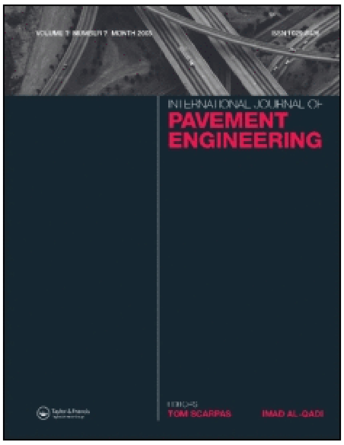

International Journal of Pavement Engineering
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713646742

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First published on: 15 April 2011

To cite this Article Miljković, Miomir and Radenberg, Martin(2011) 'Thin noise-reducing asphalt pavements for urban areas in Germany', International Journal of Pavement Engineering,, First published on: 15 April 2011 (iFirst)
To link to this Article: DOI: 10.1080/10298436.2011.569028
URL: http://dx.doi.org/10.1080/10298436.2011.569028

International Journal of Pavement Engineering
iFirst article, 2011, 1–10

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Thin noise-reducing asphalt pavements for urban areas in Germany

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(*Received 3 December 2010; final version received 2 March 2011*)

The objective of the research was the development, optimisation and evaluation of thin noise-reducing surface layers in Germany intended to be more durable than porous asphalts, thus providing better long-term acoustical properties. The basic approach was to create a smooth, open-textured surface with a stone mastic asphalt-based aggregate skeleton across the whole thickness of the layer. The test pavements in Düsseldorf were subjected to both optical 3D measurements of surface texture parameters and the continuous close-proximity method monitoring of the noise emission. The test pavements had significant noise reduction and very low changes in acoustical properties over time, and when compared to other common types of surface layers they showed the highest noise-reducing capacity. On the basis of the research results and past experience, recommendation on the specification according to the relevant European standards was developed, thus contributing to the adoption of European specifications for noise-reducing asphalt pavements.

Keywords: noise reduction; asphalt pavements; stone mastic asphalt (SMA); acoustical properties; surface texture; close-proximity method (CPX)

1. Introduction

Because of a growing number of passenger cars especially in urban areas, traffic-induced noise pollution has become an almost continuous problem. Noise pollution has arisen to a level that considerably affects the quality of life and harms the health of residents.

The European Union is dedicated to achieve a high level of health and environmental protection, and one of the objectives to be pursued is the protection against noise which is addressed as one of the main environmental problems in Europe. Regarding these long-term objectives, Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to assessment and management of environmental noise (Council Directive 2002/49/EC), also called the Environmental Noise Directive, particularly identified road infrastructure as one of the major sources of noise emission. The directive sets a time schedule for a progressive implementation of actions of which the most important are the determination of exposure to environmental noise through noise mapping, and the adoption of action plans based upon the noise-mapping results. It also included the aim of giving the public an opportunity to participate in the preparation and reviewing of action plans, as well as keeping the public informed on the decisions taken.

Figure 1 shows the time schedule of the directive. As can be seen among other things, the ultimate objective is to make strategic noise maps no later than 30 June 2012 and action plans no later than 18 July 2013 for all agglomerations with more than 100,000 inhabitants and for all major roads with more than three million vehicle passages per year.

Regarding road noise pollution, the tyre/road noise has an important role and is a predominant source at speeds higher than about 35 km/h (Reichart 2009), depending on the type of vehicle and pavement. Although porous asphalt, as the type of mixture widely recognised as a tyre/road noise-reducing measure, is included in specifications of all European countries that harmonised their standards for asphalt mixtures with European standards, mostly no specifications for pavements with noise-reducing potential have been adopted yet. Therefore, German experiences in this field could provide a significant contribution to the development and application of noise-reducing pavements in other European countries.

Porous pavements have an open structure with connected pores in the whole thickness of the layer. The typical air void content is between 24 and 28% (Arbeitsgruppe Asphaltbauweisen 2008a) and the layer thickness is between 4.5 and 6.0 cm depending on the type of mixture (Arbeitsgruppe Asphaltbauweisen 2008b). If water is poured on a new porous pavement, it disappears down into the porous structure (Bendtsen 2009). This effect keeps the pavement surfaces dry to a certain extent, and through this, reduces splash and spray and improves the visibility for the drivers as well. Unfortunately, these

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ISSN 1029-8436 print/ISSN 1477-268X online

DOI: 10.1080/10298436.2011.569028
http://www.informaworld.com

Time Schedule of the Environmental Noise Directive 2002/49/EC		
STAGE 1	**Agglomerations** (more than 250 000 inhabitants)	**NOISE MAPPING** 30 June 2007 **ACTION PLANNING** 18 July 2008
	Major Roads (more than 6 million vehicle passages per year)	
	Major Railways (more than 60 000 train passages per year)	
	Major Airports (more than 50 000 movements per year)	
STAGE 2	**Agglomerations** (more than 100 000 inhabitants)	**NOISE MAPPING** 30 June 2012 **ACTION PLANNING** 18 July 2013
	Major Roads (more than 3 million vehicle passages per year)	
	Major Railways (more than 30 000 train passages per year)	

Figure 1. Time schedule for strategic noise mapping and action planning of the Environmental Noise Directive (END) 2002/49/EC.

positive effects decrease over time due to the layer pores clogging (Bendtsen *et al.* 2005a).

