Recommendations for the successful design of high performance urban low-noise asphalts – findings from the statistics of 200 mixtures

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ABSTRACT

In many countries, porous asphalts (PA) have become an established measure to reduce road traffic noise on high-speed roads. For urban roads, however, the design of effective low-noise asphalt mixtures remains a challenge, as a pore structure is needed that does not clog at lower speeds. Frequently found solutions are fine textured asphalts in the medium void content range with small pores. The challenge in this particular range is to define mixtures that guarantee a certain acoustic performance. This is exactly where the study comes in: a combined statistical analysis of data from acoustic measurements and laboratory testing of 200 road surfaces is carried out to identify semi-dense asphalt (SDA) mixtures (with a void content between 8-18%) that lead to reliable noise reduction. Multivariate statistical analysis on over 1327 drill core examinations, 775 mixture examinations and 737 acoustic close-proximity (CPX) measurements allowed us to identify the important parameters explaining acoustic performance. With this set of relevant parameters a Random Forest model was developed to determine the optimal target values and parameter ranges as a basis for standardisation. The resulting high performance low-noise SDA mixture is designed to have a noise reduction similar to PA road surface on motorways.

1. INTRODUCTION

Porous asphalts (PA) are used successfully in many countries for noise protection on the high-speed road network [1, 2]. The problem with PA, however, is that they are not suitable for use in cities. With lower speeds (<80 km/h), self-cleaning cannot take place and the PA road surfaces become rapidly clogged and lose their noise-reducing effect [3, 4, 5]. Frequently found solutions for lower-speed roads are fine textured asphalts in the medium void content range with small pores so that water and dirt cannot easily enter the surface. Several countries have therefore developed semi-dense asphalts (SDA) with smaller aggregate sizes for use on urban roads where the number of people exposed to noise is particularly high. The advantage of fine-textured SDA is that their pore

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structure does not clog as easily at lower speeds. For an improved durability, they have a lower void content than PA (often between 8 and 18%). The challenge in this particular void content range is to define mixtures that guarantee a certain effect mechanism and acoustic performance [6]. Similar to the Swiss experience [7], unfortunately the acoustic measurements on the different SDA technologies used in countries such as NL (SMA 8 G+), D (SMA LA 8, LOA 5 D), DK (SMA 6+8, SMA 6+11) show that they currently do not reliably achieve the noise-reducing effect of PA. This was the result of our international review of the practice of low-noise road surfaces based on data from expert interviews[2]. Hence, detailed knowledge on the relevant performance parameters for successful mixture design of acoustically effective low-noise SDA is urgently needed in order to provide a reliable low-noise asphalt technology for the use on urban roads. This gain in knowledge is furthermore transferable to similar SDA technologies used in other countries.

The present study aims to fill this gap. We intend to learn from the statistics of 200 well-documented SDA constructed on urban roads in Switzerland how to design an optimal SDA mixture that guarantees a noise reduction similar to PA on motorways. To this end, an extensive dataset of 1327 drill cores analyses, 775 mixture analyses and 737 acoustic close-proximity (CPX) measurements (ISO 11819-2 [8] and ISO/TS 11819-3 [9]) was analysed. In step 1, the success factors for long-term noise reduction are identified in order to derive the optimisation objectives for SDA mixtures. In step 2, the mixture and construction parameters that have a significant influence on the acoustic performance are determined using multivariate statistics. In step 3, the acoustically optimal parameter ranges for mixture design and construction are further investigated studying their bivariate behaviour with acoustics and based on a Random Forest model developed for this purpose. With these optimal parameter ranges set, we provide as a main outcome the statistically optimal target mixture for a high performance low-noise SDA suitable for application on urban roads.

1.1. Definition of semi-dense asphalts (SDA)

Before the analyses are presented, we would like to define more precisely what is meant by low-noise semi-dense asphalts. For this purpose, it is helpful to position SDA in relation to the established asphalt standards for conventional dense asphalts on the one hand and PA on the other. From SDA we should be able to expect a comparable noise reduction as for PA on high-speed roads in order to be a suitable technology for noise abatement on urban roads. This requires an appropriate mixture design that guarantees acoustically effective pores connected to the surface. From our existing research on SDA we know that probably as much as half of the mixtures within the SDA category do not have connected pores and therefore do not bring the required noise reduction [6, 10]. Accordingly, high performance low-noise SDAs do likely not extend over the entire void content range between between SMA and PA and, therefore, this range needs to be further narrowed down based on scientific insight.

