A GUIDELINE FOR SUSTAINABLE LOW NOISE PAVEMENTS

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The development of effective and durable low noise road surfaces remains a challenge, since the required properties – a smooth surface texture and connected voids in the surface – are often in conflict with some of the road surface's primary functions. This generally reduces low noise road surfaces' technical and acoustical durability. In order to obtain an effective and durable low noise road surface, these adverse effects are to be minimised while still ensuring acoustic effectivity. As a compromise between noise reduction and durability, semi-dense asphalts are widely used as a noise mitigation measure in Switzerland. Practical experiences show, however, that the acoustic long-term performance of these road surfaces can vary substantially. This study analyses the technical properties of acoustically good and bad performing low noise road surfaces constructed since 2005 in Switzerland. Multivariate statistical analysis was carried out using various parameters of over 120 drill core analyses and bituminous mixture examinations to investigate its relationship with the acoustic data from CPX (close-proximity) measurements. Based on these analyses, in cooperation with road builders and road owners, sophisticated criteria regarding the use of different materials, production and construction techniques were defined to guarantee a low noise road surface's acoustic performance and durability.

Keywords: low noise pavements, road surface, CPX, tyre/road noise

1. Introduction

The development of effective and durable low noise road surfaces remains a challenge, since the required properties – a smooth surface texture and connected voids in the surface – are often in conflict with some of the road surface's primary functions. Several research projects showed a rather large variability in the acoustic effectiveness of low noise road surfaces [1]–[4]. There are several different Standards all over the world to allow road owners to order a low noise pavement from an arbitrary building company. Although these standards aim to guarantee the successful installation of low noise pavements, the acoustic effectiveness of the installations vary considerably. This variability constitutes a major challenge for noise abatement where assumptions about the realised noise reduction need to be made. In this study therefore, the most relevant parameters responsible for the acoustic variability were determined and investigated. Clear criteria were then established to guarantee a sustainable acoustically effective low noise pavement. The focus of the study is on all recipes of semi-dense low noise pavements (built after Swiss Standard VSS SNR 640 436 [5] as well as in-house products from construction companies) having a maximum grain size of 4 mm and 8 mm. To achieve this, a large dataset of acoustical and physical parameters of low noise pavements in the semi-dense region implemented in Switzerland were statistically interpreted and analysed. The dataset consisted of examinations of asphaltic mixtures and test-cores as well as of rolling noise data from CPX (close-proximity) measurements of about 130 implemented pavements.

This study aims to present important physical parameters and their optimum values within low noise pavements, to guarantee a sustainable acoustical and mechanical effect. Consequently, a tool will result from this study to the noise enforcement agency to ensure the acoustic effect while ordering low noise pavements.

2. Methods

2.1 Data basis

Low noise pavements implemented after the Swiss Standard [5] as well as in-house products from construction companies were used in this study to ensure a broad range of investigated low noise pavements. The investigated in-house products are rather similar to those implemented after the Swiss Standard of low noise pavements regarding its recipe and design. Frequently they even fulfil the criteria of the Swiss Standard of low noise pavements. The study is limited to the availability of technical examinations at a small scale (examinations of asphaltic mixtures and georeferenced test-cores), and the availability of a multi-year measurement series of rolling noise data obtained from CPX measurements (see Figure **1**), which cover extensive road sections with acoustic properties.

Figure 1: Close Proximity (CPX) measurement trailer of Grolimund + Partner AG after [6]

The study lies on all recipes in the semi-dense region having a maximum grain size of both 4 mm and 8 mm. Figure **2** shows the geographic distribution of all investigated 4 mm and 8 mm low noise pavements. At least one examination of test-core and one examination of asphaltic mixtures exist per location, which can be joined with the acoustic data of CPX measurements at a small scale.