Significant disadvantages of the porous pavements are clogging and intensive winter maintenance that reduces their cost-effectiveness. Specific cleaning methods are used to prevent clogging. The cleaning is normally performed by a cleaning machine driving on the pavement at very low speed. Water is sprayed on the pavement surface under high pressure followed by sucking up the water and loosened material. The present cleaning methods do not always have the intended effect on clogging. The cleaning operation is also expensive and can at best only give a partial restoration of the initial acoustic properties (Nielsen *et al.* 2006). Clogging of porous pavements is a problem on highways as well as on roads with lower speeds. There is a clear tendency that the problems due to clogging increase as the speed of the traffic decreases because the passage of high-speed vehicles has a slight cleaning effect.

Because of the disadvantages compared to dense mixtures (asphalt concrete (AC) and stone mastic asphalt (SMA)), porous pavements have not been used as a measure of noise abatement on German roads for over decades, with the exception of places where high noise-reducing effects are required regardless of compromising other requirements. This emphasises the need to develop and evaluate other types of noise-reducing surface layers, changing the focus in mixture design towards thin surface layers which might have a slightly lower noise-reducing capacity than porous asphalt, but a more durable one, so the long-term acoustical benefit will be positive (Bendtsen and Andersen 2008).

2. Mechanisms of the tyre/road noise generation

The generation of noise when tyres are rolling on a pavement surface is mainly determined by the following various mechanisms (Bendtsen 2009) even though other mechanisms might also play a minor role:

- *Vibrations in the tyres*. The vibrations are generated by the contact between the surface of the pavement and the rubber blocks of the tread pattern of the tyre. Tyre vibrations generate noise in the frequencies from 500 to 1500 Hz. The noise increases when the road surface gets rougher. Therefore, an increase in the maximum aggregate size generally leads to an increase in noise.
- *The air pumping effect*. When the rubber blocks on the tread pattern of the tyre hit the road surface, air is pressed out of the cavities between the rubber blocks. When the rubber blocks leave the road, surface air is sucked back into the cavities. This air pumping to the surroundings generates noise at high frequencies over 1000 Hz. If the pavement surface is open or porous, the air will instead be pumped down into the layer structure and the noise will be reduced.
- *The horn effect*. The curved tread pattern of the tyres and the pavement surface acts as an acoustical horn, which amplifies the road noise generated around the

contact point between the tyre and the road surface. If the road surface is porous (and therefore sound absorbing), the amplification effect will be reduced.

- *Absorption under propagation*. The engine and tyre/road noise is propagated from the vehicles to the receivers. Under this propagation, the noise might be reflected on the road surface. If the road surface is porous and, therefore, sound absorbing the noise at some frequency bands will be reduced under the propagation.
- *The effect of stiffness*. The stiffness of the pavement is important for the determination of the noise generated by the contact between the surface of the pavement and the rubber blocks of the tread pattern of the tyre. If the pavement is much less stiff, the noise generated will be reduced.

On the basis of the current knowledge (Bendtsen *et al.* 2005b), it is generally judged that the first two mechanisms are the most important for the determination of tyre/road noise on the pavements, which indicates that the optimisation of the layer surface texture should be focused primarily on these two sources.

3. Optimisation of noise reduction performance of the mixture

In contrast to porous pavements that are open across the whole thickness of the layer with connected cavities, open-textured pavements are open only on the upper part of the surface layer with cavities having a depth less than the maximum size of the aggregate used for the mixture. The basic approach in design of open-textured pavements for noise reduction is to create a layer structure with cavities at the surface of the pavement as big as possible to reduce the noise generated from the air-pumping effect to some extent, and at the same time to ensure a smooth surface, so that the noise generated by the vibrations of the tyres will not be increased. Such a noise-reducing open-textured layer can be thin, as the mechanisms determining the noise generation depend only on the surface structure of the layer (Bendtsen 2009). Figure 2 illustrates two types of layers with open surface texture. The layer with a 'positive' texture will increase the noise generated from vibrations in the tyre, whereas the layer with a 'negative' texture will reduce it.

To achieve the objective of creating a smooth negative open-textured layer, optimisation was carried out using the following principles:

Figure 2. Illustration of the two main types of the open surface texture shapes (Bendtsen and Raaberg 2005).

- Using a small maximum aggregate size of 5.6 mm to achieve an even and smooth pavement surface that could reduce noise generated from vibrations in the tyre.
- Using a high void content (Arbeitsgruppe Asphalt-bauweisen 2008a) to achieve an open surface texture that can reduce noise generated from air pumping. The target void content is about 5–6%.
- Using cubic aggregate to achieve an even and smooth pavement surface that can reduce noise generated from vibrations in the tyre.
- Using a low sand content to achieve a highly open porous surface texture and dense structure of the layer.

To ensure that the desired surface texture is achieved, both visual evaluation and optical 3D measurement and analysis of a realised surface texture were performed in the laboratory and on the test pavements.

