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LABORATORY EXPERIMENT WITH
ACOUSTIC OPTIMISATION TOOL

ASPHALT PAVEMENT TEXTURE AND NOISE

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ASPHALT PAVEMENT TEXTURE AND NOISE

Laboratory experiment with Acoustic Optimisation Tool

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CONTENT

SAMMENFATNING

Vejdirektoratet har sammen med University of California Pavement Research Centre (UCPRC) arbejdet på et projekt, der omfatter laboratorietests af lovende støjreducerende vejbelægningstyper. På UCPRC laboratoriet blev der fremstillet vejbelægningsplader af 12 lovende asfaltblandinger, som UCPRC udførte 3D teksturmålinger med høj opløsning på. Resultaterne blev sendt til Vejdirektoratet, som har analyseret og evalueret disse vejbelægningers akustiske egenskaber ved brug af det nye hollandskudviklede værktøj kaldet Acoustic Optimisation Tool (AOT). Formålet med denne rapport er at fremlægge denne akustiske evaluering. Et andet formål med denne del af projektet var at få praktisk hands-on erfaring ved brug af AOT-værktøjet og evaluere anvendelsen af AOT til sådanne evalueringer. De 12 vejbelægninger blev inddelt i tre grupper:

1. En tæt graderet asfaltbeton som referencebelægning.
2. To tynde og åbent graderede skærvemastiks-asfaltbelægninger (SMA) med maks. 4 og 6 mm stenstørrelse.
3. Ni forskellige udgaver af enkeltlags drænasfalt med maks. 4,75 til 19 mm astenstørrelse.

Støjen blev beregnet både som CPX og SPB niveau, og målte teksturdata fra de 12 belægninger blev anvendt som inddata. Der blev anvendt tre forskellige strategier ved brug af foruddefineret AOT-data om akustisk impedans og akustisk flowmodstand.

- **Strategi 1.** For alle 12 belægninger blev der anvendt foruddefinerede værdier for akustisk impedans og akustisk flowmodstand for tæt graderet asfaltbeton
- **Strategi 2.** De 12 belægninger blev underinddelt i 3 belægningsfamilier (tæt, SMA og drænasfalt). For disse tre familier blev der anvendt en foruddefineret belægning i AOT, der hørte til den relevante belægningsfamilie.
- **Strategi 3.** For hver af de 12 belægninger blev belægningen i AOT, der bedst passer med hensyn til belægningstype og aggregatstørrelse, valgt.

Den tætte graderede DG125 referencebelægning for alle tre strategier havde et lavt beregnet støjniveau svarende til SMA'erne og dræn belægninger med 4,75 mm sten. Det lader til, at AOT undervurderer støjen fra denne tætte belægning. Derfor kan denne DG125 belægning ikke anvendes som reference for disse AOT støjberegninger.

Generelt er forskellen ganske lille på de AOTberegnede støjniveauer for de 12 testbelægninger. Forskellen mellem de beregnede resultater kan ses som udtryk for, hvor godt AOT kan skelne mellem de 12 testbelægninger. En ekspertvurdering udført af forfatterne kom til konklusionen, at forskellen mellem de 12 belægninger kunne forventes at ligge på omkring 5 dB. Men det AOT beregnede forskelle er kun det halve heraf, og det indikerer, at AOT-metoden med den tilgængelige teksturdata ikke er så følsom overfor forskelle i belægningsteksturer, som det kunne forventes. Forskellen mellem deSPB beregnede støjniveauer er det samme eller mindre end forskellen for CPX beregnede støjniveauer ved brug af samme foruddefinerede AOT-data (ved brug af samme beregningsstrategi). Forskellen ved brug af Strategi 2 er mindre end 1 dB, og det tyder på, at strategien med at gruppere belægningerne i tre familier og bruge foruddefineret AOT-data om akustisk impedans og akustisk flowmodstand ikke fungerer godt for disse tre familier.

Den største forskel på 2,7 og 2,6 dB ses, når man beregner CPX-støjniveauer ved brug af enten Strategi 1 eller 3. Der er en positiv lineær korrelation for disse to strategier mellem SPB- og CPX beregnede støjniveauer. Standardafvigelsen hvad angår regressionslinjen er lavest for Strategi 1 ved 0,11 dB, hvorimod den er 0,45 dB for Strategi 3. Det peger i det hele taget hen imod, at CPX-niveauerne beregnet ved Strategi 1 er det bedste resultat. For denne strategi blev de foruddefinerede AOT-data for akustisk impedans og akustisk flowmodstand anvendt for samme tætte belægning.

Baseret på disse analyser kan det konkluderes, at de tre drænasfalt belægninger med 4,75 mm nominel maksimal stenstørrelse og SMA4P-belægningen giver de laveste støjniveauer. På grund af usikkerheden i beregningsmetoden er det ikke muligt at bestemme hvilken af de fire belægninger, der er den mindst støjende. Støjniveauet stiger for belægninger med stenstørrelse større end 4,75 mm.

FORORD

Et projekt blev startet i Californien på University of California Pavement Research Center (UCPRC) med formålet at evaluere støj og holdbarhedsegenskaber af potentielle støjreducerende belægninger. I 2009 påbegyndte Vejdirektoratet (VD) et projekt med det formål at udvikle og forbedre støjreducerende belægninger. Det danske projekt er en del af et støjforsknings- og udviklingsprogram, der blev påbegyndt i 2009 som en del af den danske regerings aftale om en grøn transportpolitik fra januar 2009.

I denne aktuelle rapport beskrives den første støjevalueringsdel fra projektet i Californien. Formålet var at udføre støjvurderinger af de i laboratoriet producerede belægningsplader ved brug af et nyt hollandskudviklet værktøj kaldet Acoustic Optimisation Tool (AOT) [1]. Resultaterne fra lasermålinger af belægningsteksturen blev anvendt som input til AOT-beregningerne. Et andet formål med projektet var at få praktisk erfaring i brugen af AOT-værktøjet, som planlægges anvendt i VD-projektet om støjreducerende belægninger.

Projektet i Californien er blevet udført indenfor rammerne for en forsknings aftale med titlen ”Supplementary Studies for the Caltrans Quieter Pavement Research Program” mellem Transportministeriet i Californien (California Department of Transportation (Caltrans)) og UCPRC som en del af opgaven: ”Politisk oplæg: Retningslinjer for Caltrans politik”. Vejdirektoratet i Danmark er blevet indbudt af UCPRC til at arbejde på projektet. Denne rapport blev udarbejdet af en projektgruppe med følgende medlemmer:

- Hans Bendtsen, Vejdirektoratet, arbejdede som gæsteforsker ved UCPRC.
- Jens Oddershede, Vejdirektoratet
- Qing Lu, University of California Pavement Research Center. Nu University of South Florida.
- Arash Rezaei, University of California Pavement Research Center (UCPRC).

Laserteksturmålinger blev udført af Qing Lu, UCPRC og beregninger ved brug af AOT-værktøjet blev udført af Jens Oddershede, Vejdirektoratet, Danmark. Rapporten er skrevet af Hans Bendtsen, Jens Oddershede og Qing Lu og med kommentarer fra Arash Rezaei. Bent Andersen, Vejdirektoratet, Danmark har udført kvalitetsvurdering af rapporten.

EXECUTIVE SUMMARY

The Danish Road Directorate (DRD) has been working together with the University of California Pavement Research Centre (UCPRC) on a project involving the laboratory testing of promising noise reducing pavement types. Pavement slabs of 12 promising asphalt mixes were produced at the UCPRC laboratory on which UCPRC performed high resolution 3D texture measurements. The results were sent to DRD who have been analysing and evaluating the acoustical performance of these pavements using the new Dutch-developed prediction tool called the Acoustic Optimisation Tool (AOT). The purpose of this report is to present this acoustical evaluation. Another purpose of this part of the project was to gain "hands on" practical experience using the AOT software tool and to evaluate the pros and cons of using the AOT for such evaluations. The 12 pavements were divided in three groups:

1. A dense graded asphalt concrete as a reference pavement.
2. Two thin and open graded stone mastic asphalt (SMA) pavements with 4 and 6 mm maximum aggre-gate size.
3. Nine different versions of single layer porous pavements with maxi-mum aggre-gate size from 4.75 to 19 mm

The noise was predicted both as CPX and SPB levels using measured texture data for the 12 pavements as input data. Three different strategies using predefined AOT data on acou-stical impedance and flow resistance were used:

- Strategy 1. For all 12 pavements the predefined values for acou-stical impedance and the flow resistance for the Dense Graded Asphalt Concrete (DAC16) was used.
- Strategy 2. The 12 pavements were subdivided into 3 pavement families (dense, SMA and porous). For these three families a predefi-ned pavement in the AOT be-longing to the relevant pavement family was used.
- Strategy 3. For each of the 12 pavements the pavement in the AOT that fits best in terms of pave-ment type and aggregate size was selected.

The dense graded DG125 reference pavement for all three strategies had a low predicted noise level similar to the SMAs and the porous pavements with 4.75 mm aggregates. It seems that the AOT underestimates the noise from this dense pavement. Therefore, this DG125 pavement cannot be used as a reference for these AOT noise predictions.

Generally, the difference between the AOT-predicted noise levels for the 12 test pave-ments is quite low. The range of the predicted results can be seen as an expression of how well the AOT can distinguish between the 12 test pavements. An expert judgement performed by the authors came to the conclusion that the range between the 12 pave-ments could be expected to be around 5 dB. But the AOT-predicted range is only half of this and this indicates that the AOT method with the available texture data is not as sen-sitive to differences in pavement textures as would be expected. The range for SPB-predicted noise levels is the same or less than the range of CPX-predicted noise levels using the same predefined AOT data (using the same prediction strategy). The range us-ing Strategy 2 is less than one, sug-gesting that the strategy grouping the pavements into three families using predefined AOT data on acoustical impedance and flow resistance for these three families does not seem to function well.

The highest range of 2.7 and 2.6 dB is seen when predicting CPX noise levels using ei-ther Strategy 1 or 3. For these two strategies there is a positive linear correlation be-tween SPB and CPX-predicted noise levels. The standard deviation in relation to the re-gression line is the lowest for Strategy 1 at 0.11 dB, whereas it is 0.45 dB for Strategy 3. All in all this points towards the CPX levels predicted by Strategy 1 as being the best result. For this strategy the predefined AOT data on acoustical impedance and flow re-sistance for the same dense pavement was used.

Based on these analyses it can be concluded that the three porous pave-ments with 4.75 mm nominal maximum aggregate size and the SMA4P pa-vement have the lowest noise levels. Due to the uncertainty in the prediction method it is not possible to determine which one of the four pavements is the most silent. The noise level increases for the pavements with an aggregate size of greater than 4.75 mm.

PREFACE

A project with the purpose of evaluating noise as well as durability properties of poten-tially noise reducing pavements was started in California by the University of California Pavement Research Center (UCPRC). In 2009, the Danish Road Directorate (DRD) started a project with the objective of developing and improving noise reducing pave-ments. This Danish project is part of a noise research and ¬development programme started in 2009 as part of the Danish Government's Agreement on a Green Transport Policy from January 2009.

This present report describes the first noise evaluation part of the Californian project. The purpose was to perform noise evaluations of the mixes produced in the laboratory using a new Dutch-developed Acoustic Optimisation Tool (AOT) [1]. The results from laser measurements of the pavement texture were used as the input for the AOT calcula-tions. Another purpose of the project was to gain practical experience from using the AOT tool, which will be used in the DRD project on noise reducing pavements.

The Californian project is being carried out within the framework of the research tech-nical agreement entitled "Supplementary Studies for the Caltrans Quieter Pavement Re-search Program" between the California Department of Transportation (Caltrans) and UCPRC as part of the task: "Policy documents: guidelines for Caltrans policy". The Danish Road Directorate (DRD) has been subcontracted by UCPRC to work on the pro-ject. The project is also an integrated part of the Laboratory Evaluation of Noise Durability Properties of Asphalt Surface Mixes carried out by UCPRC for Caltrans as the Partnered Pavement Research Program (PPRC) Strategic Plan Element (SEP) 4.20: As-phalt Surface Mix Study. The work presented in this report was carried out by a project group with the following members:

- Hans Bendtsen, Danish Road Directorate (DRD) working as a guest researcher at UCPRC.
- Jens Oddershede, Danish Road Directorate (DRD)
- Qing Lu, University of California Pavement Research Center. Now the Univer-sity of South Florida.
- Arash Rezaei, University of California Pavement Research Center (UCPRC).

Laser texture measurements were conducted by Qing Lu, UCPRC and predictions using the Acoustic Optimisation Tool were performed by Jens Oddershede DRI-DK. The re-port was written by Hans Bendtsen, Jens Oddershede and Qing Lu and commented on by Arash Rezaei. Bent Andersen DRI-DK performed a quality assessment of the report.

1. INTRODUCTION

In the ongoing research cooperation on noise between the California Department of Transportation (Caltrans) and the Danish Road Directorate (DRD) there is intense focus on the development and testing of noise reducing pavements. DRD is working together with the University of California Pavement Research Center (UCPRC) on a project involving the laboratory testing of promising noise reducing pavement types. Pavement slabs of 12 promising asphalt mixes have been produced at the UCPRC laboratory. UCPRC is performing a series of laboratory tests on these materials. The results of these tests will be documented in separate UCPRC reports and used both in Denmark and in California when full scale test sections on roads are to be constructed in the future. The results and the experiences are an important part of a DRD-run Danish project with the objective of developing and improving noise reducing pavements.

High resolution 3D texture measurements were performed by UCPRC on these pavement slabs. The results were sent to DRI-DK who have been analysing and evaluating the acoustical performance of these pavements using the new Dutch-developed prediction tool called the Acoustical Optimisation Tool (AOT) [1]. The purpose of this report is to present this acoustical evaluation. Another purpose of this part of the project was to gain “hands on” practical experience using the AOT software tool and to evaluate the pros and cons of using the AOT for such evaluations.

The California Department of Transportation (Caltrans) has identified a need for research in the areas of acoustics, friction, durability, and other performance of pavement surfaces for the state highway network. In 2005, a research project was initiated at the Partnered Pavement Research Center (PPRC) to evaluate the durability and effectiveness of Caltrans open graded mixes and some experimental mixes in increasing skid resistance and reducing noise compared to other asphalt surfaces. The project includes five years of field measurements of various asphalt surface mixes currently existing on California highways [8], and some new materials placed in experimental sections.

These studies of field mixes provide the first comprehensive evaluation of the performance of Caltrans standard surface mixes and experimental mixes, and provide invaluable information regarding mix design factors that can help reduce tyre/pavement noise and increase the durability of the surface mixes. However, as with most field studies they were constrained by the availability of asphalt surface mix types in the field and some uncontrollable traffic and climate factors specific to the physical locations of existing field mixes. To extend the evaluation scope of mix types and to develop asphalt mixes that are potentially quieter and more durable, a supplementary laboratory study was started in 2008. The laboratory study follows the interim findings of the field study, but focuses on the effect of mix design variables on the noise and durability performance of asphalt surface mixes. For comparison, the experiment also includes other asphalt mixes that have shown

Figure 1.1: Aggregate used for the production of test specimens.

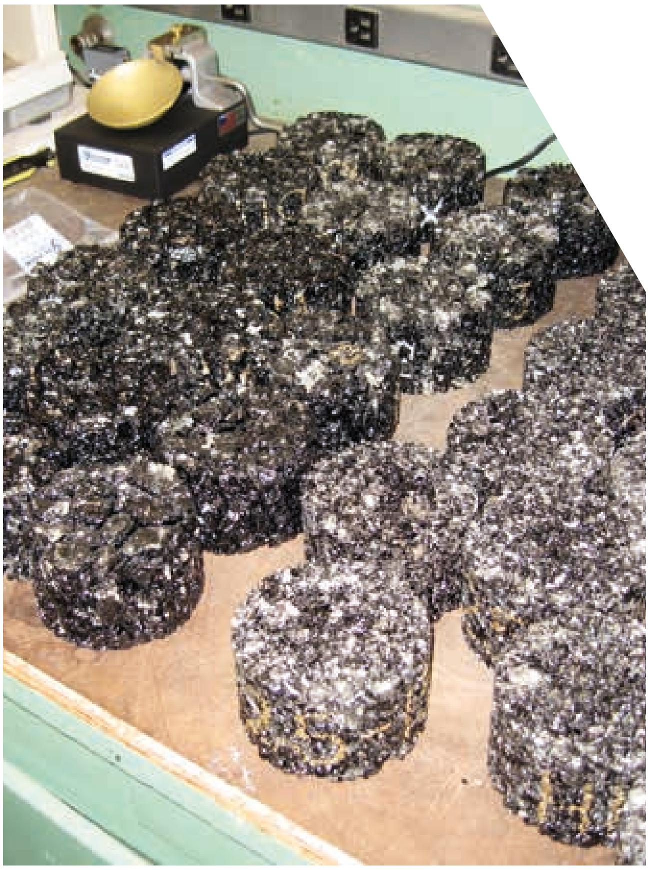


Figure 1.2: Cylindrical Marshall specimens of the 12 mixes produced in the UCPRC laboratory in California.

good performance history in other states and some European countries like some optimised Danish SMA types [10, 12]. Both small cylindrical specimens and large slab specimens were fabricated in the UCPRC laboratory in California with a Marshall compactor and a rolling wheel compactor, respectively, and are used to evaluate the pavement surface related performance, including durability (resistance to ravelling, moisture susceptibility, resistance to permanent deformation, and resistance to reflective cracking), sound absorption, permeability, surface texture, and friction.

Specifically, the following mix design factors were evaluated in the laboratory study:

- Aggregate gradation (nominal maximum aggregate sizes [NMAS]) ranging from 4.75 mm to 19 mm)
- Binder type (conventional binder, polymer modified binder, asphalt rubber-wet process and asphalt rubber-terminal blended)
- Additive (hydrated lime, cellulose fibre, and mineral fibre)
- Aggregate particle shape (three aggregate types with various aggregate particle shapes)

The other asphalt mixes that are included in the study for comparison are:

- One Arizona rubberised hot mix asphalt – open-graded, high-binder content [13]
- One Danish SMA mix with NMAS 6 mm and a few oversized aggregates [10, 12]
- One Danish SMA mix with NMAS 4 mm and a few oversized aggregates [10, 12]
- One Georgia open-graded asphalt mix [11]
- One European porous asphalt mix with NMAS of 5 mm
- One top layer of a double-layered porous asphalt mix [9]

The pavement types are presented in Chapter 4.