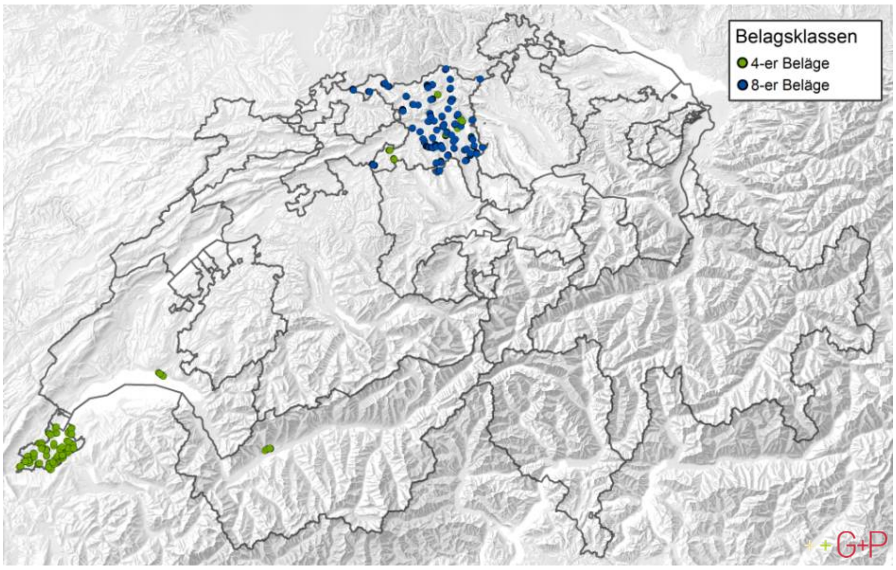

Figure 2: Geographic location of the investigated 4 mm (green) and 8 mm (blue) low noise pavements.

The study comprises data of 65 4 mm low noise pavements containing 223 test-cores and 61 8 mm low noise pavements containing 259 test-cores. Since most of the low noise pavements were built to protect population from noise at road sections characterized with high noise emissions, all of these reveal a high traffic load. The average daily traffic on the 4 mm low noise pavements is

8'200 (±2'400) vehicles and on the 8 mm pavements 5'800 (±3'900) vehicles with a heavy traffic load proportion of about 5.5 %.

All investigated physical parameters from test-core and asphaltic mixture examinations as well as initial assessments of pavement facilities are listed in Table 1.

Table 1: Investigated physical parameters

installation parameters	asphaltic mixture parameters	material parameters
void content (test-core)	degree of filling	susceptibility to water
bulk density (test-core)	binder content	binder-type
layer thickness	flow value	origin of mineral aggregates
degree of compaction	stability	
humidity	void content (Marshall-test)	
air temperature	apparent density (Marshall-test)	
slope	bulk density (asphaltic mixture)	
construction company	sieving 0.063mm	
	sieving 0.5 mm	
	sieving 2 mm	
	sieving 4 mm	
	sieving 8 mm	
	temperature of asphaltic mixture	
	"Module de Richesse"	
	time of travel (truck)	
	mixing plant	

2.2 Data treatment: relevant parameters

Multivariate linear regression models (stepwise forward; [7]) were applied to all physical parameters to identify the most crucial parameters influencing the acoustic performance. Thereby the rolling noise measurements CPX were used to describe the acoustic performance of both 4 mm and 8 mm pavements in its initial condition, 1 year, 2 years and 5 years after construction. A preselection of the physical parameters in Table **1** was done by reviewing the data for collinearity and applying a plausibility check. The acoustic performance serves as the dependent variable and the physical parameters as the independent variables in the model.

The rolling noise measurements CPX for passenger cars, 3 years after construction revealed as the most accurate variable to represent the acoustic performance and serve as the dependent variable in the model. This variable appears to be a good compromise between taking acoustic performance a long time after construction of the pavements and a sufficient size of sample.

2.3 Data treatment: elaborate optima in the acoustic properties

The identified parameters that revealed to be the most important physical parameters were investigated in detail to examine the optimum of range of values. The ranges of values of the physical parameters were examined in order to describe a persistent acoustic performance of low noise pavements.

A control data set (obtained from several studies performed in the Canton of Aargau and the Swiss national research project TP3 [1]) was used to validate and specify the elaborated optimum of ranges of values of the most important physical parameters. This data set consisted of airflow resistance measurements and the frequency of 2000 Hz from the third-octave band of rolling noise measurements CPX (indicator of air flow noise; [8]). The acoustic performance of pavements that were not included in the whole data set was characterized with this control data set regarding its air flow noise and to infer indirectly from the accessible voids from the surface of the low noise pavements.