Demands for high noise-reducing capacity are predominantly related to high traffic volume roads and streets. To avoid compromising structural durability and stability of the surface texture, and thus to keep the noise-reducing effect over time, a dense mixture structure with high permanent deformation resistance is required. Therefore, mixture development was based on the SMA aggregate skeleton applied in Germany (Arbeitsgruppe Asphaltbauweisen 2008a) with an additional requirement for noise-reducing properties. SMA is a gap-graded asphalt mixture composed of a coarse crushed aggregate bound with a rich filler/bitumen mastic (European Committee for Standardization (CEN) 2006a). It has a dense structure across the whole thickness of the layer, and is a common European-wide specified mixture that has both good mechanical performance and friction characteristics and is used for a wide range of traffic loads. With the application of a small maximum aggregate size, it can be applied in thin surface layers.

In Germany, an abbreviation widely used for this type of surface layer is LOA 5 D. Here, LOA from the German origin 'Lärmoptimierter Asphalt' is directly translated as 'noise-reducing asphalt'. Number 5 designates the maximum size of the aggregate used in the mixture to be 5.6 mm, and the letter D from the German origin 'Deckschicht' is directly translated as 'surface layer'. Up to now, LOA 5 D thin noise-reducing surface layers, although not nationally standardised, have recently been applied to between 50 and 60 streets in the Federal State of North Rhine-Westphalia (NRW) and, in total, to approximately 80 sections in the whole of Germany.

Unlike typical SMA mixtures in Germany where the air void content never exceeds 3%, for LOA 5 D the air void content is usually between 5 and 6%, and as mentioned above, the surface texture is very porous with connected pores. The mixture can be paved in a very thin layer with a thickness of 2.0–2.5 cm. Small thickness with a substantially SMA aggregate skeleton structure and polymer-modified bitumen as a binder, with proper compaction leads to an excellent permanent deformation resistance. The structure does not allow water to drain through the layer and slightly reduces water removal capacity compared to porous asphalt. However, it suppresses typical problems in winter maintenance and thus extends the service life of the whole pavement. Instead of draining through the layer structure, the rainfall water flows over the surface to the roadside through the very porous texture and still keeps good friction characteristics. Thus, the open porous surface texture reduces splash and spray from the vehicles to the minimum and has a positive effect towards avoiding aquaplaning and improves driving safety. Table 1 contains the data on compositions, and Table 2 contains the data on the properties of laboratory specimens of three representative LOA 5 D mixtures from the test pavements in NRW.

To establish the extent to which surface texture changes over time due to wear by traffic, the mixtures were subjected to sandblasting to simulate the impact of tyres in the first few years of service. The sandblasting was carried out by glass pearls of 100–200 μm in diameter. Visual evaluation of the surface showed that, except the removal of the surface bitumen film, no significant changes were noticed, indicating the possibility of long-term texture stability. Figure 3 shows the close-up appearance of a LOA 5 D surface layer in Mecumstraße in Düsseldorf after 30 months of service. It can be seen that the initial texture is mostly still well preserved, with an appearance similar to that of a new layer.

4. Analysis and evaluation of surface texture parameters

The optical 3D measurement analysis was performed using the GFMesstechnik measuring system. The characteristics of the profile were expressed through the following acoustically relevant surface texture parameters (Müller 2010):

- Mean profile depth, *MPD*, and estimated texture depth, *ETD*. These values are the most important relevant geometric texture parameters defined by EN ISO 13473-1:2004 (European Committee for Standardization (CEN) 2004) for the characterisation of pavement texture by use of surface profiles. The increase in *MPD* and *ETD* decreases noise. However, using only these values for the determination of acoustical properties of pavement surfaces is not sufficient.
- Maximum amplitude of the wavelength spectrum, $A_{\max}$.
- Wavelength corresponding to the maximum amplitude, $W_{\max}$. This parameter should be reduced as much as possible to increase the smoothness of the

Table 1. Compositions of three representative LOA 5 D mixtures.

Constituent material	Content by mass (%)[a]		
	Mecumstraße, Kennedydamm, and Bonner Street in Düsseldorf	Bismarckstraße in Essen	Hagener Street in Dortmund
Limestone filler Dornap	11.2	10.0	–
Limestone filler Hönnetal	–	–	10.0
Moraine sand 0/2 mm Flüren	26.6	22.0	–
Diabase sand 0/2 mm Halbeswig	–	–	27.0
Diabase crushed stone 2/5 mm Halbeswig	62.2	68.0	–
Greywacke crushed stone 2/5.6 mm Lasbeck	–	–	63.0
Paving grade bitumen 50/70 with addition of Lucobit	5.6	5.4	–
Polymer-modified bitumen 25/55-25	–	–	5.6

[a] The content of the aggregate fractions is provided by total mass of aggregate, and the content of the bitumen is provided by mass of asphalt mixture.

Table 2. The properties of laboratory specimens of three representative LOA 5 D mixtures.