1.2. Problem statement

Currently, to our knowledge, there are no standards for SDA mixtures available that guarantee connected pores and the required noise reduction. More knowledge needs to be gained on the optimal design of SDA mixtures that guarantee acoustic performance. To facilitate the transfer of knowledge and enable the successful application of SDA as an effective noise abatement measure for use on urban roads, the development of an international standard for high performance low-noise SDA - next to the existing standard for PA - would be highly desirable. This is all the more true from the point of view of the city authorities, who currently often have to react at an early stage with a costly replacement of the wearing course if the legally prescribed noise reductions cannot be met. The availability of standard for a reliable low-noise SDA road surface for application on urban roads may help in this regard.

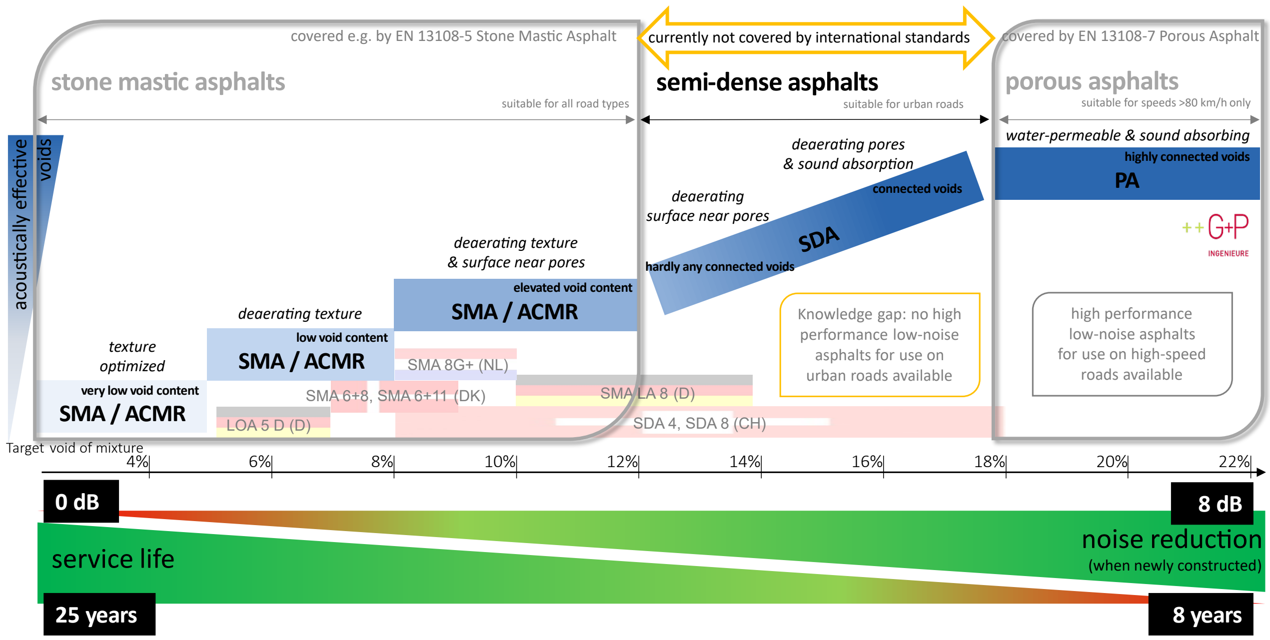


Figure 1: The definition of SDA in the context of existing international asphalt standards.