3. Results and Discussions

3.1 Decisive factors regarding acoustic performance

The relationship between the available physical parameters and the acoustic performance was identified based on multivariate statistical analysis to determine the cause of the large variability in acoustic performance of low noise pavements. A consistent significant relationship between the physical and acoustic parameters resulted from these analyses for several years after construction and both pavement categories (4 mm and 8 mm low noise pavements). The analyses revealed the filler and the sand proportion as the most relevant parameters describing the acoustics of low noise pavements.

3.2 Acoustically optimized value ranges

In Figure **3** the acoustic performance of 8 mm and in Figure 4 of 4 mm low noise pavements are depicted as a function of filler and sand proportion to understand this relationship and to identify the acoustic optimum of range of values regarding the physical parameters. The colour code illustrates the rolling noise CPX level of the third-octave band that acts as an indicator for air flow noise.

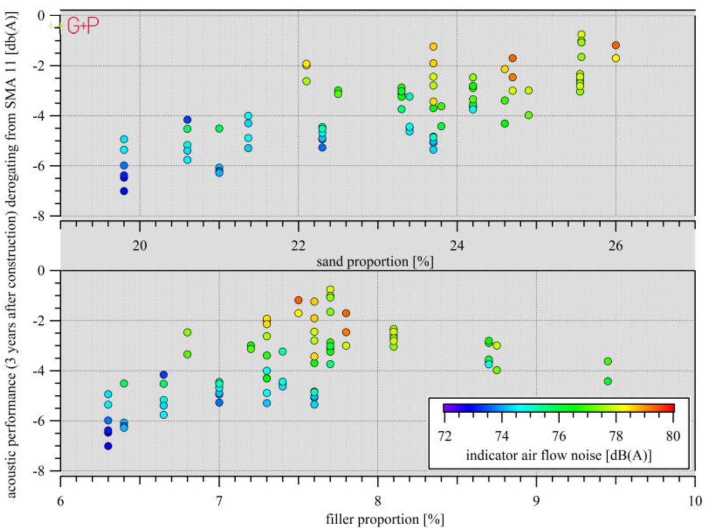

Figure 3: Relationship between the acoustic performance of 8 mm low noise pavements 3 years after construction (derogating from a conventional pavement, AC 11 or similar), and the filler (below) and sand (above) proportion in the asphaltic mixture. The colour code depicts the indicator of air flow noise (2000 Hz third-octave band of rolling noise measurements CPX).

Figure 3 shows that an increase in filler and sand proportion results in a decrease in the acoustic performance of 8 mm low noise pavements (i.e. the pavements become louder). The same relationship results for the 4 mm low noise pavement regarding the filler proportion, however, not consistently regarding the sand proportion. The reason for this less significant increase in sand proportion with a decrease in acoustic performance may be caused by different recipes of the asphaltic mixtures by in-house products, which usually consists of sand proportion above 40 %.

A high acoustic performance (i.e. smaller values of acoustic performance) of both 8 mm and 4 mm low noise pavements consistently result in low air flow noise values (depicted in colour code). This suggests that low noise pavements with a high acoustic performance reveal higher proportions of accessible void contents from the surface whereby the air flow noise is reduced. Therefore, the accessible void contents seem to strongly influence the sustainable high acoustic performance of both 4 mm and 8 mm low noise pavements. Similar results were also presented in the study [9], however for porous asphalts (PA) and with the analysis of test-cores by using computed tomography and sound absorption measurements. If both the filler and the sand proportions exceed a certain value, there is an increase in air flow noise and thus the acoustic performance of low noise pavements at 3 years after construction. It can be assumed that this effect is mainly due to a blocking of the accessible void contents from the surface due to rather high proportions of filler and/or sand. Figure 5 depicts these circumstances for low noise pavements with two different 4 mm low noise pavements consisting of similar void content, however, with different filler proportion.