Mixture property	Mecumstraße, Kennedydamm, and Bonner Street in Düsseldorf	Bismarckstraße in Essen	Hagener Street in Dortmund
Bulk density, ρ_b (kg/m^3), EN 12697-6:2003 + A1:2007	2.348	2.410	2.379
Air void content, V_m (%), EN 12697-8:2003	6.8	6.0	5.9
Voids filled with bitumen, *VFB* (%), EN 12697-8:2003	60.1	68.5	68.9
Voids in mineral aggregate, *VMA* (%), EN 12697-8:2003	20.3	18.7	19.0
Proportional rut depth, PRD_{AIR} (%), EN 12697-22:2003 + A1:2007	3.3	2.5	3.1

Figure 3. Photograph of the LOA 5 D surface layer in Mecumstraße in Düsseldorf after 30 months of service. The area of the photographed surface is 20 by 10 cm in size.

pavement surface and to reduce the noise generated by vibrations of the tyres.

- Shape factor, g. The shape factor of the surface is normally determined from a cumulative presentation of the surface profile heights. The shape factor is recognised as an especially good indicator of the acoustical properties of pavement surface. An increase in the shape factor results in the reduction in the noise level. The surfaces with negative texture shape have a high shape factor, usually over 70%, whereas the shape factor of positive textures is low, usually less than 50%.
- Shape length, gL. Shape length is a product of an average shape factor and $W_{\max}$. It is a measure of the dependence of noise generation on the surface profile irregularities. Increase in this parameter ensures the smoothness of the pavement surface and also reduces the noise generated by vibrations of the tyres.

Table 3 contains the calculated surface texture parameters based on available optical 3D measurement results, and Figure 4 shows one image of the LOA 5 D pavement surface in Mecumstraße in Düsseldorf after 30 months of service. Based on the current knowledge (Müller 2010), the parameters, especially high shape factor and length, indicate good noise reduction performance. The image is generated by the optical 3D measurement system. The surface was shown to be highly porous with well-preserved negative shape.

5. Acoustical properties of the noise-reducing layers from the test pavements

5.1 *Method of measuring acoustical properties*

The measurements of acoustical properties of the test pavements were based upon the close-proximity (CPX) method according to the working draft of the standard ISO/CD 11819-2 (International Organization for Standardization (ISO) 2000). They were carried out between 2007 and 2010 by the Engineering Company for Technical

Table 3. Surface texture parameters calculated on the basis of optical 3D measurement.

Surface texture parameter	Mecumstraße in Düsseldorf	Bonner Street in Düsseldorf	Bismarckstraße in Essen
Mean profile depth, *MPD* (mm)	0.537	0.623	0.576
Estimated texture depth, *ETD* (mm)	0.630	0.698	0.661
A_{max} (mm)	0.146	0.167	0.151
W_{max} (mm)	6.25	6.25	6.25
Shape factor, *g* (%)	82.77	85.60	85.37
Shape length, *g*L (mm)	517.32	534.98	533.57

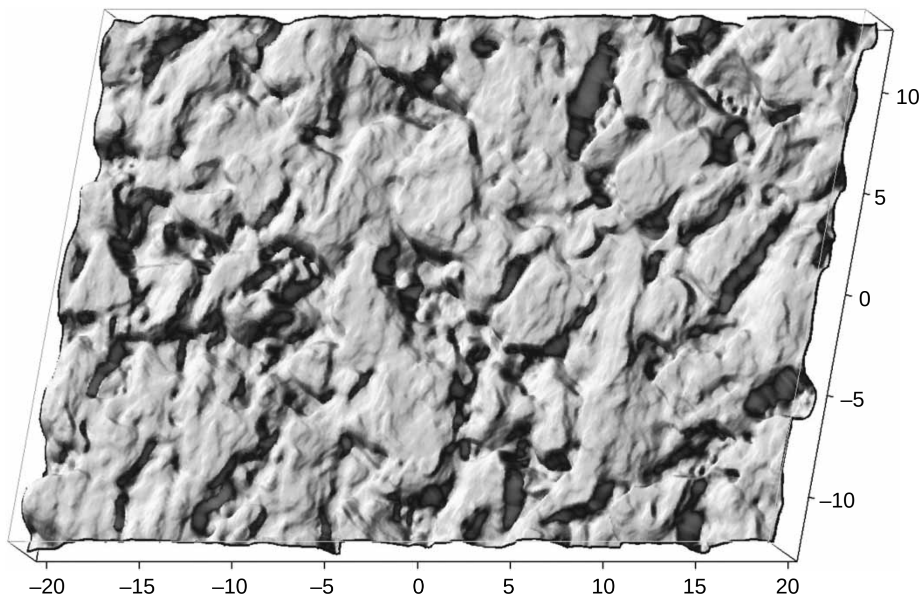

Figure 4. Optical 3D measurement image of LOA 5 D mixture in Mecumstraße in Düsseldorf after 30 months of service. The area of the surface is 40 by 30 mm in size.

Analysis (IFTA) from Essen using the SCRIM Nordrhein closed CPX trailer with two tyres, a picture of which is shown in Figure 5. Each tyre is equipped with at least two microphones close to the contact between the tyre and the test pavement surface. The measurements were accomplished using standardised reference tyre types A and D, which relate to passenger cars (light vehicles) and trucks (heavy vehicles), respectively. Unlike the statistical pass-by method, the CPX method gives a continuous measurement of the whole test section. Figure 6 shows the position of one of the microphones near the reference tyre.