In order to get an early first hand evaluation of the noise properties of these pavements the following was carried out:

- The surface texture of the laboratory produced pavement slap specimens was measured using a 3D texture scanner (see Chapter 2 for the measurement method and Chapter 5 for the results)
- Based on the measured texture, the noise emission from these pavements specimens was predicted using the AOT (see Chapter 3 for the prediction method and Chapter 6 for the results)

All the noise levels presented in this report are A-weighted. The unit “dB” is used in this report and is equivalent to what is often denoted “dB(A)” and “dBA”.

2. THE ACOUSTIC OPTIMISATION TOOL

The Acoustic Optimisation Tool (AOT) [2] was developed by a consultant M+P for the Dutch road administration (DVS) in the period from 2006 to 2008. The AOT is an acoustic optimisation tool for low-noise road surfaces to be used by scientists and engineers. The AOT is based on the SPERoN model framework [2] which originates from the so-called “Sperenberg project”. SPERoN is an acronym for Statistical Physical Explanation of Rolling Noise. The AOT is based on models that describe the mechanisms generating the tyre road noise, i.e. a contact model, an interaction model and a propagation model. The model framework was developed over a longer period including theoretical development as well as empirical measurement results. A detailed presentation of the model framework can be seen in [2].

2.1 DESCRIPTION OF THE AOT METHOD

The AOT can be used to simulate an estimate of the noise emission caused by vehicles driving on a specific pavement at different speeds in the range from 50 to 120 km/h. There are 4 main input data describing the physical and acoustical properties of the pavement, which are:

1. **Surface texture,** which is a measure for the roughness of the road. The road surface texture is influenced by the size, shape, and arrangement of the road surface elements (such as stones, binder and additives) [3].

2. **Acoustical impedance,** which is a measure that describes the influence of the road surface in terms of reflection and absorption on the sound field that impinges on the surface. This term is related to the acoustic absorption of the road surface. Porous pavements have an absorbing effect on noise. The acoustical impedance of the road surface is used in the propagation part of the model [3]. This input parameter therefore has an effect on the way side noise measured by the Statistical Pass-by method (SPB) [6], but it does not have a significant effect on noise measured close to the tyre by the use of the Close-ProXimity method (CPX) [5] or the Onboard Sound Intensity Method (OBSI) [7] normally used in the US.

3. **Flow resistance,** which is a measure for the resistance that the flow of air in the tyre profile experiences in the rolling contact area. The air flow resistance is the resistance that is experienced by the air that is expelled from the contact area between tyre and road during the rolling process. This phenomenon is often called the air pumping generated noise. If the airflow resistance is high, then the air is effectively compressed in the contact area and might produce sound when the compressed air is released at the beginning or end of the contact patch. When the airflow resistance is low as for open graded pavements and porous pavements, air flows out of the contact area with little resistance and then airflow related noise is generated [3].

4. **Mechanical impedance,** which is a measure that describes the influence of the road surface in terms of stiffness and damping on the vibrations of the tyre.

A comprehensive and extensive series of measurement data from around 40 test sections with many different kinds of noise reducing pavements was included in the AOT as default values that can be selected by the user.

These test sections were located at the "Kloosterzande test track" in the Netherlands [14] and include amongst others single and double layer porous asphalt, thin layers, poroelastic pavements and dense graded asphalt concrete and standard SMA pavements. The user can choose to use own measured data for the parameters that are available and then the relevant missing data for parameters not measured in the AOT database.

In this present project the pavement texture was measured on laboratory produced pavement slab specimens. However, no other measured data is available, so acoustical impedance, flow resistance and mechanical impedance will be selected from the AOT database.

Based on the selected input data the AOT predicts the noise for vehicles driving on the pavement described by the input data. The user can define the car type used for the simulations (passenger cars, heavy vehicles). The user can also select the type of results with the following options:

- Results related to the CPX measurement method [5]
- Results related to the SPB method [6] where the distance to the centreline of the road is 7.5 m and the height can be defined as 1.2 m, 3 m or 5 m

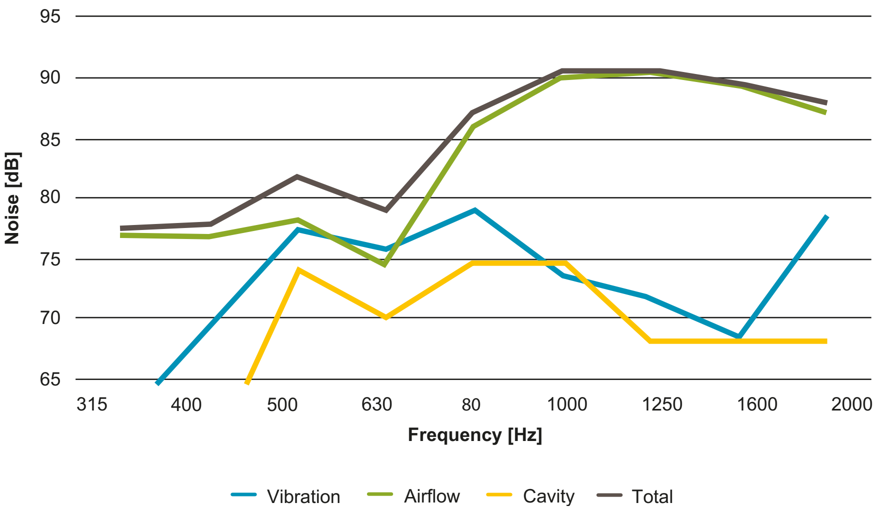


Figure 2.1: Example of the CPX spectra's output from AOT simulation of a dense graded asphalt concrete DGAC16. L_{Amax} is 96.6 dB at a speed of 100 km/h for passenger cars.

The results are given as A-weighted maximum noise levels (L_{Amax}) as well as the total noise in third octave band spectra in the frequency range from 315 to 2000 Hz. The spectral contributions from three individual noise generating mechanisms are also predicted. These are:

- Tyre vibration generated noise (vibration)
- Air pumping generated noise (airflow)
- Noise related to absorption (cavity)

Figure 2.1 is an example of the spectral output. The output data can be exported to Excel for further analyses and comparison.

Results related to the OBSI method are not available as this is a European developed tool following the ISO international standards. But there is a close relation between the results measured by the CPX and the OBSI methods, depending on the reference tyres used in the two methods etc. [15].

In principle, the predicted noise levels and spectra are the SPB and CPX levels for the tyre group selected when the AOT was developed. They do not necessarily correspond to the standard indices for SPB and CPX (either survey or investigatory) methods. However, the validation has shown e.g. that the extended group of passenger car tyres corresponds well with the CPX cars from the CPX standard [4].

A licence to use the AOT software can be purchased from the Dutch consulting company M+P [15]. The licence comes with software that can be installed on one PC and a user manual [3]. The software package itself is a Windows based client/server application. The software helps the user to set up prediction cases using own data, predefined data from the AOT or a combination of the two. When the data has been finalised the software calls up a server in Germany. Here the calculations are performed and the results are transmitted to the user's PC.

2.2 SIMULATIONS AND TESTING OF THE AOT

In order to perform a survey on the functionality of the AOT a series of simulations was conducted using only the predefined data in the method. The actual measurement results as L_{Amax} and spectra can be seen in the report documenting the measurements performed at the "Kloosterzande test track" [14]. The results of the simulations and the measurements will be compared at the end.

The measurement results used for the development of the AOT are given in the AOT documentation report (Appendix N) and are listed at 70 km/h [14]. Therefore, a comparison between the calculated and measured overall noise levels and frequency spectra can be performed.

The calculations were performed for a few pavements just to see whether the calculated total noise levels and frequency spectra matched the results of the measurements made for the model, e.g. chosen surface texture, acoustic impedance, resistance, and mechanical impedance for the same pavement, calculated with the AOT and then compared with the measurement results given in the report. The CPX noise calculations were made for 60, 70 and 80 km/h with the "Extended group of passenger car tyres" and then compared to the "ruler measurement" of the measured spectra from the graphs in the report [14].

The main results of this comparison can be seen in Table 2.1 and Figure 2.2. The measured total noise level at 70 km/h is generally higher than the calculated level at 70 km/h. For the pavements with the smallest aggregate size of 8 mm there is just a 0.7 to 0.8 dB difference, but for the pavements with 11 and 16 mm aggregates the difference is around 2.5 dB, which must be considered quite high. This small indicative comparison study shows that the AOT has a tendency to underestimate absolute noise levels for different pavements by around 1 to 2.5 dB. Even though this seems to be the case the AOT might still be used for predicting the relative ranging between different pavements in relation to noise, which is the main purpose of this current study.

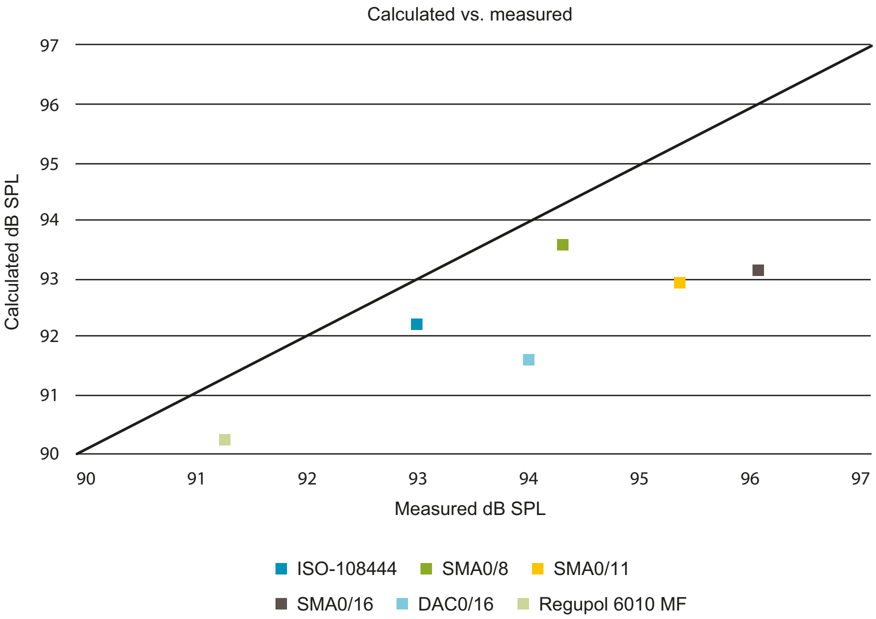


Figure 2.2: Measured and calculated CPX noise at 70 km/h with the AOT for selected pavements included in the AOT database.

Figures 2.3 and 2.4 are examples of how the measured spectra compared to the calculated spectra. As can be seen in Figure 2.3, for the SMA8 pavement there is a very fine compliance between measured and calculated spectra (see the two light blue lines), whereas for the SMA16 in Figure 2.4 the compliance is less convincing.

Table 2.1: Measured and AOT calculated CPX noise levels at 70 km/h for selected pavements included in the AOT database.

PAVEMENT TYPE	COMMENT	SECTION NO. IN AOT DATABASE	MEASURED [dB]	CALCULATED [dB]	DIFFERENCE [dB]
ISO-10844	Dense asphalt concrete 8 mm	1	93.0	92.2	0.8
SMA0/8	SMA type	20	94.3	93.6	0.7
SMA0/11	SMA type	21	95.3	93.0	2.3
SMA0/16	SMA type	22	96.0	93.2	2.8
DAC0/16	Dense asphalt concrete 16 mm	23	94.0	91.6	2.4
Regupol 6010 MF	Proelastic asphalt	35	91.3	90.2	1.1

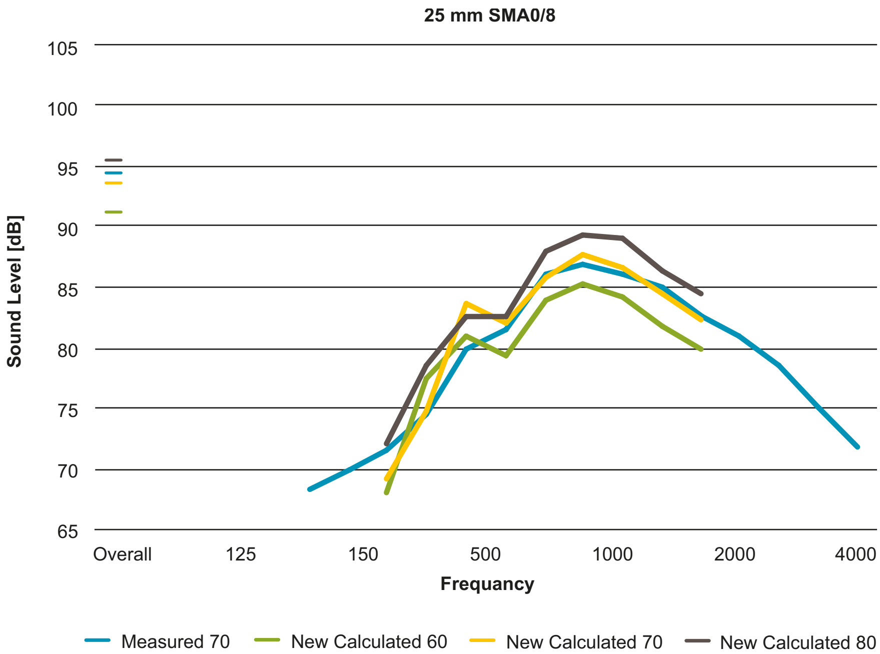


Figure 2.3: Measured (at 70 km/h) and calculated (at 60, 70 and 80 km/h) spectra for the SMA8 pavement in the AOT database.

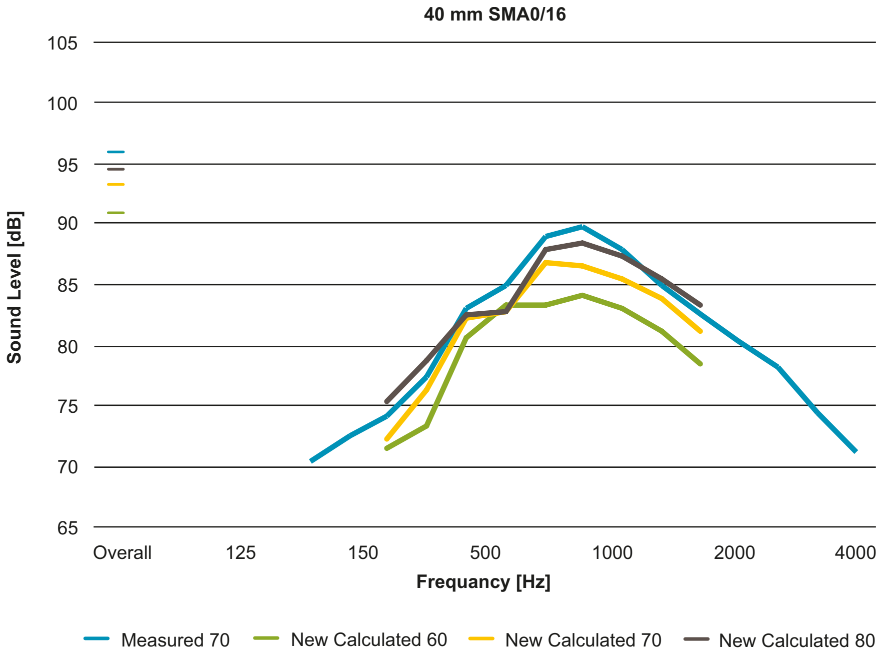


Figure 2.4: Measured (at 70 km/h) and calculated (at 60, 70 and 80 km/h) spectra for the SMA8 pavement in the AOT database.

Figure 3.1:
AMES Engineering Laser Texture Scanner.

3. TEXTURE MEASUREMENT PROCEDURE

In this study the surface texture of slab specimens was measured with a laser texture scanner from AMES Engineering, as shown in Figure 3.1.

The AMES Engineering Laser Texture Scanner is a stand-alone unit that can be placed on a surface on three point contact feet. It is designed to measure the two decades (50 mm to 0.5 mm) in the macrotexture waveband and one decade (0.5 mm to 0.05 mm) of the microtexture waveband. The laser has a dot size of approximately 0.050 mm at 42 mm standoff distance, a vertical sample resolution of 0.015 mm, and a horizontal sample spacing of 0.015 mm.

The scanner scans a surface directly under the scanner in multiple line scans with a scan line length of 100 mm and a maximum scan width of 75 mm. The number of lines to be scanned can be set by the user up to 1200 lines, so the average spacing between scan lines at maximum can be as small as 0.064 mm. It takes about 9 seconds to complete one scan line. The greater the number of lines scanned, the longer it takes to complete one test.

The scanned data can be downloaded to a computer using a standard Ethernet interface, and reanalysed by software to display a 3D graph of the scanned surface and to calculate the surface indices. Figure 2.2 shows an example of the 3D plot of a scanned surface.

Five index calculations are also available for calculation in the software, including Mean Profile Depth (MPD), Estimated Texture Depth (ETD), Texture Profile Index (TPI), Root Mean Squared (RMS) and band passed filtered elevation and slope variance calculations.