1.3. The purpose of this study

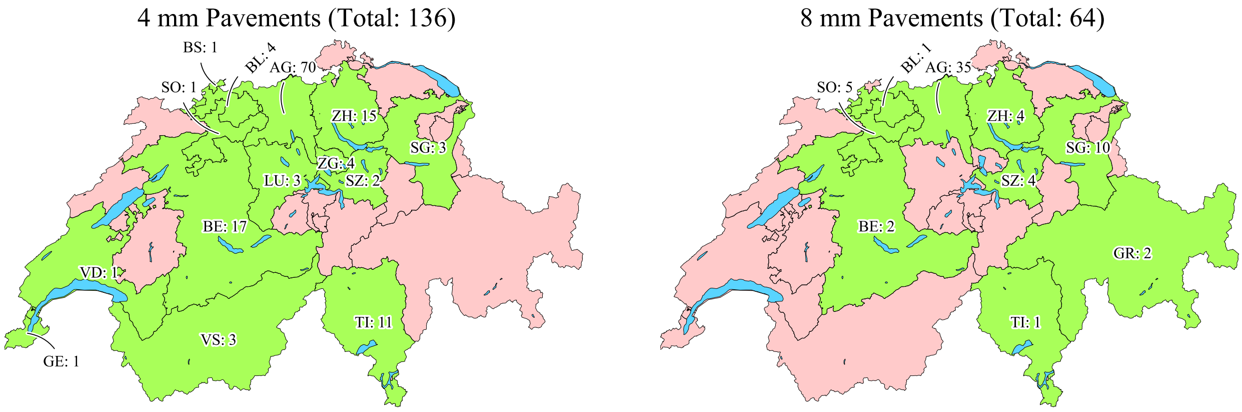
This paper is the result of a research project funded by the Federal Office for the Environment (FOEN), the Federal Roads Office (FEDRO) and several cantons, which was completed in April 2022. The objective of this research project was to define additional acoustic requirements to address the high variability in the acoustic performance of SDA road surfaces of two aggregate sizes built according to the Swiss standard SN 40 436 [11] providing the scientific basis for its improvement. The purpose of this paper is to identify and specify a high performance low-noise SDA suitable for the use on urban roads while guaranteeing a noise reduction similar to PA road surface on motorways. The paper further analyses the dataset of 200 well-documented asphalt mixtures constructed on Swiss roads to gain knowledge on a) the success factors for long-term noise reduction of SDA; b) the key mixture design parameters affecting acoustic performance; c) the optimal acoustic mix designs for high performance SDA as a robust basis for the development of a standard for low-noise asphalt mixtures for the use on urban roads.

2. MATERIALS & METHODS

2.1. Description of dataset

When creating the dataset, care was taken to include data from as many parts of the country as possible. The aim was to include a wide range of mixtures, stone aggregate properties, manufacturing and construction practices in order to create the broadest possible coverage of parameters in the dataset and thus a robust basis for the statistical analyses. The hurdle for Switzerlands around 1000 SDA surfaces to qualify for inclusion into this dataset was the availability of mixture and drill core analyses with simultaneous availability of acoustic data from CPX measurement contracts. As Figure 2 shows, data from altogether 200 well documented SDA road surfaces from 14 different Cantons were eligible for the dataset.

The dataset comprises of a extensive set of 1327 drill cores analyses, 775 mixture analyses and 737 acoustic close-proximity (CPX) measurements within the time frame from 2012 to 2021. The most detailed level of the database consists of the 1327 cores and the geographically assigned data from mixture analyses and from CPX tyre/road noise measurements on this road surface (using the values from the 20 m standard segment surrounding the drill core).



(a) SDA 4 (max. aggregate size 4 mm) (b) SDA 8 (max. aggregate size 8 mm)

Figure 2: Spatial distribution of the 200 SDA road surfaces incorporated in the dataset.

2.2. Mixture and construction parameters included in the analysis

For the analysis, the construction protocols and the laboratory tests of mixture and drill core probes were requested and digitised. The following construction parameters, as depicted in table 1 were recorded for each drill core and tyre/road noise levels from CPX measurements aggregated to a standard segment of 20 m length.

Table 1: Parameters recorded

Mixture	Drill-core	Acoustic parameters
Sieve 0.063 mm (Filler)	Degree of compaction	$L_{\text{CPX, P \& H}}$
Sieve 0.5 mm	Void content	Spectral 3$^{\text{rd}}$-Band CPX - Levels ($L_{\text{CPX, f, P \& H}}$)
Sieve 1 mm	Layer thickness	
Sieve 2 mm (Sand)		
Sieve 4 mm		
Sieve 5.6 mm		
Mixture temperature		
Marshall-Void content		
Soluble binder content		

2.3. Data preparation & homogenisation

After receiving the laboratory tests of the 200 road surfaces, the logs were digitised and transferred to a geodatabase. The exact locations of the drill cores were digitised from the attached maps. The mixture analyses, where the samples are taken from truckloads, are more areal in nature and were therefore recorded as polygons. As there were different methods applied to determine the void content in the mixture and drill cores, we applied a linear model to homogenise the dataset to the current standard method (volumetric analysis). The CPX tyre/road noise levels were converted to *Statistical Pass-By* (SPB) levels using the Swiss conversion model [12]. Acoustic performance is expressed as noise reduction compared to the Swiss road traffic noise model StL86+. Its reference corresponds to a noise emission on a conventional dense asphalt of medium texture - roughly a mixture of DAC 11 and SMA 11 with 5 to 10 years of age. In a next step, the drill core and mixture data were combined with the CPX measurements, resulting in a complete dataset with acoustic and technical parameters.