Reference speeds for the noise measurements were 30 and 50 km/h. In Germany, speed limit of 30 km/h is usual only in residential streets, near schools, etc. which slightly differs depending on the federal state. Therefore, the acoustic properties of pavements regarding heavy vehicles in these areas were considered irrelevant due to their relatively rare presence, and the measurements were carried out just for light vehicles. The noise data were processed to give A-weighted noise levels. The results from two reference tyres were averaged to CPX indices. On all sections, the measurements were collected in both directions. All results were normalised to a reference temperature of 20°C.

5.2 *Development of the acoustical properties over time*

The development of noise emission over time was continuously monitored at test pavements in two streets in Düsseldorf where this type of mixture was first applied, and thus, where the longest measurement history is available. As the other pavements have been recently constructed, no long-term data were available for these pavements. Figure 7 shows the noise levels over time for the test pavements in Mecumstraße and Kennedydamm in Düsseldorf. Both streets have a speed limit of 50 km/h. Mecumstraße is a section of the German federal road B326, whereas Kennedydamm is a section of the German federal road B1. Both are six-lane central city streets. Additionally, Mecumstraße also has a bus lane along the greater part of its length. The annual average daily traffic (AADT) in Mecumstraße is around 40,400 vehicles and the portion of heavy vehicles is around 1.7%. The surface layer in Mecumstraße was constructed in April 2007. Kennedydamm is a highly trafficked street with an AADT of around

Figure 5. IFTA measuring trailer with towing vehicle used for the CPX measurements.

59,600 vehicles of which heavy vehicles make up around 3.6%, and is one of the major streets in Düsseldorf having an important role in the traffic network of the city. Because of the high traffic loading and the importance in the street network, one side of the pavement structure in Kennedydamm was constructed in July 2007, whereas the other side was constructed a year later. The data in Figure 7 refer to the part of the street built in 2007. CPX data for the old asphalt concrete pavements in both streets are also provided.

Average CPX values are between 86.5 and 88.9 dB(A). The initial noise reductions compared to the old pavements are 6.7 and 4.3 dB(A). For both pavements, the range between maximum and minimum CPX value during approximately 3 years of service is no more than 1.3 dB(A). This indicates a very stable surface texture. Thus, Figure 7 shows that the influence of pavement age on the acoustical performance of LOA 5 D is very low. This is very different from porous asphalt pavements where the average increase in noise level for light vehicles in streets with low traffic speed is expected to be approximately 0.9 dB(A) per year, where most of that increase occurs in the first year of service (Bendtsen *et al.* 2009, ViaNova Plan og Trafikk 2009).

Figure 6. Position of one of the microphones near the reference tyre of the CPX trailer.

5.3 *Comparison of the acoustical properties of LOA 5 D with other surface layers*

The CPX noise measurements of LOA 5 D were compared with those of asphalt concrete, SMA and block pavements commonly used in Germany and Europe in general. In the mixture designations, the numbers stand for the upper sieve size of the aggregate in the mixture (5.6 or 11 mm), letter D stands for asphalt concrete for surface layers and letters N and S stand for traffic load (normal or special) (Arbeitsgruppe Asphaltbauweisen 2008a). The comparative overview is shown in Figures 8–10. Except for LOA 5 D data, the measurements were performed by the Dresden University of Technology (Institut Stadtbauwesen und Straßenbau 2005) within the first 3 years of service of the asphalt pavements. LOA 5 D data are an overall average from the test pavements in Mecumstraße and Kennedydamm. Figures 8 and 9 show that LOA 5 D provided a significant reduction in noise emission compared with the other pavements. The noise reduction compared to AC and SMA mixtures was the highest for light vehicles at a speed of 50 km/h. The data for LOA 5 D for a speed of 30 km/h were not available. Regarding heavy vehicles, differences between mixtures were lower, but block pavements, often used in Germany for very low traffic and pedestrian areas, had the highest noise emission. Therefore, block pavements are normally