The required input for the AOT are at least 6 parallel texture profile lines measured with a sampling interval of 1 mm or smaller and a distance

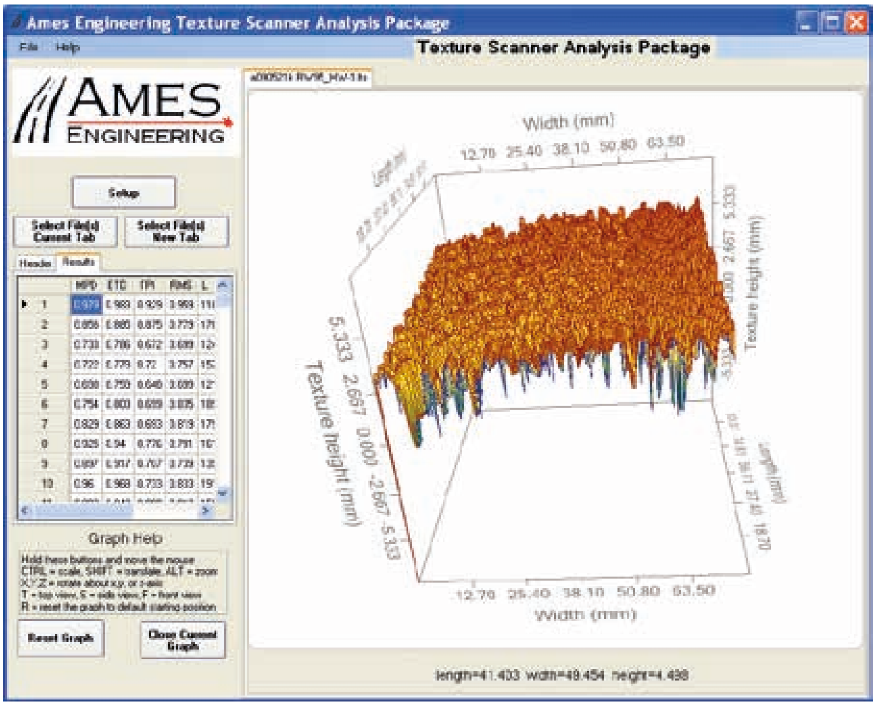


Figure 3.2: Example of 3D plot of scanned surface from AMES Engineering Laser Texture Scanner.

of 10 mm between the profile lines, where the length of each profile is at least 2 m. The AMES Engineering Laser Texture Scanner, however, can only measure a 10-cm long patch of surface in one operation. Stitching or transformation of the data has to be performed to allow the AOT to use the texture data measured with the laser texture scanner. The following methods of data conversion were tried and compared in this study and shown in Chapter 5:

1. Repeatedly mirror one 10-cm profile line to obtain the 2-m texture profile;
2. Randomly select 120 10-cm profile lines from a pool of scanned texture profiles and combine them into 6 200-cm profile lines;
3. Randomly select 10-cm profile lines from a pool of scanned texture profiles, cut them into various lengths (from 3 cm to 10 cm) determined randomly and paste into 6 200-cm profile lines.

The results of the texture measurements can be seen in Chapter 5.

4. THE TEST PAVEMENTS

A total of 12 mixes were included in this study, including one dense-graded asphalt mix, two stone mastic asphalt mixes, and nine open-graded (or porous) asphalt mixes. One basaltic-volcanic nature aggregate was used in all 12 mixtures. The nominal maximum aggregate size, binder type and binder content, and use of additives (fibres or hydrated lime) for each mixture are shown in *Table 4.1: Mix design information of 12 asphalt mixtures included in the study.*4.1, and the aggregate gradations are shown in *Figure 4.1*.

Table 4.1: Mix design information of 12 asphalt mixtures included in the study.

MIX ID	NMAS (MM)	BINDER TYPE	BINDER CONTENT [%]	FIBRE (BY MASS OF TOTAL MIX)	HYDRATED LIME (BY DRY MASS OF AGGREGATE)
RW475	4.75	PG 64-16	7.90%	none	0
RW95	9.5	PG 64-16	5.90%	none	0
RW125	12.5	PG 64-16	5.90%	none	0
RW19	19	PG 64-16	5.00%	none	0
SMA4P	4+	PG 58-34PM	6.70%	0.3% cellulose fibre	0
SMA6P	6+	PG 58-34PM	6.50%	0.3% cellulose fibre	0
AR475	4.75	Asphalt Rubber	9.48%	none	0
P475	4.75	PG 76-22PM	7.90%	none	0
AZ95	9.5	Asphalt Rubber	9.20%	none	1.0%
E8	8	PG 64-16	6.40%	0.25% cellulose fibre	1.5%
G125	12.5	PG 76-22PM	6.30%	0.4% mineral fibre	1.4%
DG125	12.5	PG 64-16	6.00%	none	0

DG125 is a conventional dense-graded asphalt concrete (DGAC) mix with anominal maximum aggregate size of 12.5 mm. The aggregate gradation follows the middle values of Caltrans standard specifications for 12.5-mm DGAC. This mix is included in the study to provide reference values for performance evaluation of OGFC or porous asphalt mixes.

The first four mixes in *Table 4.1* (denoted RW) differ in the nominal maximum aggregate size (NMAS) and corresponding aggregate gradation and binder content. The aggregate gradation of mixture RW475 was selected from one European fine (5 mm) open graded friction course (OGFC) gradation [9]. RW95 and RW125 were selected from Caltrans 9.5-mm and 12.5-mm OGFC gradation specifications, respectively, while RW19 is determined based on Indiana DOT 19-mm OGFC gradation specifications.

SMA4P and SMA6P are two stone mastic asphalt (SMA) mixtures designed in Denmark to solve the clogging issue that often occurs in OGFC. The idea is to use thin surface layers with less air voids which might have a slightly less noise reducing capability than double-layer porous asphalt (DLPA), but a better durability, so the long term acoustical benefit will be positive [10]. These two mixtures use small maximum aggregate sizes (4 and 6 mm) and a small proportion of oversized aggregates to achieve a smooth but open surface.

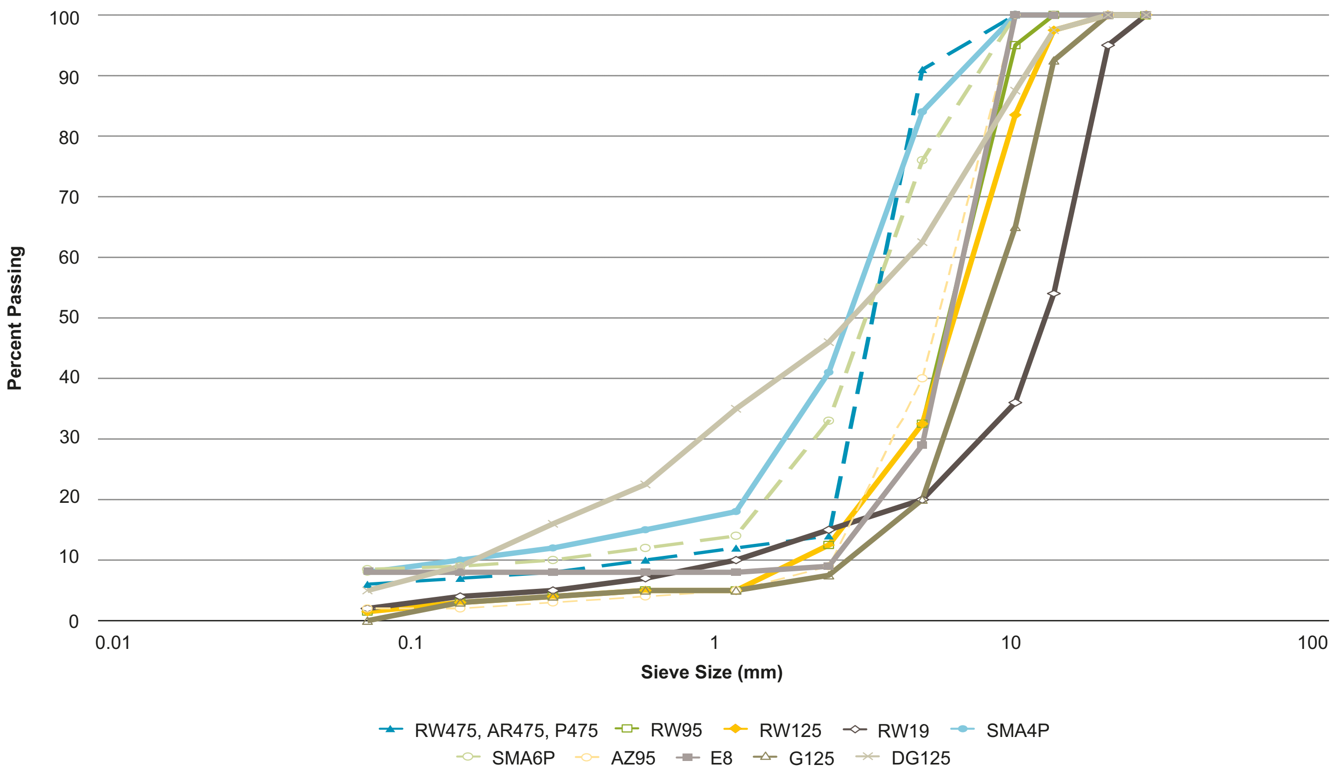


Figure 4.1: Aggregate gradation curves of mixtures included in the study.

AR475 and P475 have the same aggregate gradation as RW475, but different binders. AR475 uses an asphalt rubber binder (PG 64-16 base asphalt with 18% of crumb rubber modifier) at a binder content 20% higher than the binder content of RW475. P475 uses the PG76-22PM binder which is modified with polymers. Asphalt rubber and polymer are used to improve the durability of the porous asphalt mixtures.

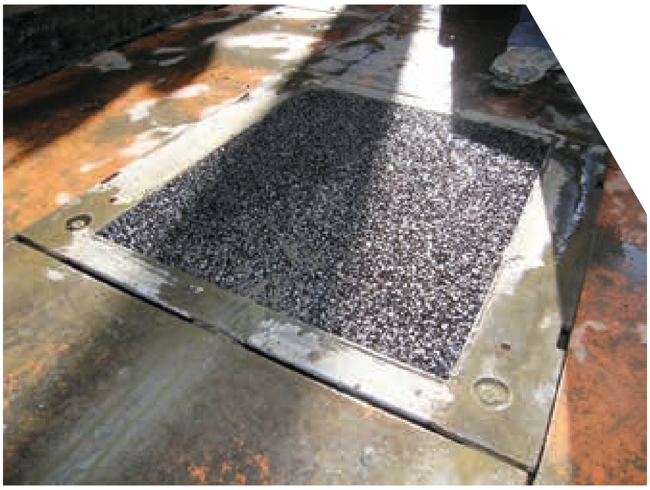
AZ95 is a high-binder rubberised open-graded mixture that has been used widely and successfully in Arizona. It has a nominal maximum aggregate size of 9.5 mm and contains over 50% more binder than an OGFC with conventional binder.

E8 is a porous asphalt mixture that is used in some European countries [9]. It is used as the upper layer of double layer porous asphalt (DLPA). Both cellulose fibre and hydrated lime are added in the mixture to improve its durability.
G125 is an OGFC developed by the Georgia Department of Transportation (GDOT) in the early 1990s and has been used extensively statewide since then. The mix uses polymer-modified asphalt binder, and contains both fibre and hydrated lime. It has shown good performance history in terms of noise reduction, permeability, durability, and smoothness in Georgia [11].

Slab specimens of each mix were fabricated in the laboratory for measurement of surface texture and other properties (see Figure 4.2 and 4.3). The air-void content of each slab was selected at a level that is typical in the field, as shown in Table 4.2. The

Figure 4.2: Roller and moulds used for production of pavement slabs in the UCPRC laboratory in California.

Figure 4.3: Compacted pavement slabs still in the mould.



amount of material to be compacted was then calculated and pre-weighed based on this design air-void content and the volume of a compaction mould. The pre-weighed loose mix was then distributed in the steel mould of 635 mm length and 560 mm width, and then compacted by a BOMAG 90 AD ride-on tandem roller (with an approximate weight of 2000 kg). The compaction was done in the static mode and generally 30 passes were applied to make the slab surface flush with the mould edge. After surface measurements, cores were then taken from the slab specimen for sound absorption test and other performance tests.

The design and actual air-void content and average MPD (measured with the AMES texture scanner) of slabs of each mix are also shown in Table 4.2. Figure 4.5 shows a close-up picture of the slab surface of each mix.

Table 4.2: Air-void contents and MPD of each mix.

MIX ID	NMAS [MM]	DESIGN AIR-VOID CONTENT [%]	OBTAINED AVERAGE AIR-VOID CONTENT [%]	AVERAGE MPD [MM]
RW475	4.75	20	18.7	0.80
RW95	9.5	20	20.2	1.06
RW125	12.5	20	21.9	1.24
RW19	19	20	15.3	1.95
SMA4P	4+6	11	13.5	0.56
SMA6P	6+8	14	16.3	0.71
AR475	4.75	20	18.1	1.03
P475	4.75	20	20.0	0.24
AZ95	9.5	20	17.8	1.32
E8	8	26	20.5	1.17
G125	12.5	20	20.5	1.33
DG125	12.5	5	3.9	0.33

Based on the data of the test pavements in Table 4.1 and 4.2 as well as Figure 4.1 the authors performed a rough expert judgement of the noise reduction that can be expected for these pavements. The dense graded DG125 pavement was used as a reference pavement. This pavement seems quite close to the dense graded asphalt concrete with 11 mm maximum aggregate size (DGAC11 or AC11) normally used as a reference pavement in Denmark [17, 18]. The expert judgement is based on SPB noise levels when the pavements are a few months old and a speed of around 90 km/h. About the same results can be expected as CPX levels. The result can be seen in Figure 4.4. The three porous pavements with a maximum aggregate size (RW475, AR475 and P475) are expected to have the best noise reduction of around 5 dB. These are followed by the SMA4P and the porous pavements with 8 to 9.5 mm maximum aggregate size (RW95, AZ95 and E8) with a noise reduction around 4 dB. The porous pavements with 12.5 mm maximum aggregate size (RW125 and G125) are expected to have a noise reduction of around 3 dB.

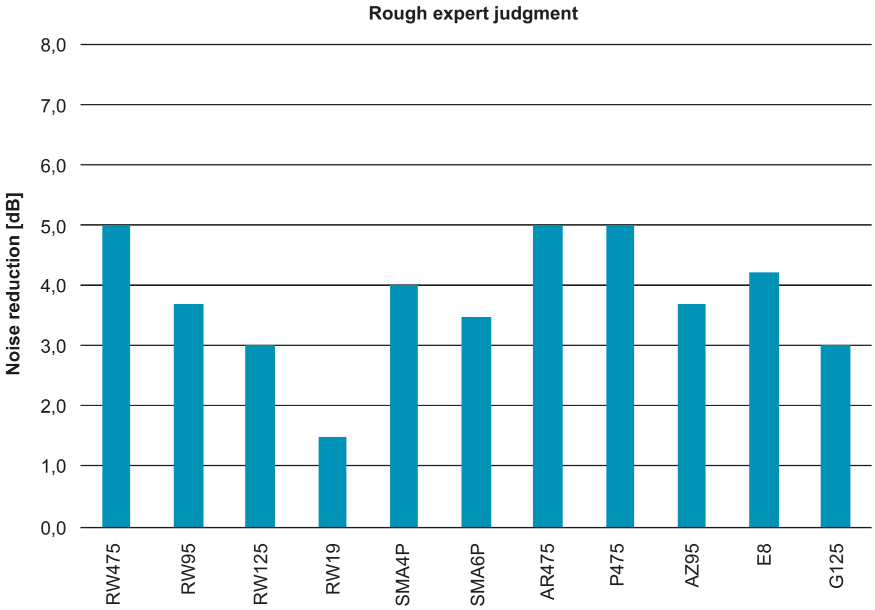
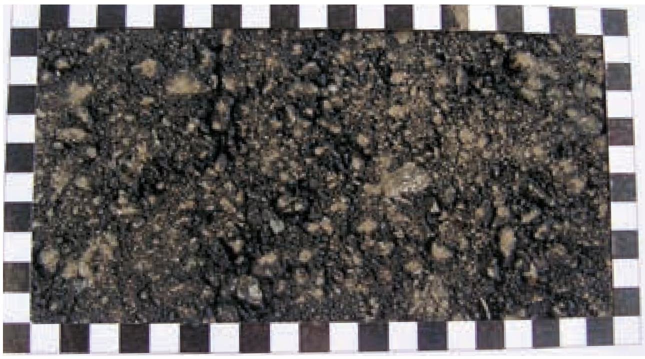
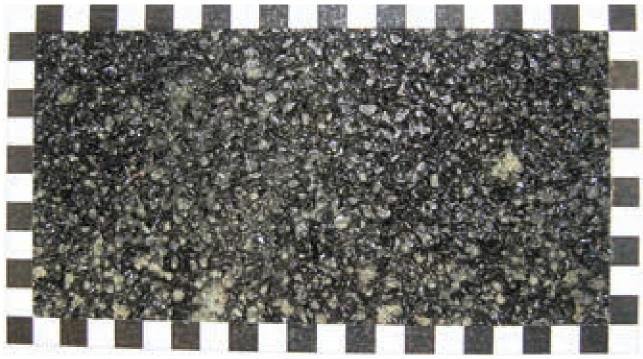


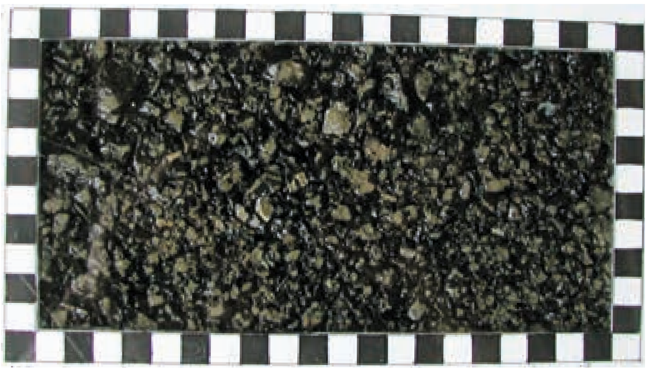
Figure 4.4: Rough expert judgement by the authors on the noise reduction of the test pavements relative to the dense graded DG125 pavement.



