards Association.

Sandberg, U. & Ejsmont, J. A. 2002, *Tyre/road noise reference book*, 1 edn, Informex, Kisa.

Thagesen, B. 1998, *Veje og stier* Polyteknisk Forlag, Lyngby.

Thomsen, S., Andersen, B., & Bendtsen, H. 2006, *Noise reducing thin pavements - urban roads*, Road Directorate - Danish Road Institute, Hedehusene, Report 149.

Thomsen, S., Bendtsen, H., & Andersen, B. 2008, *Optimized thin layers - urban roads. The Kastrupvej experiment*, Road Directorate - Danish Road Institute, Hedehusene, Technical note 66.

Rapport / Report		
Nr. No.	Titel/Title/Shortcut	Forfatter/Author
146	Cost-benefit analysis on noise-reducing pavements	Lars Ellebjerg
147	Traffic management and noise – INTER-NOISE 2006	Hans Bendtsen Lars Ellebjerg
148	Noise reducing thin layers for highways – INTER-NOISE 2006	Hans Bendtsen Sigurd N. Thomsen
149	Noise reducing thin pavements – urban roads	Sigurd N. Thomsen Hans Bendtsen Bent Andersen
150	Integration of noise in PM Systems – Pavement Management and noise	Hans Bendtsen Bjarne Shmidt
151	Noise Control through Traffic Flow Measures – Effects and Benefits	Lars Ellebjerg
152	Noise from Railway Crossings – Inter·Noise Paper 2007	Hans Bendtsen Sigurd Thomsen
153	Optimized thin layers for highways – Inter·noise paper 2007	Hans Bendtsen Bent Andersen Sigurd Thomsen
154	Noise from streets with paving stones – paper for Inter-Noise 2007 in Istanbul	Bent Andersen Hans Bendtsen Jørgen Kragh Sigurd Thomsen
155	Traffic management and noise – Paper for Inter·Noise 2007 in Istanbul	Lars Ellebjerg Hans Bendtsen
156	Traffic noise at rumble strips – Inter·noise paper 2007	Jørgen Kragh Bent Andersen Sigurd Thomsen
157	Assessment of porous pavements – How to look inside	Carsten B. Nielsen
158	Dutch – Danish Pavement Noise Translator	Jørgen Kragh
159	DRI – DWW Thin Layer Project – Final report	Hans Bendtsen Erik Nielsen
160	Thin Asphalt Layers for Highways – Optimised for low tyre / road noise	Bent Andersen Hans Bendtsen
161	Road Surfacings – Noise reduction time history	Jørgen Kragh
162	Optimized thin layers for urban roads – Paper for Acoustics '08 in Paris	Bent Andersen Hans Bendtsen
163	Råstofforsyning i Danmark	Caroline Hejlesen Michael Larsen
164	Livscyklusvurdering af vejbefæstelser – Projekt Bording – Funder MV	Knud A. Pihl Jørn Raaberg Helle Blæsbjerg Michael Quist Morten Bendsen Harpa Birgisdóttir
165	Two-layer porous asphalt – lifecycle - The Øster Søgade experiment	Lars Ellebjerg Hans Bendtsen

Road Directorate
Niels Juels Gade 13
P.O. Box 9018
DK-1022 Copenhagen K
Denmark
Telephone +45 7244 3333
Telefax +45 3315 6335

Road Directorate
Guldalderen 12
DK-2640 Hedehusene
Denmark
Telephone +45 7244 7000
Telefax +45 7244 7105

Road Directorate
Thomas Helsteds Vej 11
P.O. Box 529
DK-8660 Skanderborg
Denmark
Telephone +45 7244 2200
Telefax +45 8652 2013

vd@vd.dk
Roadinstitute.dk