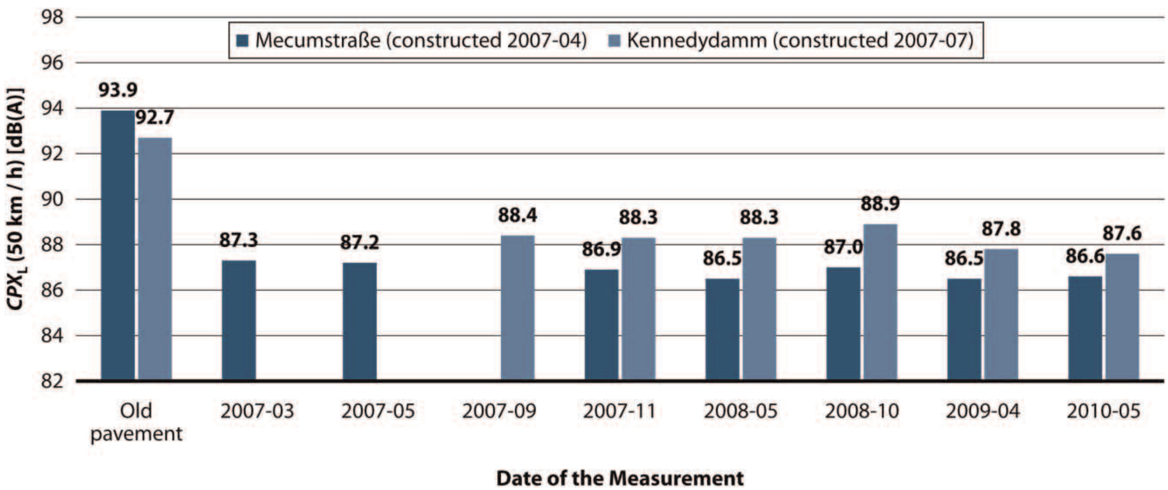

Figure 7. CPX noise measurement results over time for LOA 5 D pavements in Mecumstraße and Kennedydamm in Düsseldorf for light vehicles at a reference speed of 50 km/h.

excluded from tyre/road noise reduction measures as a particularly noise-unfriendly solution. However, block pavements do not lead to such negative effects on the environmental noise levels, as they are applied in the sections with low traffic volume and rigorous speed limitations.

Assuming an average of the noise levels of the AC mixtures AC 8 D N and AC 11 D N, and SMA 8 S, presented in Figure 8, of 90.6 dB(A) as a reference value, as these mixture types are the most often used in Germany when no special noise-reducing properties are required, the average noise reduction would be 3.7 dB(A) for Mecumstraße and 2.4 dB(A) for Kennedydamm. This is considered to be a very good noise-reducing capacity (Kragh 2007), especially when taking into account the age of the reference pavements.

6. Recommendation on specifications for thin noise-reducing surface layers

On the basis of the results presented here and experience after more than 3 years of monitoring the performance of test pavements in Germany, the specifications of the thin noise-reducing LOA 5 D are recommended. The requirements refer to constituent materials, mixture composition, asphalt mixture and constructed asphalt layer, as described in Table 4. These requirements are in accordance with the European standards for material specifications for asphalt mixtures, EN 13108-5:2006 (European Committee for Standardization (CEN) 2006a) and EN 13108-20:2006 (European Committee for Standardization (CEN) 2006b). Some of the properties are outside these specifications but are also required due to

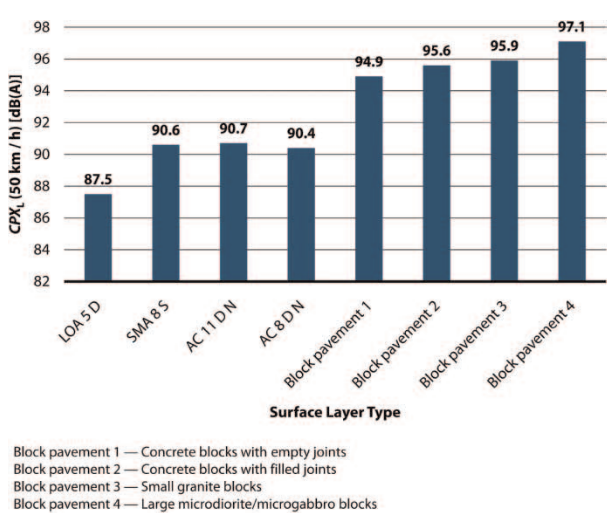

Figure 8. Comparative overview of the CPX results for LOA 5 D and other common types of surface layers for light vehicles at a reference speed of 50 km/h.

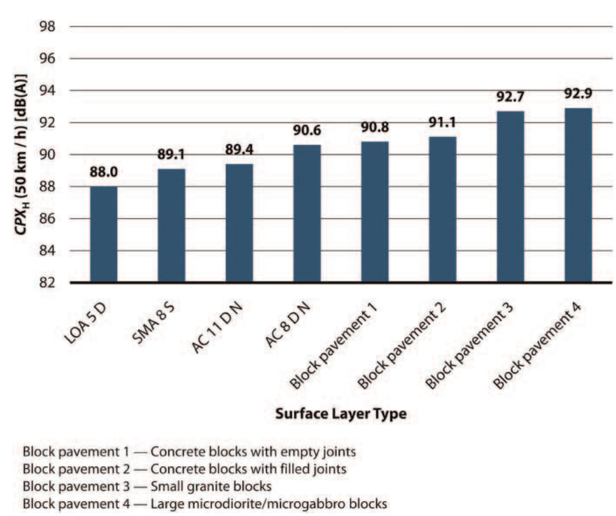

Figure 9. Comparative overview of the CPX results for LOA 5 D and other common types of surface layers for heavy vehicles at a reference speed of 50 km/h.