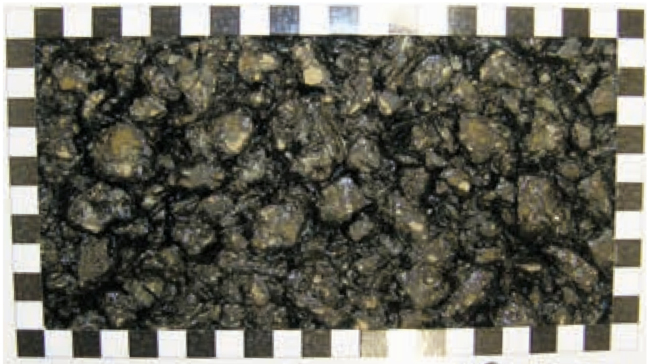
DG125



RW475



RW125



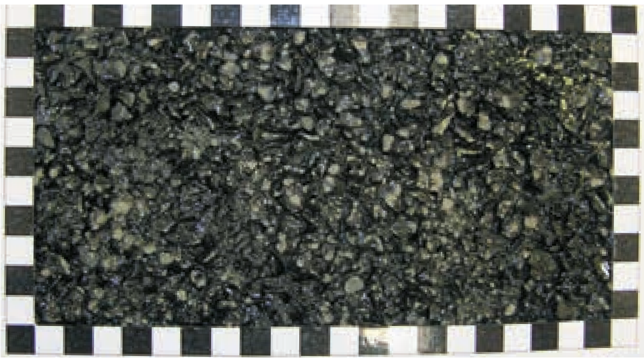
RW19

SMA6P

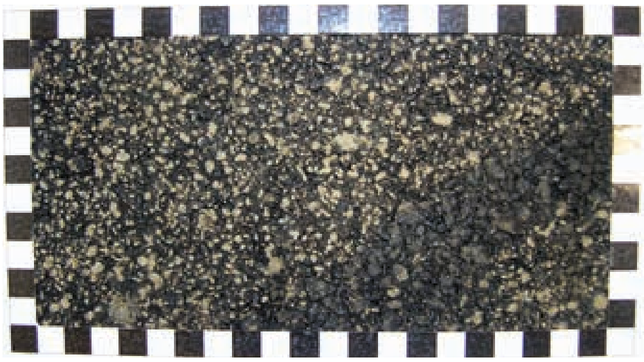
AR475

AZ95

E8



RW95



SMA4P

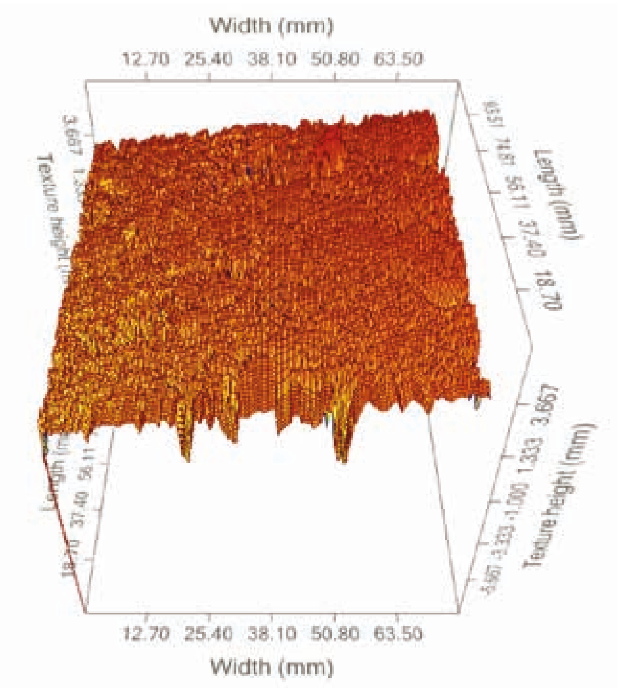
P475

G125

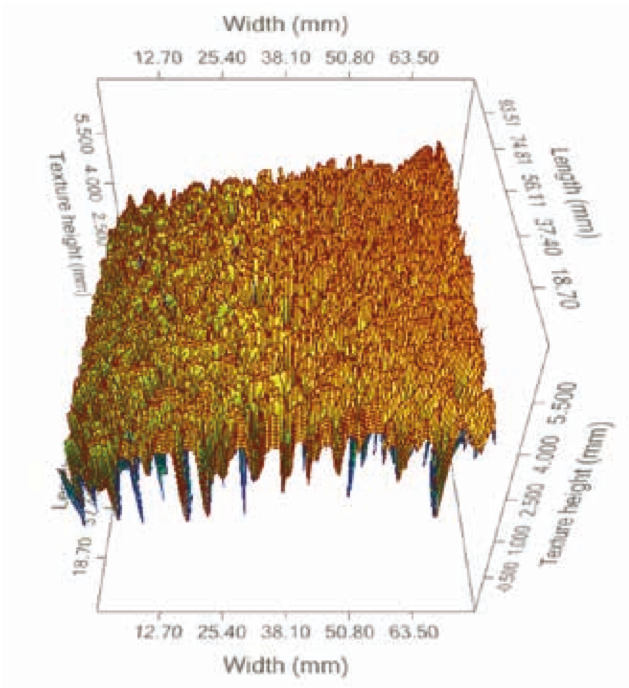
Figure 4.4: Surfaces of slab specimens of 12 asphalt mixes (The size of the black and white squares in the photos is 10 mm times 10 mm).

5. MEASUREMENT OF TEXTURE

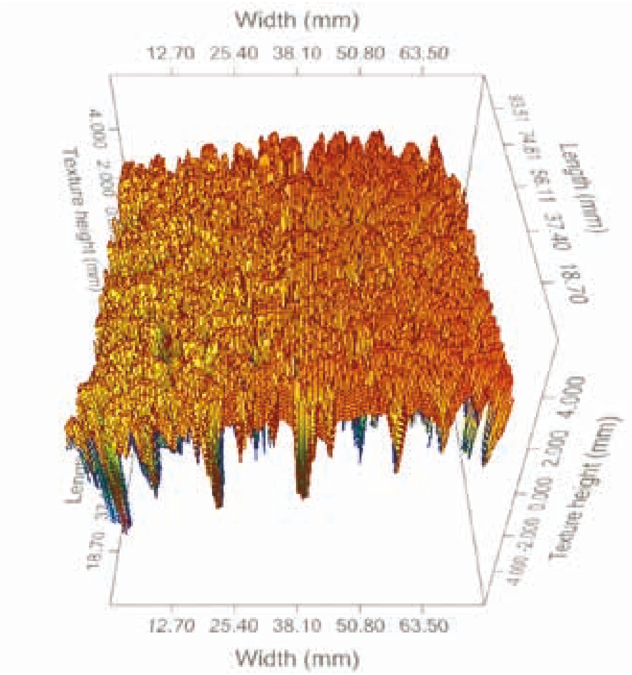
The texture for each of the 12 laboratory produced slab specimens was measured using the AMES equipment (see Chapter 3). The pavement specimens were not exposed to traffic when the measurements were performed. 3D pictures of ten of the pavement textures can be seen in the below figures.



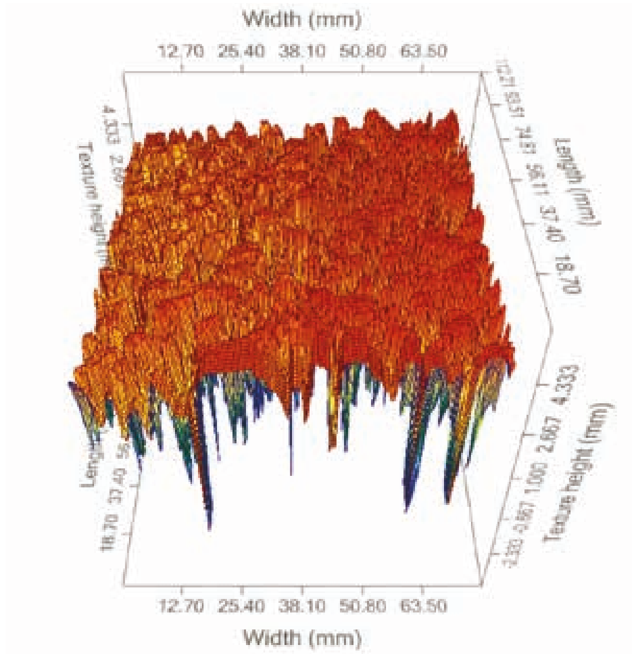
DG125



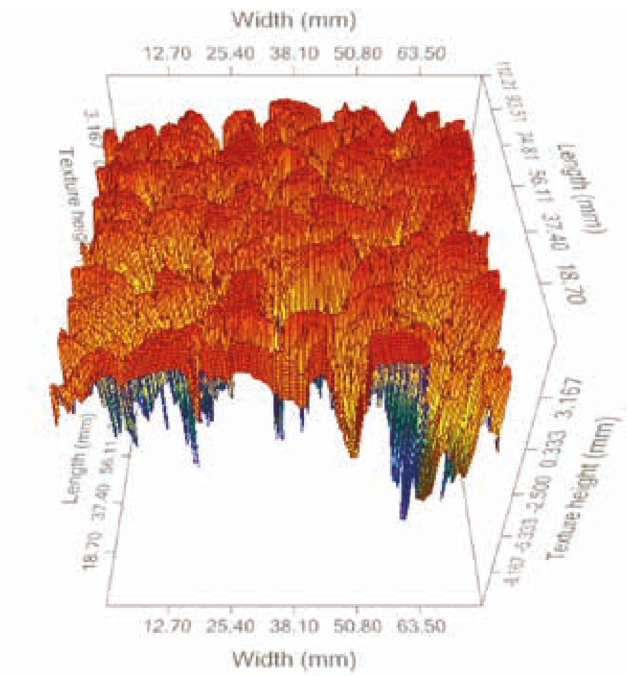
RW475



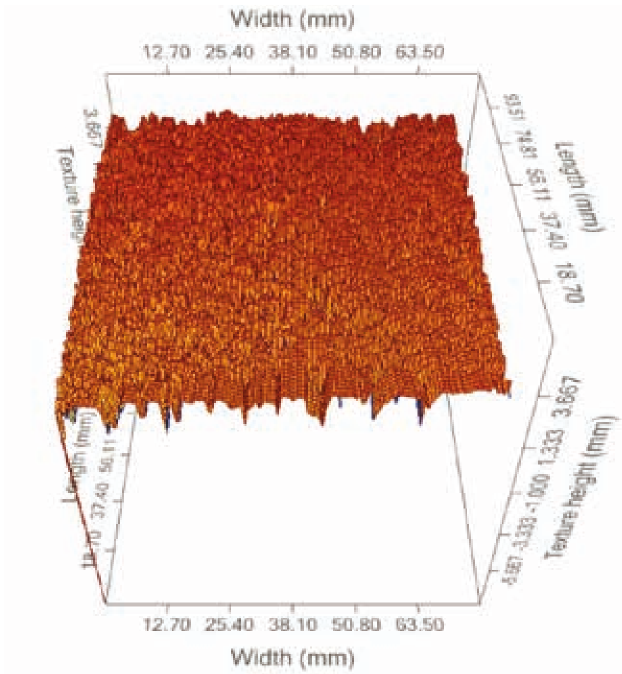
RW95



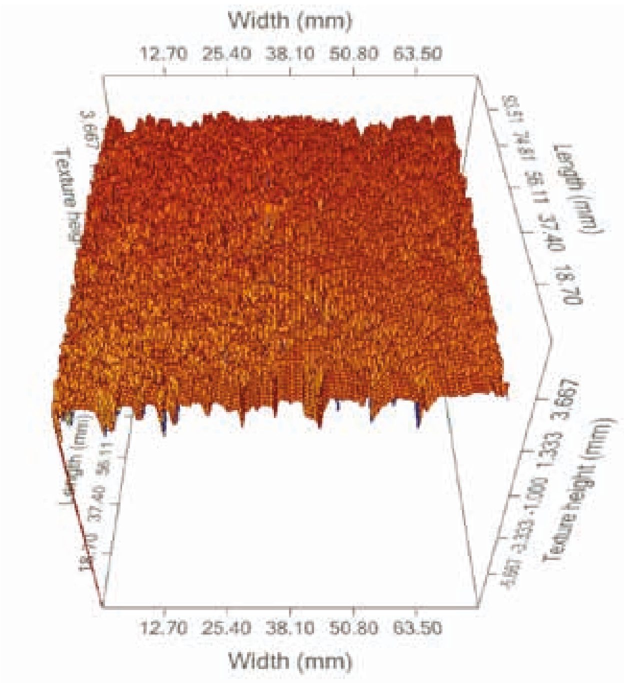
RW125



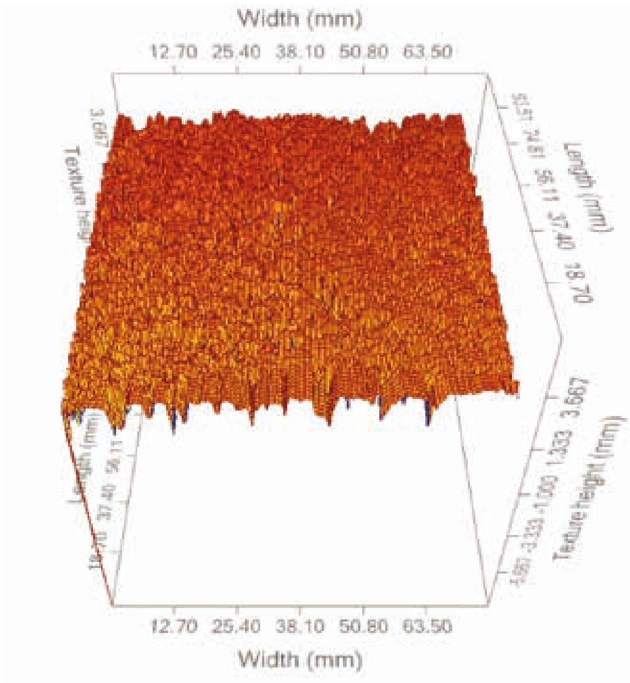
RW19



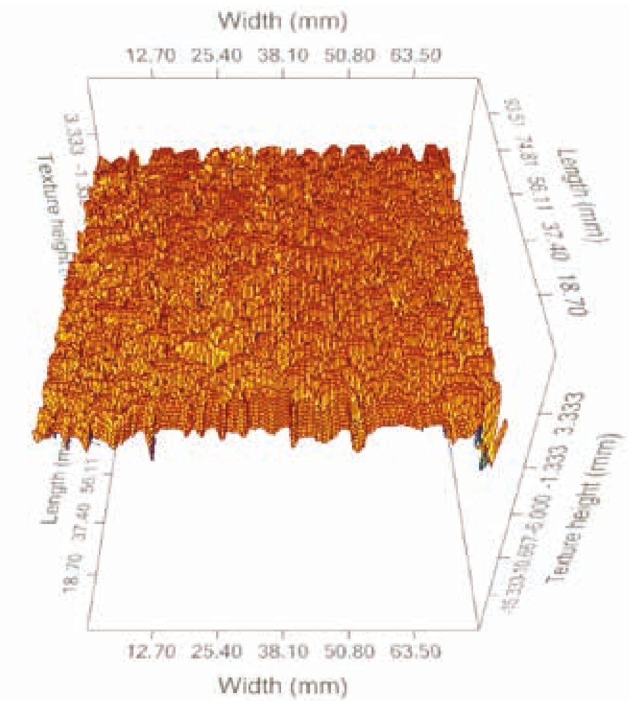
SMA4P



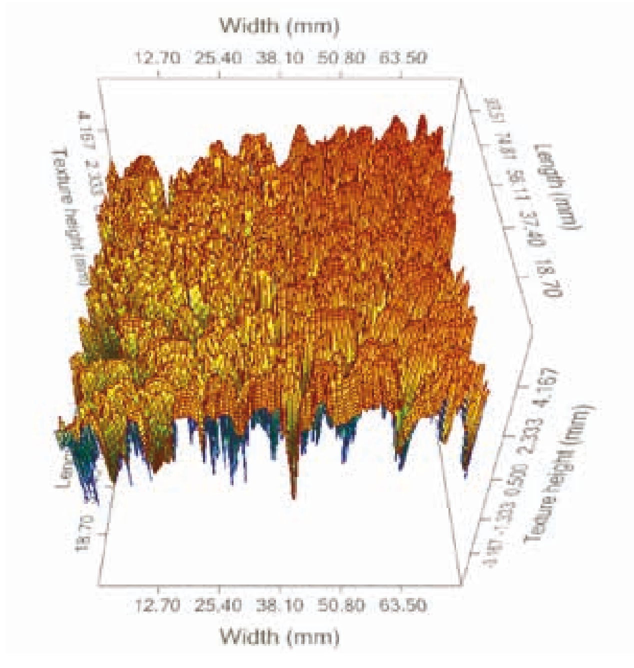
SMA6P



E8



P475



G125

Figure 5.1: 3D pictures of the results of the laser texture scanning of 10 of the laboratory produced slab specimens.

Based on these texture measurements 2-m long texture strings were "constructed" for each pavement according to the three relevant strategies described in Chapter 3. These strings were used in the AOT predictions presented in Chapter 6. Randomly selected 10-cm long sections of these texture strings for each pavement can be seen in Figure 5.2 together with the MPD in mm.

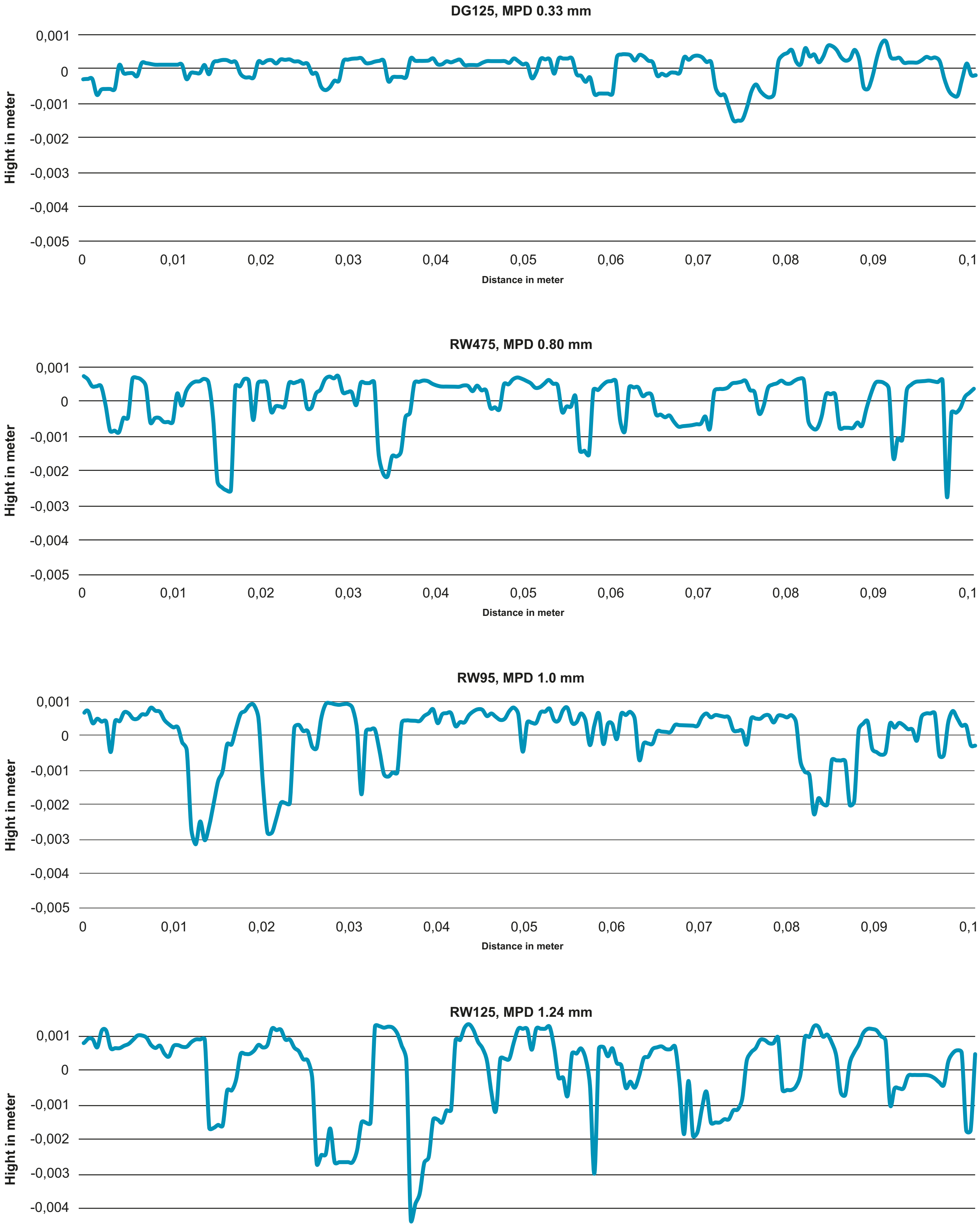


Figure 5.2: Randomly selected 10-cm long sections of these texture profiles for each of the 12 pavements.