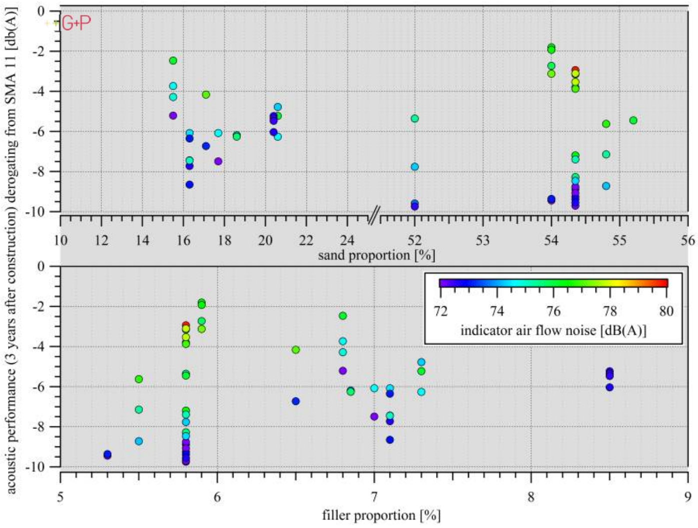

Figure 4: Relationship between the acoustic performance of 4 mm low noise pavements 3 years after construction (derogating from a conventional pavement, AC 11 or similar), and the filler (below) and sand (above) proportion in the asphaltic mixture. The colour code depicts the indicator of air flow noise (2000 Hz third-octave band of rolling noise measurements CPX).

The slight increase in acoustic performance with an increase of the indicator for air flow noise at filler proportions > 8.5% reveals a crucial relationship between filler and sand proportion to achieve a good acoustic performance of low noise pavements having both 4 mm and 8 mm maximum grain size. Therefore, the parameters filler and sand proportion cannot be investigated independently in a bivariate regression but must be investigated in relationship to each other.

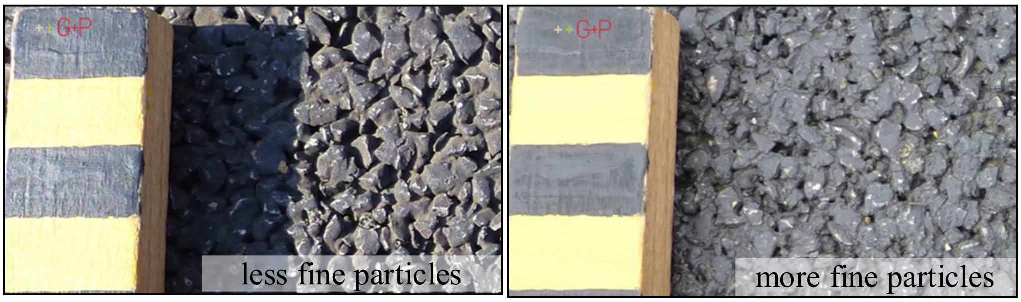

Figure 5: Two different 4 mm low noise pavements consisting of similar void content at Marshall with 11.9% (left) and 11.5% (right) and measured at the test-core with 12.5% (left) and 13% (right) at different fine particle proportions.

3.3 Relationship between filler proportion - sand proportion – acoustics

In the previous section it was shown that the accessible void content from the surface is of great relevance in obtaining a high acoustic performance from low noise pavements (both 4 mm and 8 mm pavements). Accessible void content reduces the air flow noise and are a requirement for the sound absorbing effect of a low noise pavement. The interaction of filler proportion, sand proportion and acoustics is of great importance to the accessibility of void content and will therefore be investigated in detail in order to understand the interaction of these parameters.

It can be assumed that the two relevant parameters, filler and sand proportion, affect the acoustic performance, or rather, the accessible void content from the surface, to different extents. Therefore, trivariate linear regression analyses were performed to define the relative importance of the two parameters, filler and sand proportion, to the crucial acoustic parameters such as acoustic performance, indicator for air flow noise and air flow resistance. The weighting applied to the importance of filler to sand proportion resulted in 3:1 at almost all acoustic criteria for the 4 mm low noise pavements (see Table 2). It means that the impact of filler proportion, compared with sand proportion, on the acoustic performance of the road surface is almost three times higher.

Table 2: Weighting of the filler and sand proportion to explain the relationship of filler proportion-sand proportion-acoustic performance.

	weighting	
	4 mm	8 mm
filler proportion	3	2
sand proportion (w/o filler)	1	1

The relative importance of filler to sand (w/o filler) proportion for 8 mm low noise pavements resulted in 2:1 at almost all acoustic criteria. Therefore, it can be assumed that the filler proportion is twice as important as the sand proportion for 8 mm low noise pavements to the acoustic performance and to guarantee accessible void content from the surface.