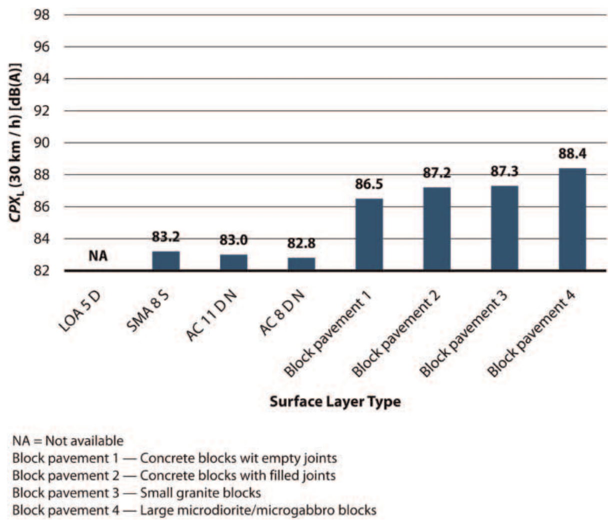

Figure 10. Comparative overview of the CPX results for LOA 5 D and other common types of surface layers for light vehicles at a reference speed of 30 km/h.

their importance in achieving a maximum positive effect on noise reduction.

The recommended aggregate gradation is almost the same as for the mixtures SMA 5 S and SMA 5 N specified by the German national specifications for asphalt mixtures (Arbeitsgruppe Asphaltbauweisen 2008a). The only deviation is in the percentage passing a 0.063 mm sieve, as LOA 5 D requires slightly higher filler content.

The layer in Mecumstraße was the first to be constructed and was the initial reference for optimisation. Therefore, some of the mixture properties presented in Table 2 differ slightly from these recommended values.

7. Conclusion

The development and optimisation of thin noise-reducing surface layers in Germany were based on achieving a smooth open-textured surface with an SMA-based aggregate skeleton across the whole thickness of the layer.

The surface texture parameters and monitoring of the acoustical properties of the highly trafficked test pavements in Düsseldorf indicated very good noise-reducing performance consequent to low surface texture changes. The laboratory tests showed good permanent deformation resistance. Additionally, no signs of ravelling and structural defects such as cracking have been registered, up to now. Compared with the common types

Table 4. Recommendation of the specifications for the thin noise-reducing LOA 5 D surface layer.

Subject	Property	Test method	Requirement
Constituent materials	Percentage of crushed and broken surfaces in coarse aggregates	EN 933-5:1998	$C_{90/1}$[a]
	Resistance to fragmentation of coarse aggregate	EN 1097-2:2010	LA_{20}, SZ_{18}
	Resistance to polishing of coarse aggregate for asphalt surfaces	EN 1097-8:2009	PSV_{51}[b]
	Class of bitumen	EN 14023:2010	Polymer-modified bitumen 25/55-55
Mixture composition	Percentage by mass passing 8 mm sieve	EN 933-1:1997/A1:2005	100%
	Percentage by mass passing 5.6 mm sieve		90–100%
	Percentage by mass passing 2 mm sieve		30–40%
	Percentage by mass passing 0.125 mm sieve		12–18%
	Percentage by mass passing 0.063 mm sieve		10–13%
	Bitumen content by volume	–[c]	12.5–13.5%
Asphalt mixture	Minimum void content	EN 12697-8:2003	V_{min5}
	Maximum void content		V_{max6}
	Minimum voids filled with bitumen		VFB_{min65}
	Maximum voids filled with bitumen		VFB_{max75}
	Resistance to permanent deformation	EN 12697-22:2003 + A1:2007	$PRD_{\mathrm{AIR4,0}}$[d]
	Mean texture depth, *MTD*[e]	EN 13036-1:2010	0.6–0.7 mm
	Shape factor, *g*	NA	NR, To be determined[f]
	Shape length, *g*L	NA	NR, To be determined
Constructed asphalt layer	Layer thickness	EN 12697:2003	2.0–2.5 cm
	Compaction degree	EN 13108-20:2006	≥ 97%
	Profile irregularity (by 4 m straightedge)	EN 13036-7:2003	≤3 mm

NA = Not available; NR = No requirement.
[a] Aggregates obtained from crushing rock shall be assumed to be category $C_{100/0}$ and do not require further testing.
[b] The requirement for a polished stone value of 51 is specified in accordance with the German national specification document (Arbeitsgruppe Asphaltbauweisen 2008a), but is not provided with EN 13108-5:2006 (European Committee for Standardization (CEN) 2006a). Therefore, when specifying in accordance with the EN standard, the category PSV_{50} is recommended.
[c] Determined from bitumen content by mass, bitumen specific gravity (EN 15326:2007 + A1:2009) and bulk density of the specimen (EN 12697-6:2003 + A1:2007).
[d] Although the specification of the proportional rut depth of 4.0% is not in accordance with EN 13108-5:2006 (European Committee for Standardization (CEN) 2006a), this value is considered from the research to be the most suitable.
[e] Because of the testing simplicity and widespread usage, mean texture depth, *MTD*, is specified instead of the mean profile depth, *MPD*.
[f] It is strongly recommended that values greater than 80% should be achieved.

of surface layers, LOA 5 D thin noise-reducing mixtures indicated better acoustical properties.