Figure 5.2: Randomly selected 10-cm long sections of these texture profiles for each of the 12 pavements.

Figure 5.2: Randomly selected 10-cm long sections of these texture profiles for each of the 12 pavements.

The following were performed in order to evaluate the consequences of using the three different methods for generating the texture string inputs for AOT simulations using the three strategies:

1. Repeatedly mirror one 10-cm profile line to obtain the 2-m texture profile
2. Randomly select 120 10-cm profile lines from a pool of scanned texture profiles and combine them into 6 200-cm profile lines
3. Randomly select 10-cm profile lines from a pool of scanned texture profiles, cut them into various lengths (from 3 cm to 10 cm) determined randomly and paste into 6 200-cm profile lines

Three of the 12 pavements included in this project were selected for the testing of these three strategies to produce texture profile input data for the AOT. These three were the porous RW95, SMA6P and the dense DG125. The main results can be seen in Table 5.1, in which the results from using a pavement from the AOT database similar to the three tested pavements were included in the right-hand column. It can be seen that Strategies 2 and 3 give almost the same results and that they are also close to the results of using the AOT standard texture data for the different pavements. The results of using Strategy 1 are around one dB higher. The spectral results are shown in Figures 5.3 to 5.5. It can be seen that at the higher frequencies of over 800 Hz there is a reasonable correspondence between the results using Strategy 2 and the predefined AOT data whereas Strategy 2 for SMA6P and DG125 gives higher results at the lower frequencies of below 800 Hz, reflecting the tyre vibration generated noise.

Based on this it was decided to use Strategy 2 for producing the texture data for the AOT in the following analysis presented in Chapter 6.

Table 5.1: Summary of results of testing three strategies to produce texture profile input data for the AOT shown as CPX noise levels at 90 km/h. The predicted noise levels using the different strategies are shown together with the results using the AOT-predefined texture data for similar pavements.

PAVEMENT	TYPE	STRATEGY 1 [dB]	STRATEGY 2 [dB]	STRATEGY 3 [dB]	AOT STANDARD [dB]
RW95	Porous	100.6	99.0	99.1	98.7
SMA6P	SMA	95.3	95.0	94.8	94.9
DG125	DGAC-ref.	96.2	95.0	95.1	95.1

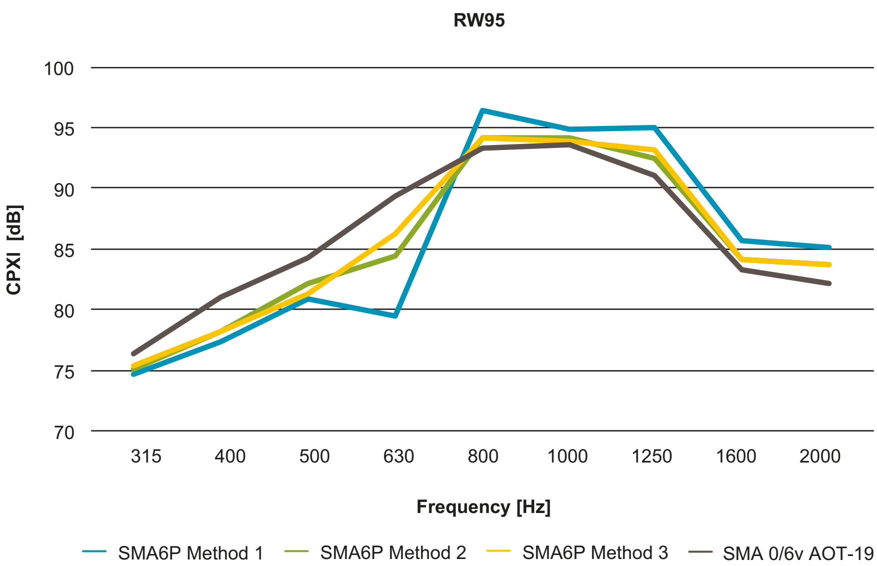


Figure 5.3: Spectra for the porous RW95 pavement using the three different strategies as well as using AOT-predefined texture data (45 mm PAC8/11 AOT-L31).

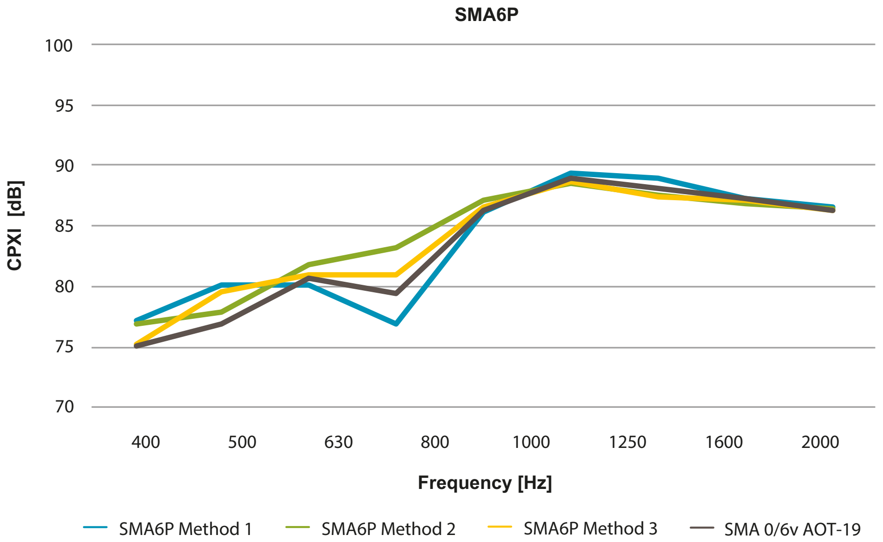


Figure 5.4: Spectra for the SMA6P pavement using the three different strategies as well as using AOT-predefined texture data (SMA0/6 AOT-19).

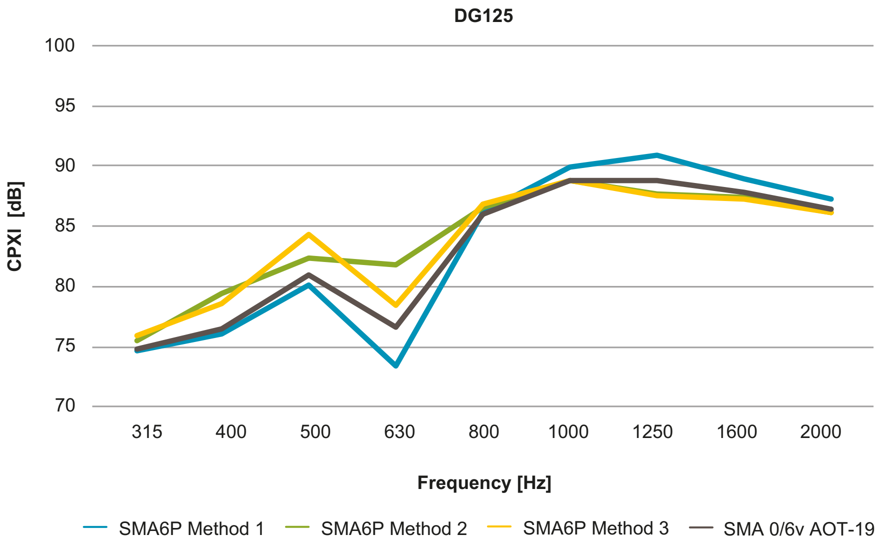


Figure 5.5: Spectra for the dense DG125 pavement using the three different strategies as well as using AOT-predefined texture data (40 mm DAC0/16 AOT-23).

6. RESULTS OF THE AOT PREDICTIONS

The four main input parameters for the AOT noise predictions are related to the surface properties of the pavement:

- Pavement surface texture
- Acoustical impedance
- Flow resistance
- Mechanical impedance

The nominal maximum aggregate size used for these 12 pavements varies from 4 to 19 mm. The aggregates used and their size are very important for the shape of surface texture of a pavement (see Figure 5.2). Therefore the nominal maximum aggregate size of each pavement will be reflected in the measured surface textures. These measured surface textures for each of the 12 pavements will be used as the main variable in the AOT predictions.

The acoustical impedance and the flow resistance are both parameters related to the level of open structure in the different mixes which as an overall indicator can be described using the built in air-void. In relation to air-void (see Table 4.2) the pavements can be divided in three groups:

1. The dense group, which is the dense graded reference pavement (DG125) with air void of 3.9 %.
2. The thin open but not really porous group that are the two SMA pavements (SMA4P and SMA6P) with air-voids of 13.5 and 16.3%.
3. The single layer porous group, which is the remaining nine pavements with air-voids varying from 17.8 to 21.9 %.

There are no measurements of either acoustical impedance or flow resistance available for the 12 pavements. Therefore it is necessary to rely on the predefined values for these parameters in the AOT.

In some of the pavements rubber granulates are used. It is the judgement of the authors that all the 12 pavements are so stiff that the mechanical impedance in this case is not a factor that can cause differences in the noise. The predefined values for this parameter in the AOT will be used.

For all the AOT predictions the measured texture (using method 2, see Chapter 5) for each of the 12 pavements will be used. But three strategies for using predefined values for acoustical impedance and the flow resistance will be tested:

1. For all 12 pavements the predefined values for acoustical impedance and the flow resistance for the Dense Graded Asphalt Concrete (DAC16) was used (see Sections 6.1.1 and 6.1.2). Using this strategy the noise reducing effect of high frequency air pumping generated noise (over 1000 Hz) will presumably be underestimated (see Figure 2.1) as dense graded pavement has lower acoustical impedance than the 11 open and porous pavements.
2. The 12 pavements were subdivided into 3 pavement families (see Sections 6.2.1 and 6.2.2). For these 3 families a predefined pavement in the AOT was used belonging to the relevant pavement family:

   A. Dense Graded Pavements (mix ID: DG125). AOT reference dense graded asphalt concrete with maximum aggregate size of 16 mm (name in AOT: DAC16) as 11 mm maximum aggregate size is not available.
   B. Thin open layers which are not really porous (mix ID: SMA4P and SMA6P). AOT references a thin layer SMA with maximum aggregate size of 6 mm (name in AOT: SMA 0/6).
   C. The single layer porous types with a built in air-void of over 18% (mix ID: RW475, RW95, RW125, RW19, AR475, P475, AZ95, E8, and G125). AOT references a porous asphalt concrete with maximum aggregate size of 11 mm (name in AOT: PAC 2/6).

3. For each of the 12 pavements the pavement in the AOT that fits best in terms of pavement type and aggregate size was selected (see Sections 6.3.1 and 6.3.2). This selection can be seen in Table 6.1.

Table 6.1: The 12 pavements and the best fitting AOT standard pavement selected for predictions using Strategy 3.

PAVE-MENT	DG 125	RW 475	RW 95	RW 125	RW 19	SMA4P	SMA6P	AR 475	P 475	AZ 95	E8	G125
AOT	DAC16	PAC2/6	PAC0/11	PAC0/11	PAC11/16	SMA0/6	SMA0/6	PAC2/6	PAC2/6	PAC0/11	PAC0/11	PAC0/11

The main objective with this investigation was to get a noise ranking of the 12 pavements produced in the laboratory.

Table 6.2: Measured CPX noise on the Dutch Kloosterzande pavement test site at 70 km/h and MPD for the six AOT pavements included in this study. Levels were read from Figure 51 in [19].

PAVEMENT	DAC16	SMA0/6	PAC2/6	PAC0/11	PAC8/11	PAC11/16
TYPE	Dense	SMA	Porous	Porous	Porous	Porous
NUMBER IN AOT [19]	23	19	15	6	31	7
CPX NOISE [dB]	94.0	92.5	91.0	94.5	96.5	93.0
MPD [MM]	0.45	0.55	0.83	2.00	2.31	1.86

As the AOT predictions were based on up to five different AOT predefined pavements it would be relevant as a starting point to see how these five pavements are ranked in the AOT. [19] contains a figure showing an overview of the measured CPX noise at 70 km/h for all the approx. 40 pavements that are included with predefined data in the AOT. Most of these measurements were performed on the Dutch Kloosterzande pavement test site. The results for the pavements used in this investigation can be seen in Table 6.2. As there are two porous pavements with 11 mm aggregates PAC 0/11 (AOT no. 6) and PAC 8/11 (AOT no. 31) they are both included in Table 6.2. The spectra for these six pavements is shown in Figure 6.1.

The dense graded DAC16 with 16 mm maximum aggregate size can be regarded as a kind of reference pavement. The measured noise level is 94.0 dB (see Table 6.2). The SMA with 6 mm maximum aggregate size has a 1.5 dB lower noise level at 92.5 dB and the porous pavements also with 6 mm aggregate size have a 3 dB lower noise level at 91.0 dB. These differences could be expected to be larger. The two porous pavements with 11 mm aggregates (PAC0/11 and PAC8/11) both have higher noise levels (0.5 and 2.5 dB) than the reference DAC16 even though it could be expected that they would have remarkably lower levels. These two PAC pavements have a difference of 2.0 dB in noise which is quite a large difference. Looking at the spectra (Figure 6.1) it can be seen that in the lower frequencies the PAC8/11 has remarkably higher noise levels than the PAC0/11 indicating that this pavement has a rougher surface texture. This might also be reflected by the MPD levels of 2.31 mm versus 2.00 mm. The porous pavements with 16 mm aggregates have a 1 dB lower noise level than the DAC16 reference even though this difference could be expected to be larger. All in all these comments indicate that the reference pavement has a relatively low noise level.

In the AOT predictions the PAC0/11 pavement was used as the PAC8/11 seems to have a rough surface texture causing a 2 dB higher noise level than the PAC0/11.

The AOT predictions were carried out both for CPX noise levels as well as for SPB noise levels at a measurement microphone height of 1.2 m. [5] presents each test pavement as figures with spectra and tables with L_A noise levels (CPX). A reference speed of 90 km/h (56 mph) was used to simulate the noise situation on highways. Using 90 km/h made it possible to directly compare the results to measurements on two Danish test sections with thin open noise reducing pavements called “Herning I” [17] and “Herning II” [18] and it is also close to normal speed on some Californian highways.

The predictions were performed using the version of the AOT model that was up and running at the beginning of 2012 from January to April.

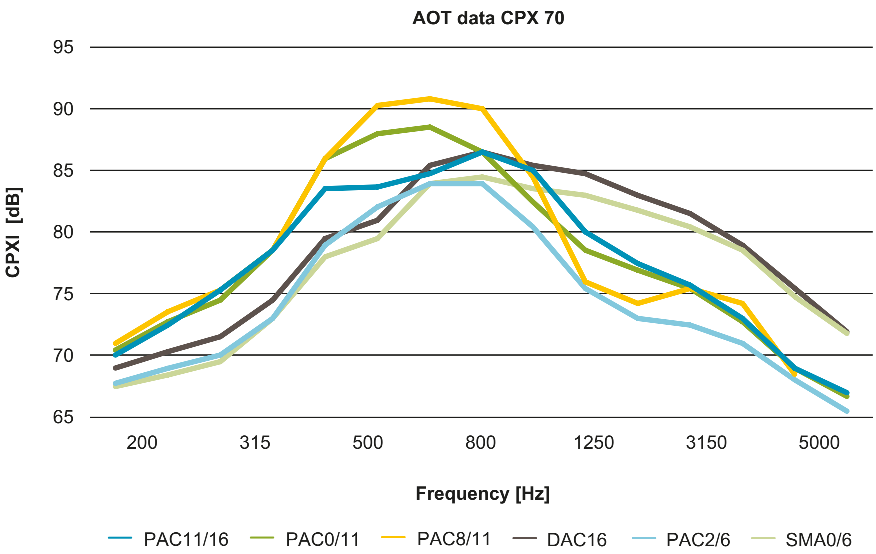


Figure 6.1: Measured frequency spectra (CPX at 70 km/h) for the six AOT pavements included in this study [19].

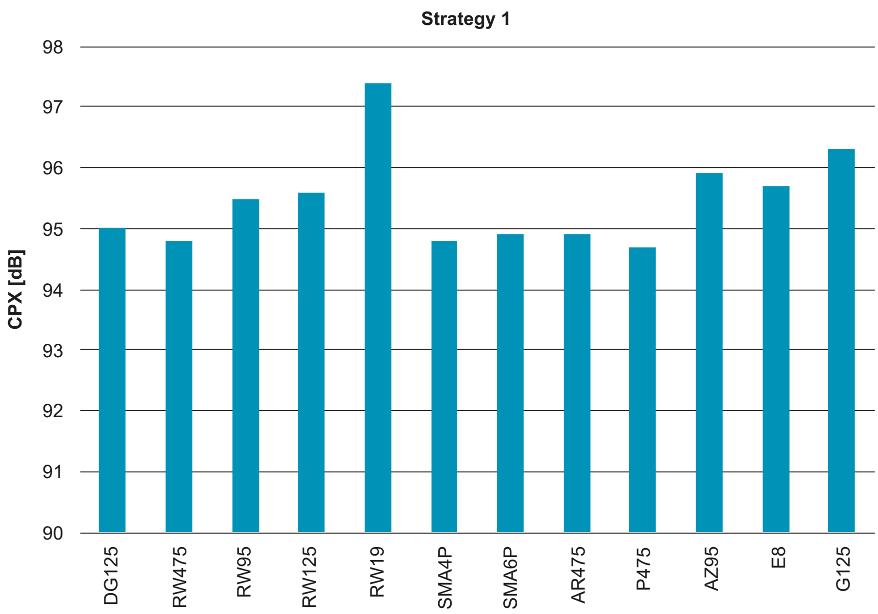


Figure 6.2: CPX results of AOT predictions using Strategy 1 at 90 km/h.