2.4. Data analysis

With the homogenised dataset, a three step approach was chosen: In a first step, the most important parameters for an acoustically optimal pavement were identified. With these acoustically optimal parameters, secondly, a set of optimal ranges was defined through bivariate analysis of the acoustic quality in combination with the important parameters. Thirdly, these optima ranges were checked with a separate Random Forest model to identify the statistically optimal mixture while accounting for the multivariate behaviour between the different variables and acoustic performance.

3. RESULTS & DISCUSSION

3.1. Success factors for long-term noise reduction of SDA

The large dataset of combined CPX measurements and mixture analyses, allowed the representation of the long-term acoustic performance of SDA road surfaces as a function of their void content class, as shown in Figure 3 for SDA 8 and Figure 4 for SDA 4. The acoustic performance is given for mixed traffic with 8 % heavies and refers to the noise reduction that can be expected compared to medium textured conventional dense asphalts - a mix of DAC 11 and SMA 11 at 5 to 10 years of age.

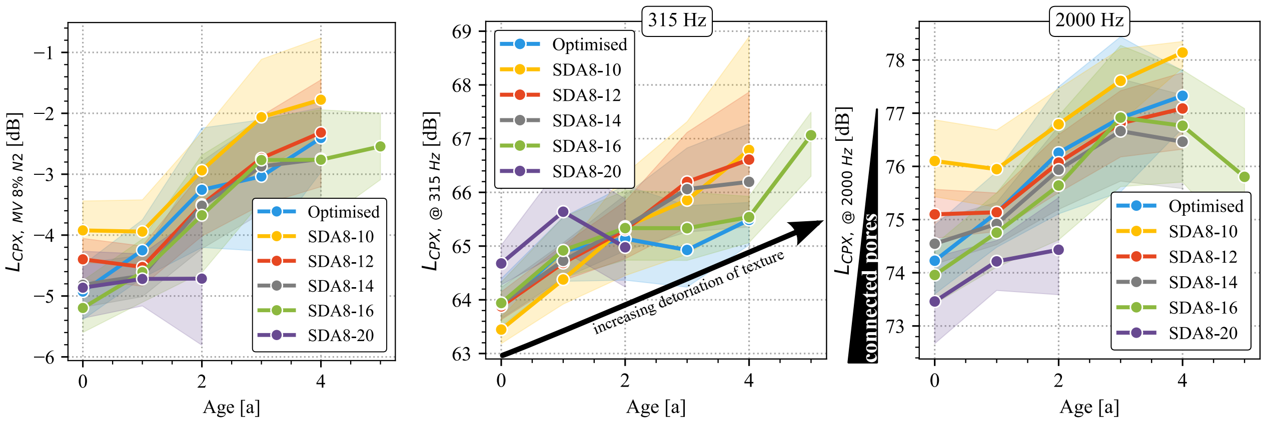


Figure 3: Acoustic long-term performance of SDA 8 mixtures in function of void content based on the statistics of 64 road surfaces (SDA 8 - 10 –> max. aggregate size 8 mm, void content 10 ± 2%).