3.4 Acoustic threshold to guarantee accessible void content

The acoustic threshold between semi-dense and acoustically dense recipes of low noise pavements will be elaborated in this chapter. Generally, there is an essential difference between semi-dense and acoustically dense low noise pavements in terms of acoustic performance. The acoustic threshold in the present study is defined as the minimum of available accessible and consequently acoustically operative void content. While exceeding this threshold, the pavement may still exhibit void content but they are sealed or rather clogged from the surface. Therefore, low noise pavements beyond this threshold between semi-dense and acoustically dense recipes act as a dense pavement and the acoustic performance is fairly restricted to effects of the surface texture.

Taking into account the control data set consisting of data from rolling noise measurements CPX, air flow resistance measurements and indicator for air flow noise (from CPX measurements) an acoustic threshold for semi-dense (accessible void content from the surface) and acoustically dense (no accessible void content from the surface) relation between air flow and acoustics (see Figure 6) was retrieved for both 4 mm and 8 mm low noise pavements.

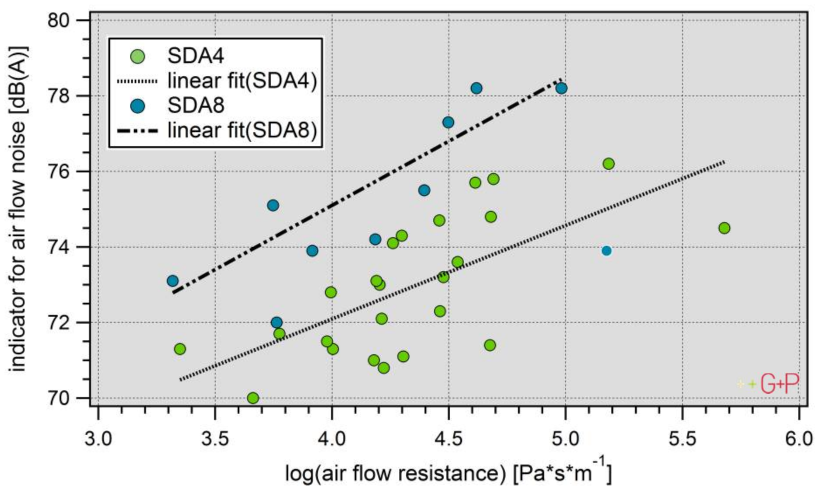

Figure 6: Indicator for air flow noise (from CPX measurements) as a function of air flow resistance (from air flow resistance measurements) for 4 mm and 8 mm low noise pavements. The white circled blue data point was treated as an outlier and neglected in the linear regression.

An acoustic factor was defined with the findings of the elaborated acoustic threshold from the indicator for air flow noise (see Figure 6) and the relationship of filler and sand proportion (see Table 2). This acoustic factor assembles both the acoustical and the technical properties. For 4 mm low noise pavements the acoustic factor $F_{4\text{ mm}}$ is defined as:

$$F_{4\text{mm}} = 3 \cdot filler + 1 \cdot (sand - filler) \tag{1}$$

The acoustic factor for 8 mm low noise pavements $F_{8\text{ mm}}$ is defined as:

$$F_{8\text{mm}} = 2 \cdot filler + 1 \cdot (sand - filler) \tag{2}$$

The variables $filler$ and $sand$ indicate the filler and sand proportion respectively.