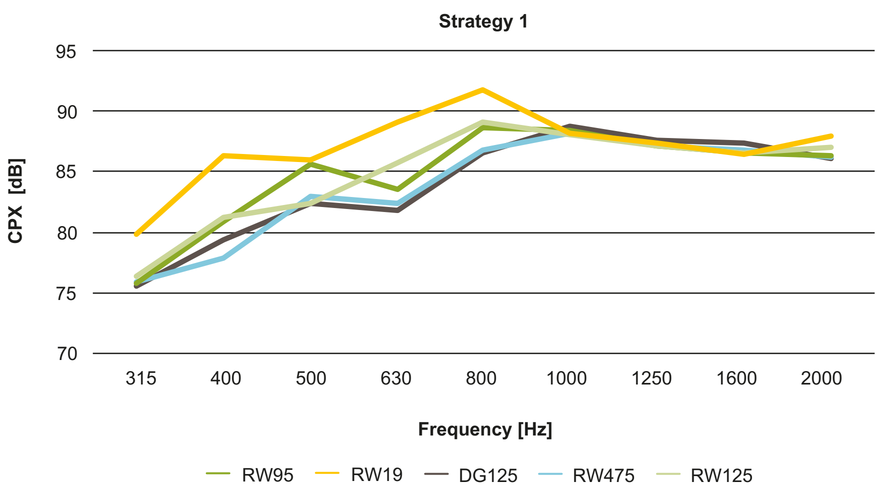


Figure 6.3: CPX spectra for the dense graded (DG125) reference pavement and the four porous “RW” pavements predicted by the AOT using Strategy 1.

6.1 STRATEGY 1

6.1.1 Strategy 1 CPX

In the AOT predictions of CPX levels using Strategy 1, the predefined values for acoustical impedance and the flow resistance for the Dense Graded Asphalt Concrete (DAC16) were used for all 12 pavements. The results can be seen in Figure 6.2. The results are within a range of 2.7 dB. The most silent pavements are the three porous pavements with 4.75 mm nominal maximum aggregate size and the SMA4P with a noise level of around 94.8 dB. It is not possible to point out one single pavement as the best in terms of low noise emission. The dense graded pavement (DG125) has nearly the same noise level of 95.0 dB. This reference pavement generally has an unexpected low predicted noise level. For the pavements with larger aggregate size than 4.75 mm the noise level increases.

Figure 6.3 shows the predicted frequency spectra for the four porous “RW” pavements. At less than 1000 Hz the noise increases as the aggregate size increases, indicating that the pavement has a rougher surface texture, thus increasing the low frequency tyre vibration generated noise. At over 1000 Hz the spectra are alike, indicating that noise generated from air pumping is the same.

Figure 6.4 shows the predicted spectra for the two SMA pavements. At less than 1000 Hz the pavement with the largest aggregates (SMA6P) has the highest noise level. At over 1000 Hz the two pavements are alike.

Finally, Figure 6.5 shows the predicted spectra for the five other pavements. The same tendencies as seen in Figures 6.3 and 6.4 can be seen here. At less than 1000 Hz the noise increases as the aggregate size increases, indicating that the pavement has a rougher surface texture, thus increasing the low frequency tyre vibration generated noise. At over 1000 Hz the spectra are alike, indicating that noise generated from air pumping is the same.

Figures 6.3 to 6.5 show identical spectra for all the 12 pavements at over 1000 Hz. The differences in the open structure of the AMES measured texture profiles (see Figure 5.2) used as input are not reflected in the results of the AOT predictions. This is presumably caused by using a dense pavement as a reference pavement for the AOT predictions with predefined values for acoustical impedance and the flow resistance for a dense pavement

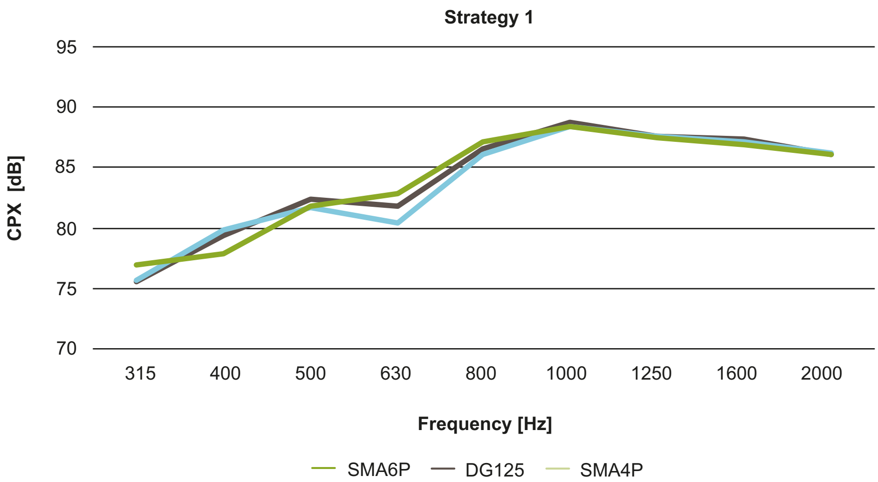


Figure 6.4: CPX spectra for the dense graded (DG125) reference pavement and the two SMA pavements predicted by the AOT using Strategy 1.

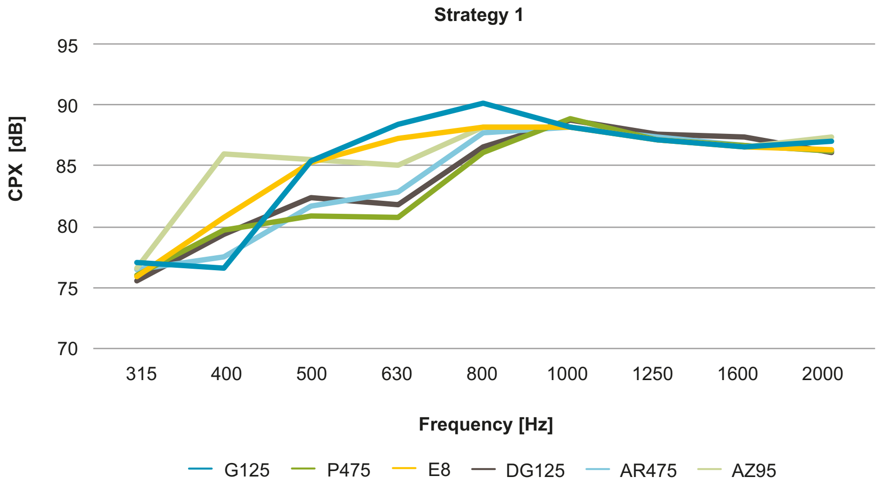


Figure 6.5: CPX spectra for the dense graded (DG125) reference pavement and the five other porous pavements predicted by the AOT using Strategy 1.

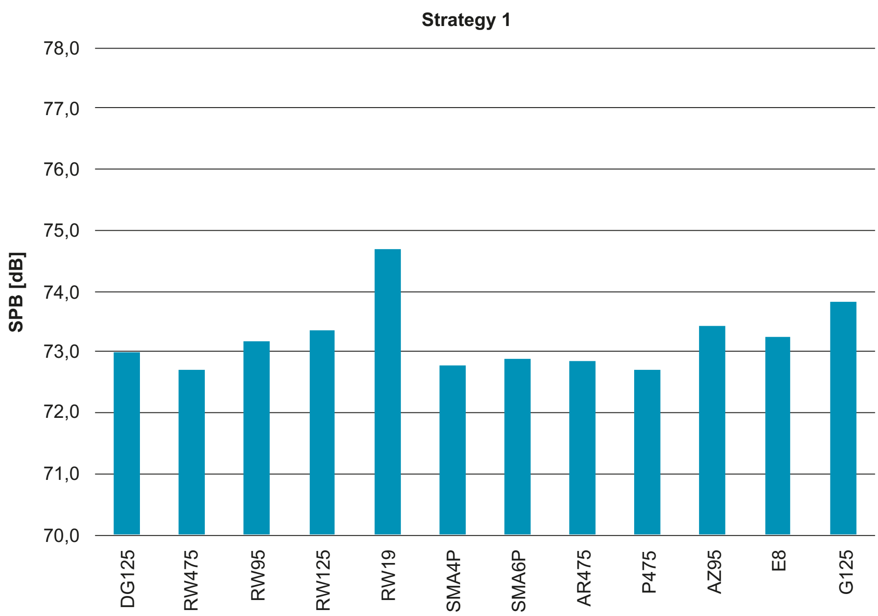


Figure 6.6: SPB results of AOT predictions using Strategy 1 at 90 km/h.

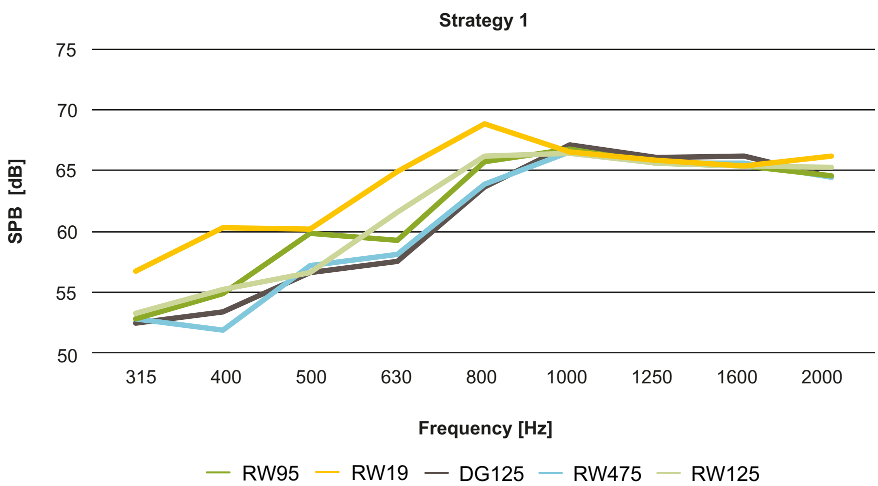


Figure 6.7: SPB spectra for the dense graded (DG125) reference pavement and the four porous “RW” pavements predicted by the AOT using Strategy 1.

6.1.2 Strategy 1 SPB

In the AOT predictions of SPB levels using Strategy 1, the predefined values for acoustical impedance and the flow resistance for the Dense Graded Asphalt Concrete (DAC16) were used for all 12 pavements. The results can be seen in Figure 6.6. The results are within a range of 2.0 dB which is less than the range for the predicted CPX levels, which was 2.7 dB (see Section 6.1.1). The most silent pavements are the three pavements with 4.75 mm nominal maximum aggregate size with a noise level of around 72.8 dB. It is not possible to point out one single pavement as the best in terms of low noise emission. The dense graded pavement (DG125) has nearly the same noise level of 73.0 dB. This must be considered a very low noise level for a dense pavement with a nominal maximum aggregate size of 12.5 mm compared to the open and porous pavements with much smaller aggregate size. For the pavements with aggregate size larger than 4.75 mm the noise level increases. These were the same tendencies as seen for the CPX predictions in Section 6.1.1.

The spectra for the SPB noise predictions can be seen in Figures 6.7 to 6.9. The results show the same tendencies as were seen for the CPX predictions using Strategy 1 and presented in Section 6.1.1.

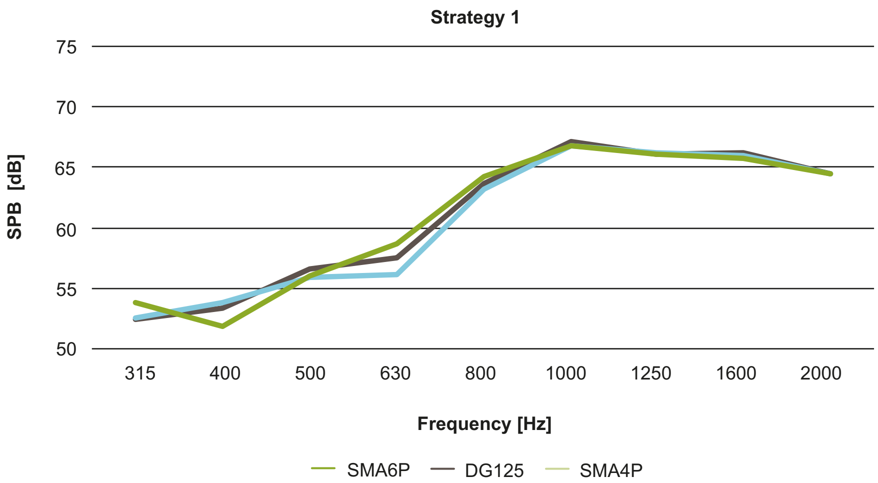


Figure 6.8: SPB spectra for the dense graded (DG125) reference pavement and the two SMA pavements predicted by the AOT using Strategy 1.

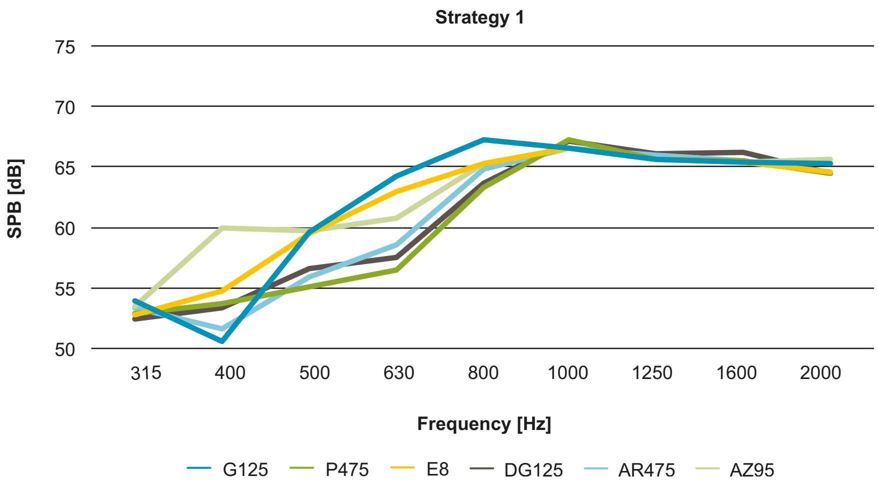


Figure 6.9: SPB spectra for the dense graded (DG125) reference pavement and the five other porous pavements predicted by the AOT using Strategy 1.

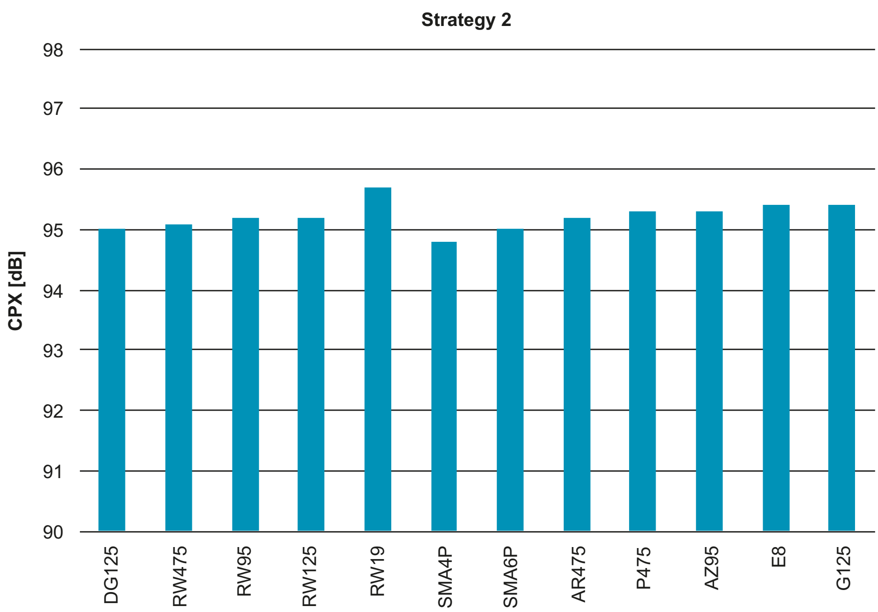


Figure 6.10: CPX results of AOT predictions using Strategy 2 at 90 km/h.

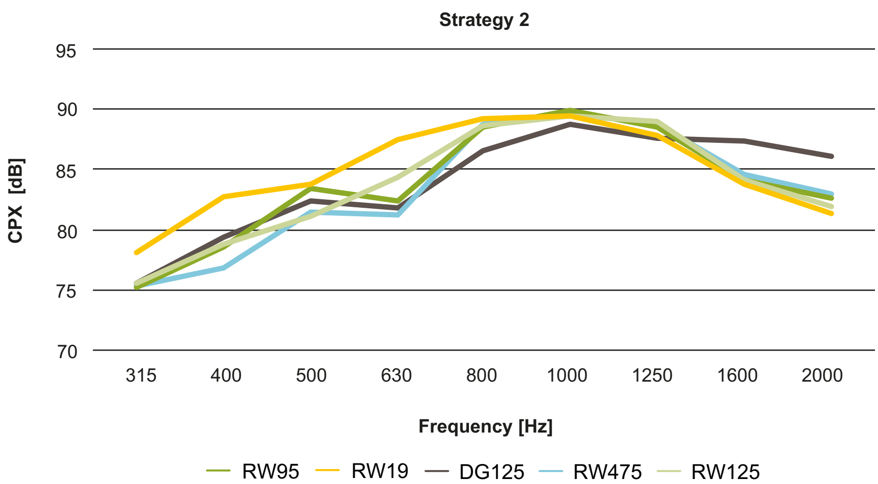


Figure 6.11: CPX spectra for the dense graded (DG125) reference pavement and the four porous "RW" pavements predicted by the AOT using Strategy 2.

6.2 STRATEGY 2

6.2.1 Strategy 2 CPX

In the AOT predictions using Strategy 2, the 12 pavements are subdivided into three pavement families. For these three families a predefined pavement in the AOT is used that belongs to the relevant pavement family. The results can be seen in Figure 6.10. The results fall within a range of 0.9 dB, which is less than the range of 2.7 dB for CPX predictions using Strategy 1. The noise level for the three pavements with 4.75 mm aggregates varies from 94.8 to 95.3 dB with SMA4P having the lowest level.