High shape factor and length were identified as the most important surface texture parameters by having the highest influence on the acoustical performance of the pavement. Therefore, further research on the influence of the optical 3D measurement-based parameters on the noise reduction potential of a pavement surface would significantly contribute to a wider application of these pavements. Finally, this should result in the adoption of the requirements in terms of shape factor and length and their implementation to the recommended specification.

To get a better understanding of long-term changes of acoustical properties over time, further research should be focused on monitoring noise emission data from the test pavements throughout the whole service life and models of any changes developed. Further research on the influence of the mechanical properties of bitumen and mixture on the noise-reducing capacity of the layer would also be useful.

The results reported here and future research on thin noise-reducing surface layers, together with experience from other European countries should lead to the adoption of European specifications for noise-reducing asphalt pavements, thereby contributing to achieving a high level of protection against environmental noise.

Acknowledgements

The authors would like to express their gratitude to Ronald Blab, MSc, PhD, Professor of Vienna University of Technology, Stephen Quarrie, PhD, Visiting professor of Newcastle University, and to other colleagues that provided a valuable assistance in preparation of the article.

Note

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References

Arbeitsgruppe Asphaltbauweisen, 2008a. *Technische Lieferbedingungen für Asphaltmischgut für den Bau von Verkehrsflächenbefestigungen (TL Asphalt-StB 07)*. Cologne: Forschungsgesellschaft für Straßen- und Verkehrswesen (FGSV) Verlag, FGSV 797.

Arbeitsgruppe Asphaltbauweisen, 2008b. *Zusätzliche Technische Vertragsbedingungen und Richtlinien für den Bau von Verkehrsflächenbefestigungen aus Asphalt (ZTV Asphalt-StB 07)*. Cologne: Forschungsgesellschaft für Straßen- und Verkehrswesen (FGSV) Verlag, FGSV 799.

Bendtsen, H., 2009. *Urban thin quiet SMA pavements: paper TRB in Washington 2009*. Copenhagen: Road Directorate – Danish Road Institute, DRI Report 167.

Bendtsen, H. and Andersen, B., 2008. *Optimized thin layers for urban roads: paper for acoustics '08 in Paris*. Hedehusene: Road Directorate – Danish Road Institute, DRI Report 162.

Bendtsen, H. and Raaberg, J., 2005. *French experiences on noise reducing thin layers*. Hedehusene: Road Directorate – Danish Road Institute, DRI Technical note 28.

Bendtsen, H., *et al.*, 2005a. *The DRI-DWW noise abatement program: project description*. Hedehusene: Road Directorate – Danish Road Institute, DRI Technical note 24.

Bendtsen, H., Raaberg, J., and Thomsen, S.N., 2005b. *International experiences with thin layer pavements*. Hedehusene: Road Directorate – Danish Road Institute, DRI Technical note 29.

Bendtsen, H., Lu, Q., and Kohler, E., 2009. *Acoustic aging of asphalt pavements: a Californian/Danish comparison*. Copenhagen: Road Directorate – Danish Road Institute, DRI Report 171.

Council Directive 2002/49/EC, June 2002 relating to the assessment and management of environmental noise.

European Committee for Standardization (CEN), 2004. EN ISO 13473-1:2004. *Characterization of pavement texture by use of surface profiles: part 1: determination of mean profile depth (ISO 13473-1:1997)*.

European Committee for Standardization (CEN), 2006a. EN 13108-5:2006. *Bituminous mixtures: material specifications: part 1: stone mastic asphalt*.

European Committee for Standardization (CEN), 2006b. EN 13108-20:2006. *Bituminous mixtures: material specifications: part 20: type testing*.

Institut Stadtbauwesen und Straßenbau, 2005. *Beurteilung des Einflusses von Straßenoberflächen auf die Verkehrsgeräusche: Asphalt- und Pflasterbeläge im Vergleich*. Dresden: Technische Universität Dresden, Fakultät Bauingenieurwesen.

International Organization for Standardization (ISO), 2000. ISO/CD 11819-2:2000. *Acoustics: measurement of the influence of road surfaces on traffic noise: part 2: the close-proximity method*.

Kragh, J., ed., 2007. *Noise classification: asphalt pavement*. Hedehusene: Road Directorate – Danish Road Institute, DRI Technical note 61.

Müller, I., 2010. *Erfassung von Straßenoberflächentexturen und Untersuchung der Klassifizierungsfähigkeit von Straßenbelägen mittels (akustisch) relevanter Texturkenngrößen (LeiStra uAG SrtaTex)*. Bergisch Gladbach: Bundesanstalt für Straßenwesen (BASt), AP- Projekt 04 336/S1.

Nielsen, E., Raaberg, J., and Bendtsen, H., 2006. *Noise reducing SMA pavements: mix design for silence – F2*. Hedehusene: Road Directorate – Danish Road Institute, DRI Technical note 39.

Reichart, U., 2009. *Lärmmindernde Fahrbahnbeläge – Ein Überblick über den Stand der Technik*. Dessau-Roßlau: Umweltbundesamt.

ViaNova Plan og Trafikk, 2009. *Environmentally friendly pavements: final report*. Oslo: Norwegian Public Roads Administration, Teknologirapport Nr. 2578.