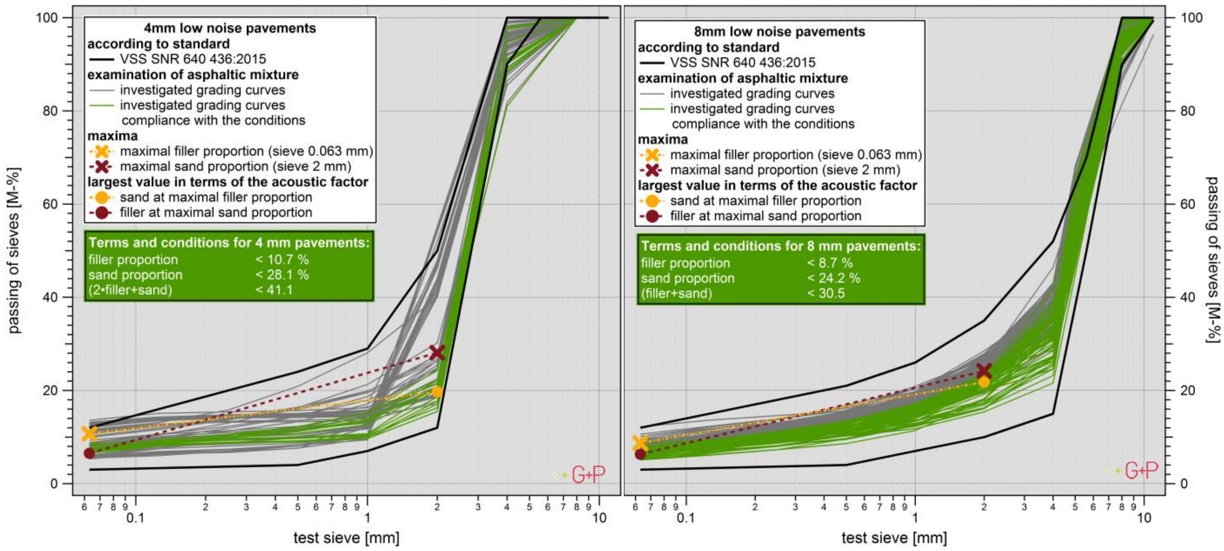

Figure 7: All investigated grading curves of 4 mm (left) and 8 mm (right) pavements with the minimal and maximal thresholds given by the standard VSS SNR 650 436:2015. The maximal values for filler proportion (yellow cross; passing of sieve 0.063 mm) and sand proportion (red cross; passing of sieve 2 mm) taking into account the terms and conditions of the acoustic factors $F_{4\text{ mm}} < 41.1$ and $F_{8\text{ mm}} < 30.5$ (yellow and red dots).

Figure 7 shows the maximal values of proportions of filler and sand that are required for compliance to guarantee sustainable high acoustic performance for 4 mm and 8 mm low noise pavements. These maximal values are additionally linked to the terms and conditions of $F_{4\text{ mm}}$ and $F_{8\text{ mm}}$ stated in the green box. It means that if the maximum of the filler proportion is chosen the maximal value of the sand proportion gets smaller (see yellow dot in Figure 7) and vice versa. This is because the acoustic factors need to be satisfied as well in order to guarantee acoustically effective void contents of low noise pavements.

4. Conclusions

Accessible void content from the surface is necessary. The analyses of this study consistently showed that low noise pavements having high acoustic performance are characterized by low air flow noise and therefore accessible void content from the surface. This result is not only given for low noise pavements in its initial condition but also 3 years after construction. If low noise pavements reveal flawless mechanical properties 3 years after construction experiencing high traffic load, then it can be concluded that accessible void content from the surface provide low air flow noise and a certain degree of sound absorption.

Filler and sand proportion are crucial parameters for sustainable low noise pavements. The void content defining the acoustic performance of porous asphalts (PA) is given directly at the void content of the asphaltic mixture. However, for semi-dense asphalts the acoustic mechanism is more complicated and cannot directly be controlled by the void content itself. The results of the present study show that the accessible void content from the surface is mainly dependent on the filler and sand proportion within the recipe of the low noise pavement. A blocking of the void content from the surface reduces the acoustic performance significantly even if the low noise pavement still exhibits a rather high void content. Therefore, void content that is not accessible from the surface is not acoustically effective.

The acoustic threshold between semi-dense and acoustically dense must not be exceeded. The acoustic threshold between semi-dense and acoustically dense recipes of low noise pavements should not be exceeding to maintain the accessibility and connectedness of voids. This can be done by preventing a blocking of the accessible void content from the surface by taking care with the filler and sand proportions. The proposed acoustical implementation rules form an essential component in order to minimize the void content in low noise pavements maintaining high acoustic performance and thus a sustainable effect of low noise pavements.

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