The spectra for the "RW" pavements are shown in Figure 6.11. At over 1250 Hz the porous "RW" pavements (with a built in air-void of around 20%) now have a 3 to 5 dB lower noise level than the dense DG125. This is presumably the result of using predefined values for acoustical impedance and flow resistance for a porous pavement (PA0/6) as the AOT reference for these predictions. The same is seen in Figure 6.13 for the other porous pavements included in this experiment. This is not seen for the two SMA pavements (with a built in air-void of around 15%) (See Figure 6.12).

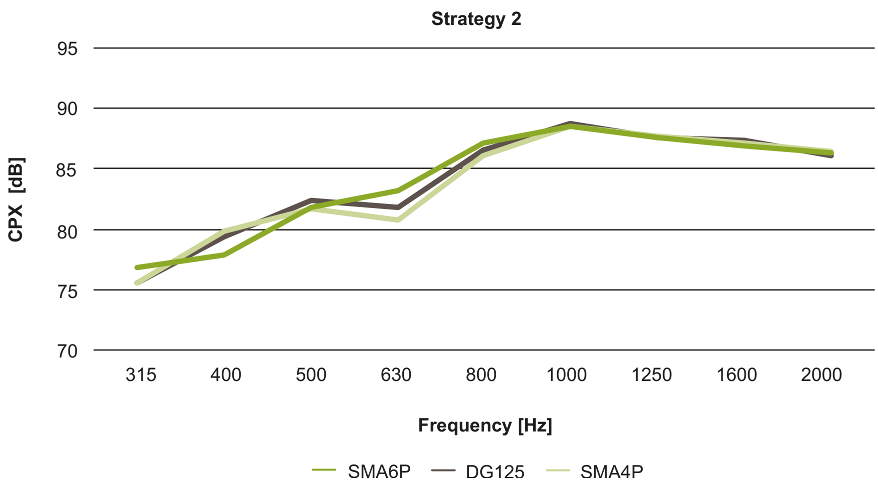


Figure 6.12: CPX spectra for the dense graded (DG125) reference pavement and the two SMA pavements predicted by the AOT using Strategy 2.

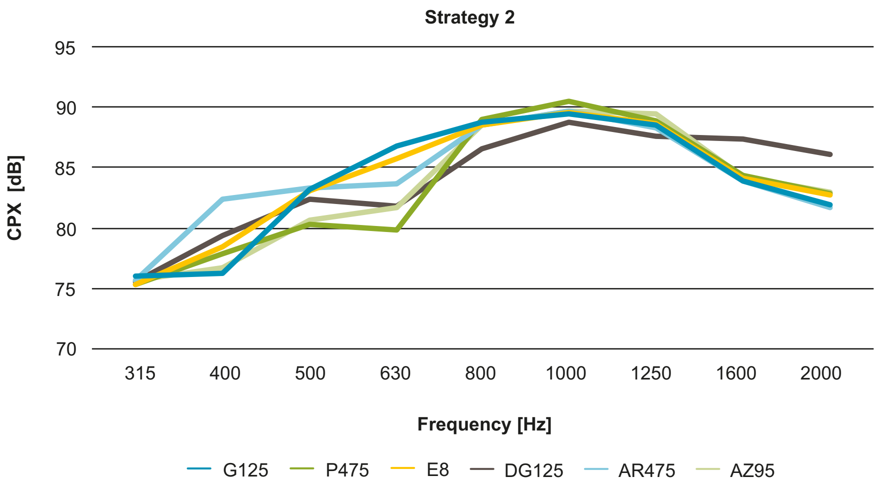


Figure 6.13: CPX spectra for the dense graded (DG125) reference pavement and the five other porous pavements predicted by the AOT using Strategy 2.

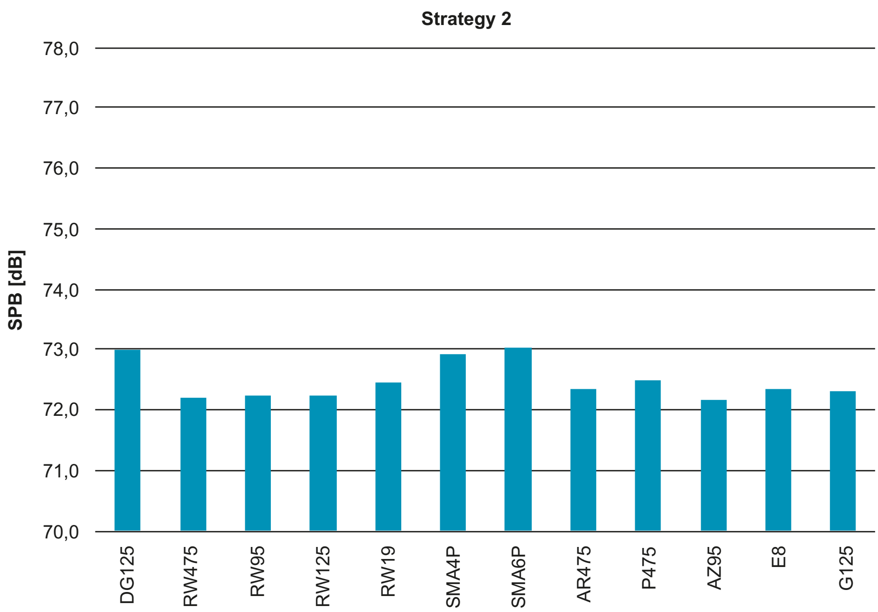


Figure 6.14: SPB results of AOT predictions using Strategy 2 at 90 km/h.

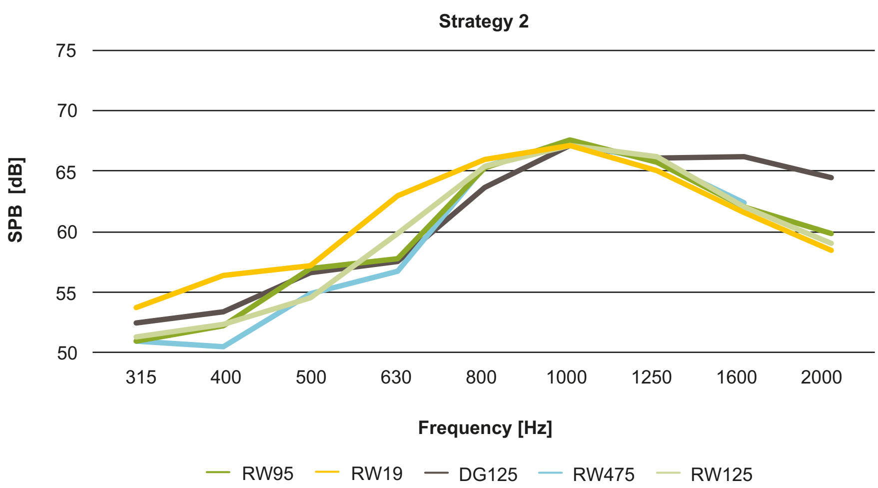


Figure 6.15: SPB spectra for the dense graded (DG125) reference pavement and the four porous "RW" pavements predicted by the AOT using Strategy 2.

6.2.2 Strategy 2 SPB

The predicted SPB results using Strategy 2 can be seen in Figure 6.14. The results fall within a range of 0.8 dB which is nearly the same as the range of 0.9 dB for CPX predictions using Strategy 2. The noise level for the three pavements with 4.75 mm aggregates varies from 72.2 to 72.9 dB with RW475 having the lowest level.

The predicted SPB spectra are shown in Figures 6.15 to 6.17 using Strategy 2. The figures show the same tendencies as were seen for the CPX spectra predicted using Strategy 2 (see Section 6.2.1).

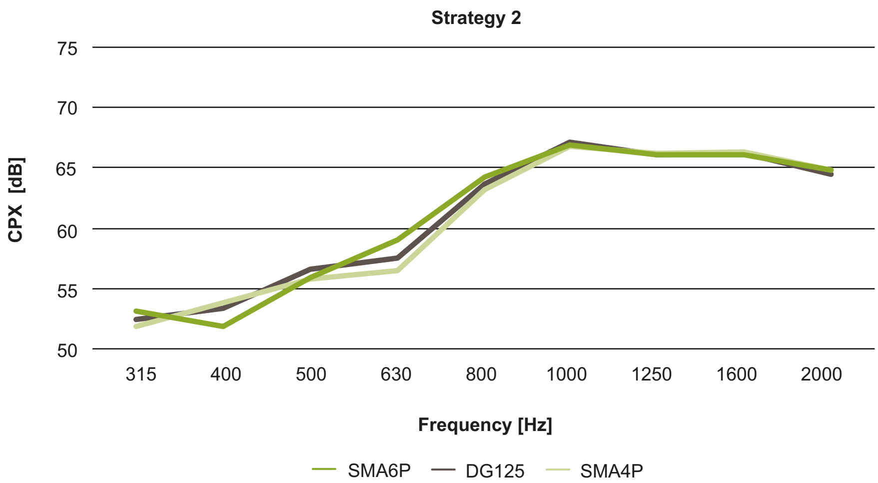


Figure 6.16: SPB spectra for the dense graded (DG125) reference pavement and the two SMA pavements predicted by the AOT using Strategy 2.

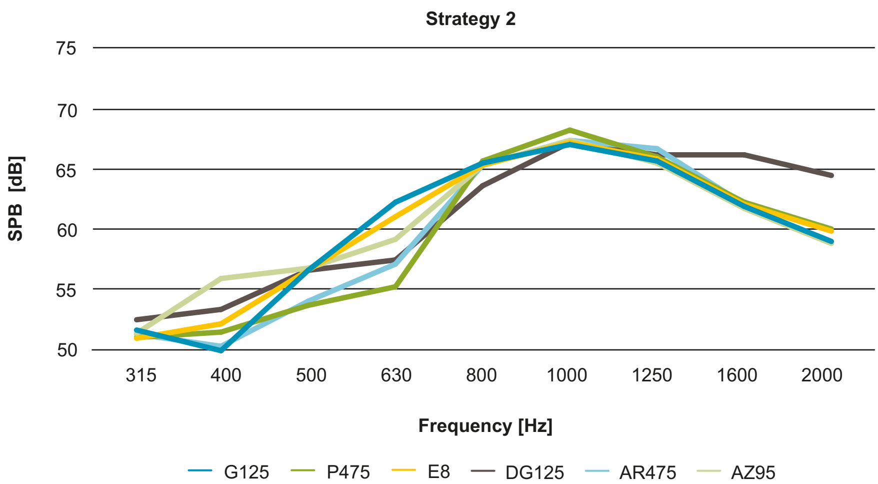


Figure 6.17: SPB spectra for the dense graded (DG125) reference pavement and the five other porous pavements predicted by the AOT using Strategy 2.

6.3 STRATEGY 3

6.3.1 Strategy 3 CPX

In the AOT predictions using Strategy 3, the predefined pavements in the AOT that fits best in terms of pavement type and aggregate size was selected. The results can be seen in Figure 6.18. The results fall within a range of 2.6 dB, which is nearly the same as the range of 2.7 dB for CPX predictions using Strategy 1. The noise level for the three pavements with 4.75 mm aggregates varies from 94.8 to 95.3 dB with SMA4P having the lowest level. The porous pavements with an aggregate size of 8 to 12.5 mm have a two dB higher noise level at around 95 dB. It is remarkable that the porous RW19 pavement with 19 mm aggregates has a one dB lower predicted noise level than the porous pavements with an aggregate size of 8 to 12.5 mm.

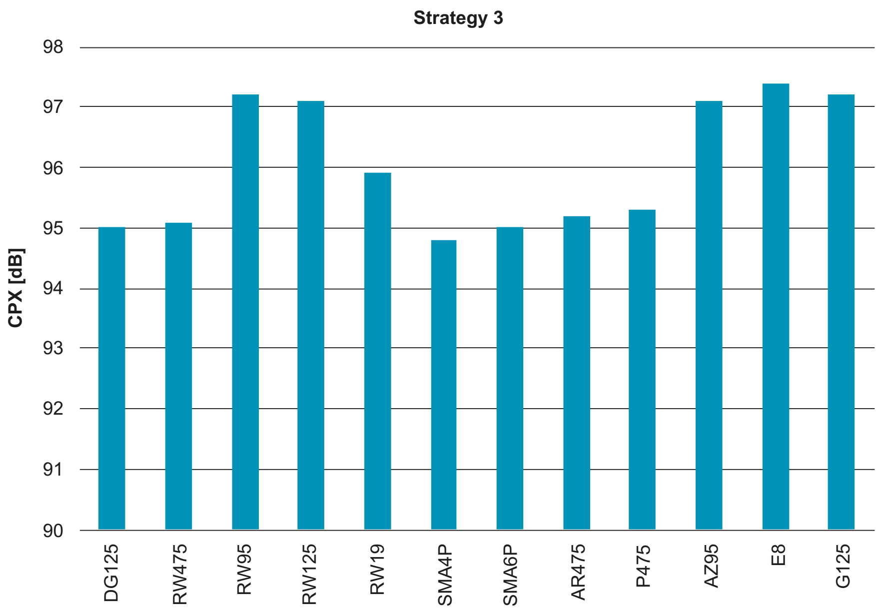


Figure 6.18: CPX results of AOT predictions using Strategy 3 at 90 km/h.

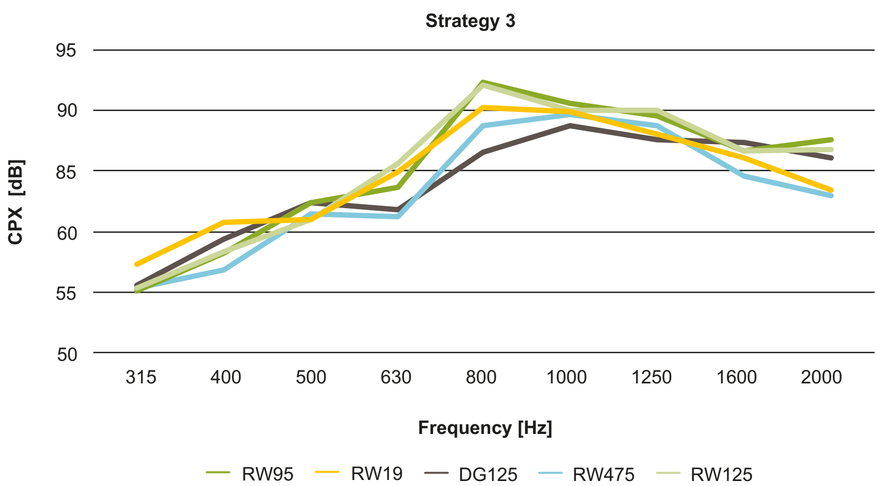


Figure 6.19: CPX spectra for the dense graded (DG125) reference pavement and the four porous "RW" pavements predicted by the AOT using Strategy 3.

The predicted CPX spectra are shown in Figures 6.19 to 6.21 using Strategy 3. Some of the porous pavements have reduced noise levels at the higher frequencies as were seen when using Strategy 2 (see Figure 6.19 and 6.21) where as others do not have such a reduction.

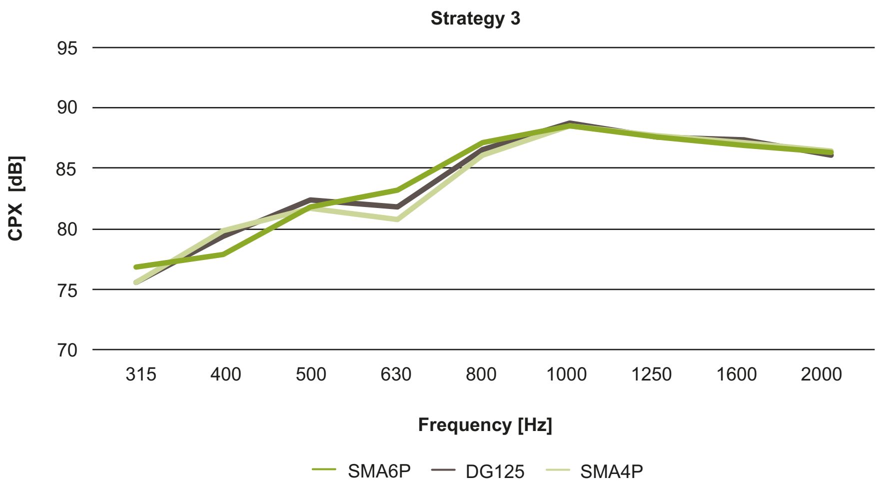


Figure 6.20: CPX spectra for the dense graded (DG125) reference pavement and the two SMA pavements predicted by the AOT using Strategy 3.

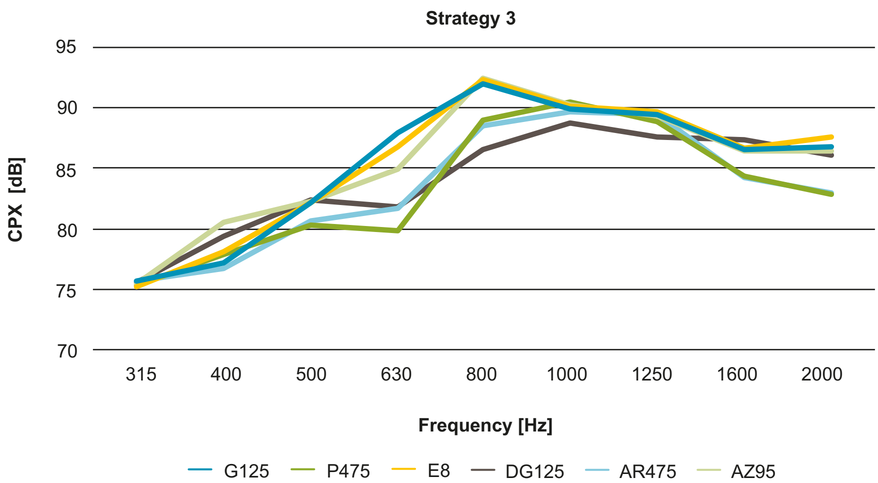


Figure 6.21: CPX spectra for the dense graded (DG125) reference pavement and the five other porous pavements predicted by the AOT using Strategy 3.

6.3.2 Strategy 3 SPB

The predicted SPB results using Strategy 3 can be seen in Figure 6.22. The results fall within a range of 2.2 dB, which is slightly less than the range of 2.6 dB for CPX predictions using Strategy 3. The noise level for the three pavements with 4.75 mm aggregates varies from 72.2 to 72.9 dB with RW475 having the lowest level and the SMA4P the highest level.

The predicted SPB spectra are shown in Figures 6.23 to 6.25 using Strategy 3. These spectra show the same tendencies as the CPX predictions using Strategy 3.

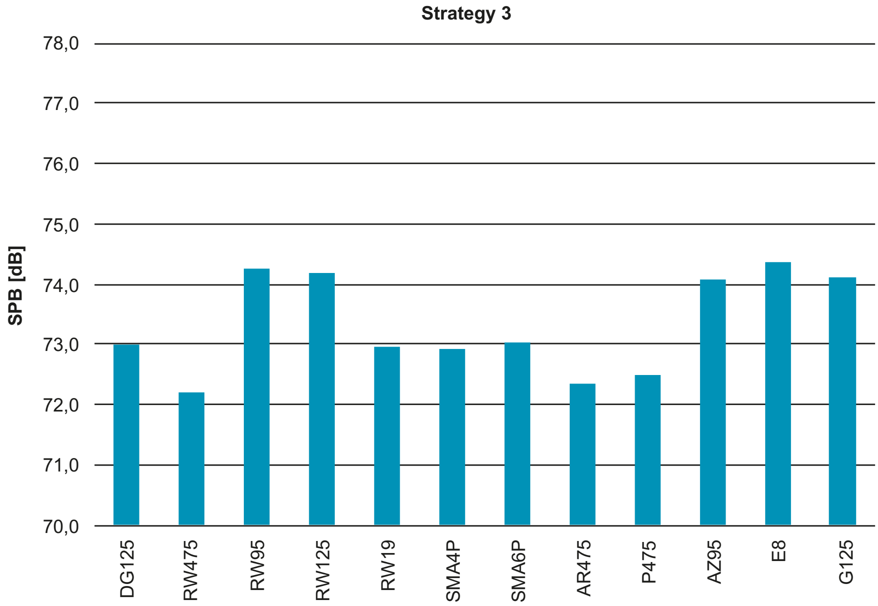


Figure 6.22: SPB results of AOT predictions using Strategy 3 at 90 km/h.

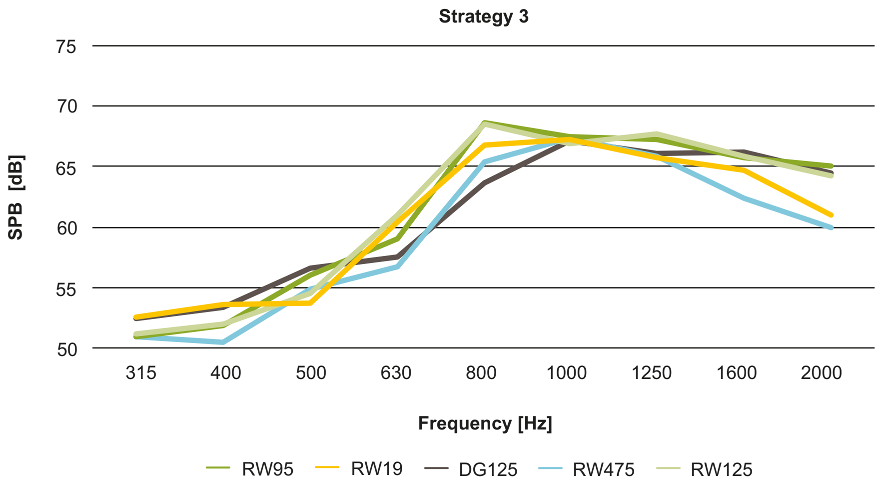


Figure 6.23: SPB spectra for the dense graded (DG125) reference pavement and the four porous “RW” pavements predicted by the AOT using Strategy 3.

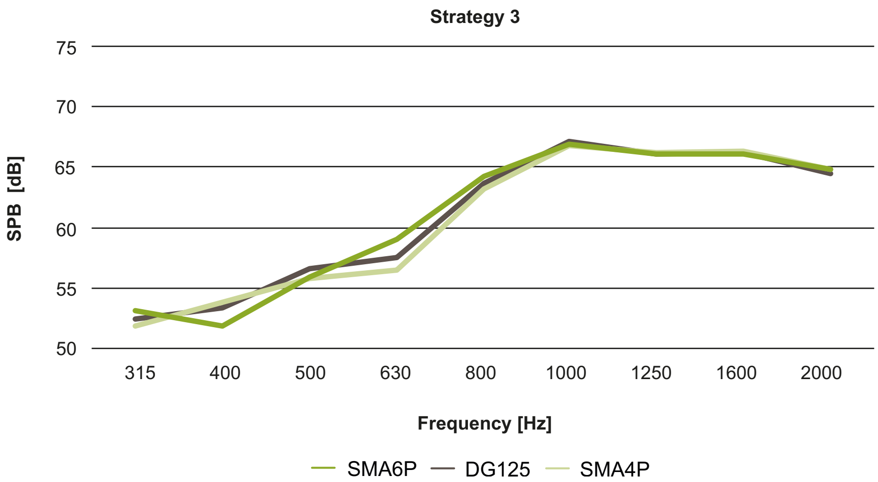


Figure 6.24: SPB spectra for the dense graded (DG125) reference pavement and the two SMA pavements predicted by the AOT using Strategy 3.

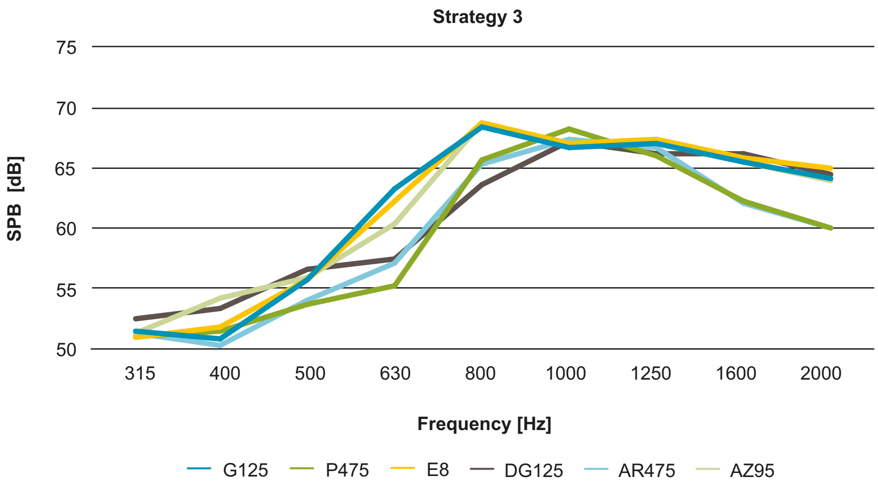
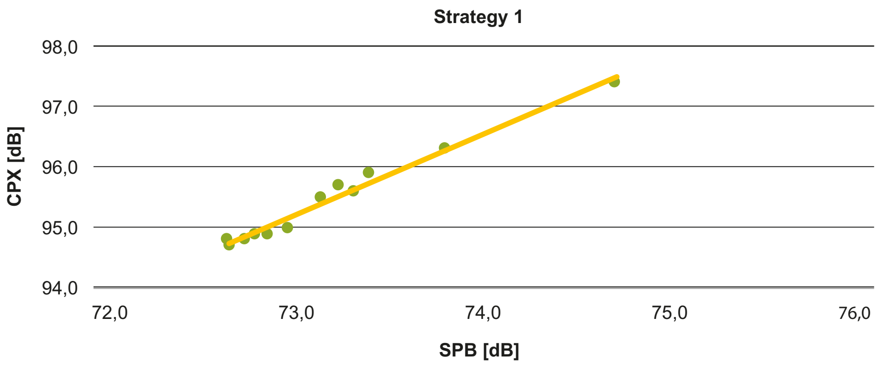


Figure 6.25: SPB spectra for the dense graded (DG125) reference pavement and the five other porous pavements predicted by the AOT using Strategy 3.

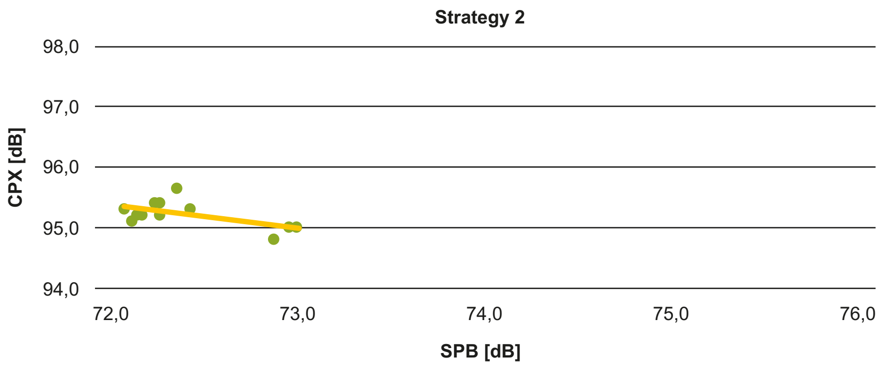
6.4 COMPARISON OF SPB AND CPX

In the following three figures the AOT-predicted SPB and CPX noise levels for the 12 pavements are compared and linear regression lines shown for the three prediction strategies used above.



y= -0.40x + -6.31
R^2= 0.98
Standard deviation 0.11

Figure 6.26: Comparison of the AOT-predicted SPB and CPX noise levels using Strategy 1 for the 12 pavements at 90 km/h.

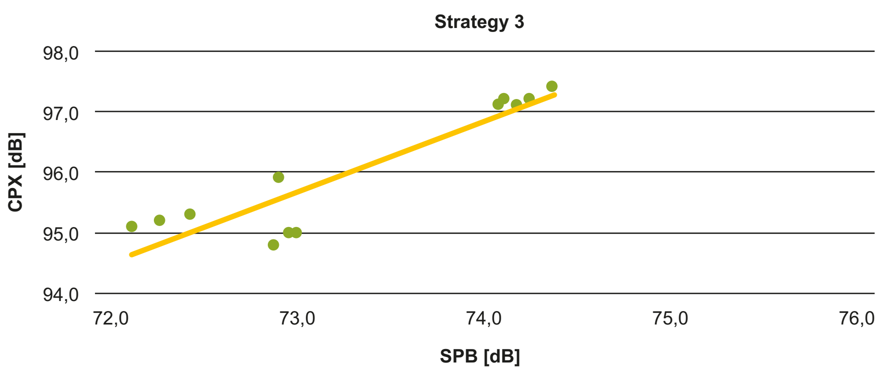


y= -0.40x + 124.41
R^2=0.32
Standard deviation 0.20 dB

Figure 6.27: Comparison of the AOT-predicted SPB and CPX noise levels using Strategy 2 for the 12 pavements at 90 km/h.

Figure 6.26 shows the comparison for Strategy 1. There is a fine correlation between the predicted SPB and CPX levels with a low standard deviation of 0.11 dB in relation to the regression line.

Figure 6.27 shows the AOT-predicted SPB and CPX levels for Strategy 2. It can be seen that when CPX increases the SPB levels decrease. This is unexpected and does not seem correct. The results fall into two groups, one at around an SPB level of 72 dB and the other at around an SPB level of 73 dB. For these two groups both SPB and CPX increase.



y= 1.21x + 7.17
R^2= 0.84
Standard deviation 0.45 dB

Figure 6.28: Comparison of the AOT-predicted SPB and CPX noise levels using Strategy 3 for the 12 pavements at 90 km/h.

Figure 6.28 shows the correlation between SPB and CPX levels for Strategy 3. There is a reasonably fine correlation between the predicted SPB and CPX levels with a standard deviation of 0.45 dB in relation to the regression line.

When evaluated on the basis of the correlation between the AOT-predicted SPB and CPX levels, Strategy 1 and 3 seem to produce good results, whereas Strategy 2 does not seem to function well. The standard deviation in relation to the regression line is the lowest for Strategy 1 with 0.11 dB, whereas it is 0.45 dB for Strategy 3.

7. CONCLUSIONS AND DISCUSSION

The purpose of this project was two sided:

1. To predict a noise ranking of the 12 pavement slabs produced in the laboratory.
2. To investigate how the AOT prediction tool works and to evaluate whether this tool can be used for such pavement ranking.

The noise was predicted both as CPX and SPB levels using measured texture data for the 12 pavements as input data. Three different strategies using predefined AOT data on acoustical impedance and flow resistance were used. The results can be seen in Figures 7.1 and 7.2.

The dense graded DG125 reference pavement for all three strategies had a low predicted noise level similar to the SMAs and the porous pavements with 4.75 mm aggregates. It seems that the AOT underestimates the noise from this dense pavement. Therefore, this DG125 pavement cannot be used as a reference for these AOT noise predictions for the 12 test pavements.

Generally the difference between the AOT-predicted noise levels for the 12 test pavements is quite low. The range of the predicted results can be seen

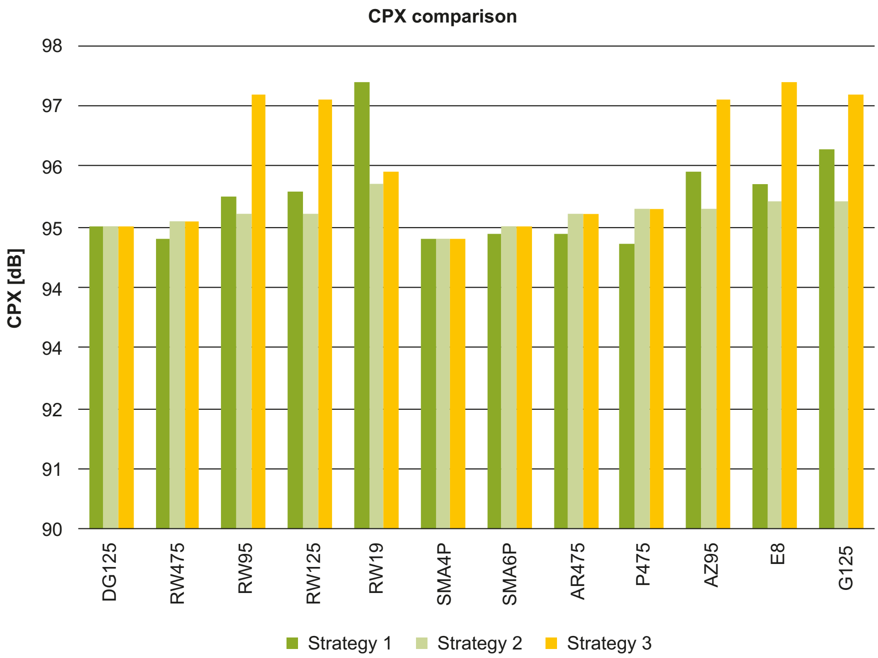


Figure 7.1: Comparison of the CPX results using the three different AOT prediction strategies.

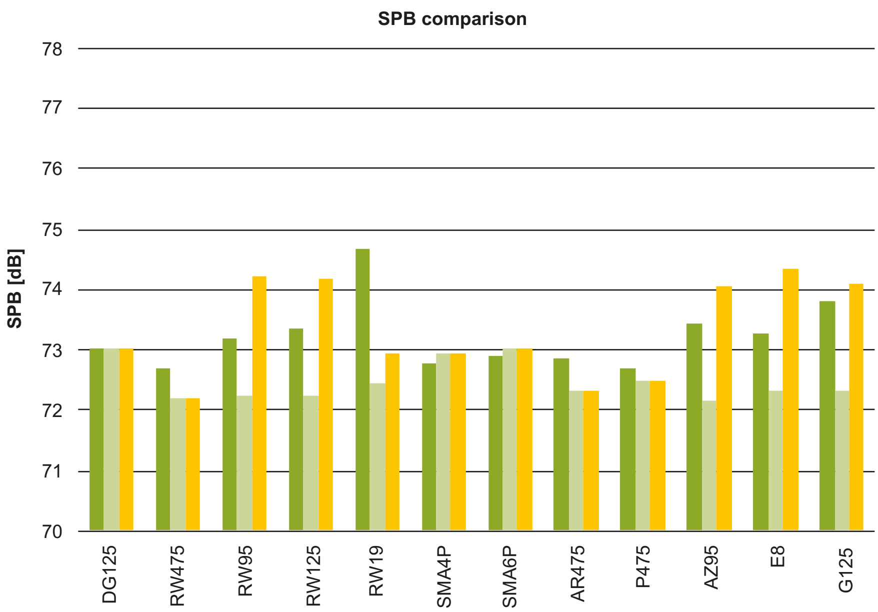


Figure 7.2: Comparison of the SPB results using the three different AOT prediction strategies.

as an expression of how well AOT can distinguish between the 12 test pavements. An expert judgement performed by the authors came to the conclusion that the range between the 12 pavements could be expected to be around 5 dB. But the AOT-predicted range (see Table 7.1) is only half of this and this indicates that the AOT method with the available texture data is not as sensitive to differences in pavement textures as would be expected. The range for SPB-predicted noise levels is the same or less than the range of CPX-predicted noise levels using the same predefined AOT data (using the same prediction strategy). The range using Strategy 2 is less than one, suggesting that the strategy grouping the pavements into three families using predefined AOT data on acoustical impedance and flow resistance for these three families does not seem to function well.

Table 7.1: Range of predicted CPX and SPB noise levels using the three strategies.

AOT PREDICTION STRATEGY	CPX [dB]	SPB [dB]
Strategy 1	2.7	2.0
Strategy 2	0.9	0.8
Strategy 3	2.6	2.2

The highest range of 2.7 and 2.6 dB is seen when predicting CPX noise levels using either Strategy 1 or 3. For these two strategies there is a positive linear correlation between SPB and CPX predicted noise levels. The standard deviation in relation to the regression line is the lowest for Strategy 1 with 0.11 dB whereas it is 0.45 dB for Strategy 3. All in all this points towards the CPX levels predicted by Strategy 1 as being the best result. For this strategy the predefined AOT data on acoustical impedance and flow resistance for the same dense pavement was used.

Based on these analyses it can be concluded that the three porous pavements with 4.75 mm maximum aggregate size (RW475, AR475, P475) and the SMA4P pavement have the lowest noise levels. Due to the uncertainty in the prediction method it is not possible to determine which one of the four pavements is the most silent. For the pavements with a larger aggregate size than 4.75 mm the noise level increases as can be seen in Figure 7.1.

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