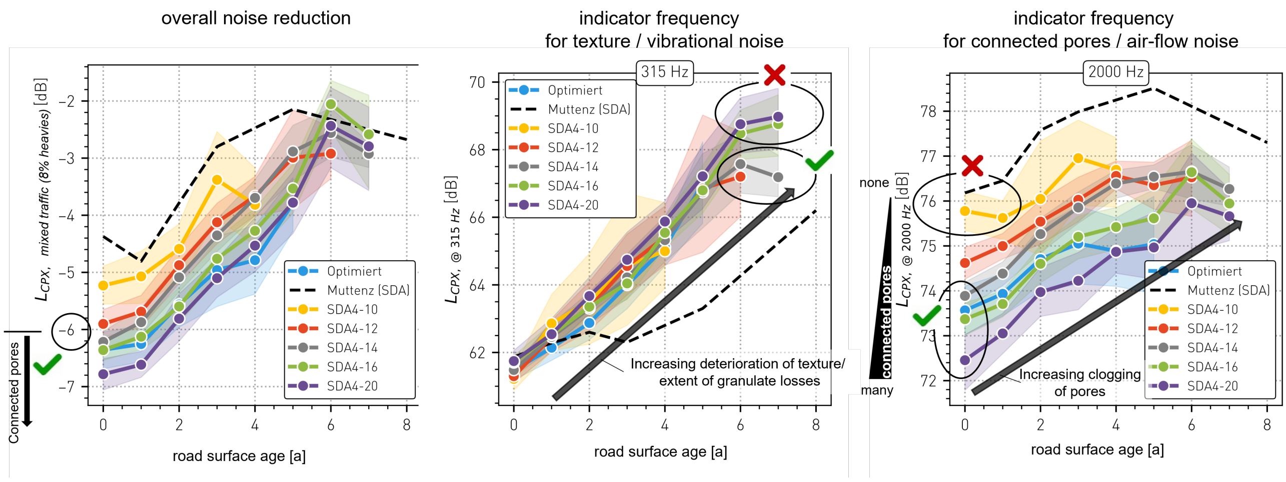


Figure 4: Acoustic long-term performance of SDA 4 mixtures in function of void content based on the statistics of 136 road surfaces (SDA 4 - 10 –> max. aggregate size 4 mm, void content 10 ± 2%).

The graphs on the left show the evolution of overall acoustic performance in function of age. With a noise reduction of around -2 to -3 dB after 4 years the SDA 8 road surfaces with max. aggregate size 8 mm do not show sufficient long-term noise reductions to be considered as high performance low-noise SDA for urban roads, as shown in Figure 3. The SDA 4, on the other hand, reduce noise considerably more effectively with a noise reduction of around -4 to -5 dB in the 4th year after construction (see Figure 4). The distinct difference in acoustic long-term performance becomes also evident from Table 2: with an average noise reduction of -4.6 dB over 6 years SDA 4 perform much better than SDA 8, with -2.6 dB as long-term average. Since the purpose of this paper is to identify an high performance low-noise pavement for urban roads, further analysis in this study will focus solely on SDA 4 due to space constraints. Analytical results on SDA 8 are documented in the research report [7], which provides useful information for the acoustic optimisation of 8 mm asphalt mixtures in the semi-dense range. For the use of SDA 8 on high-speed roads, it is recommended to conduct a separate research on optimisation.

Considering the performance of different void categories of SDA, a clear trend becomes visible with the highest void content category performing consistently better than the category with the lowest void content. The reasons for this are visualised in the right graph, where the indicator frequency for connected pores and airflow noise shows, that higher void SDA categories outperform the lower ones with regard to airflow noise reduction and probably also sound absorption over the entire lifespan covered. On the other hand, however, there appears to be some evidence that mixtures with high to very high void content (SDA 4 -20 and SDA 4 -16) have poorer acoustic performance after 6 years than those with medium to low void content. The probable reasons for this are indicated in the graph in the middle, where the indicator frequency for texture and vibrational noise shows a continuous degradation of texture which does not much vary in function of void content up to year 5. From year 6 onward, however, there seems to be an indication that texture degradation stabilises only for mixture classes SDA 4 -14 and SDA 4 -12 after noise levels reached around 67 dB(A) at 315 Hz. This seems to signify a durability plus for SDA with lower void content in terms of texture degradation and the subsequent cause of additional vibrations noise. Please keep in mind that these conclusions are preliminary as the database for older pavements is not equally robust due to smaller sample sizes available and the lack of longer time series.

Table 2: Average noise reduction of SDA 4 and SDA 8 road surfaces when new and 6 years after construction. Including average total impact over 6 and 10 years respectively.

Road surface/Age	0 year	after 6 years	Av. red. 6a	Av. red. 10a
SDA4	-6.2±1.07 dB (260)	-2.7±0.85 dB (39)	-4.6 dB	-3.7 dB
SDA8	-4.4±1.03 dB (152)	-1.3±1.07 dB (16)	-2.6 dB	-2.2 dB

From Table 2 it can be concluded that an initial noise reduction of at least -6 dB is to be achieved for SDA in order to achieve a probable long-term reduction of at least -3 dB (with a time-average at -4.6 dB after 6 years). As measurements of the surface properties of acoustically well performing SDA mixtures show, they all have good sound absorption properties and a connected pore structure in common. From the analysis in this chapter, the following optimisation objective can be derived for the acoustic optimisation of SDA:

Optimsation objective: *A target void content and mixture design must be chosen that guarantees connected pores in the constructed SDA layer and an initial noise reduction of at least -6 dB, but at the same time voids should be kept as low as possible to avoid a greater deterioration of the texture and and poorer acoustic performance in the second half of a road surface's lifetime.*

3.2. Identification of important mixture and construction parameters & model validation

In a second step we intend to identify the statistically important mixture and construction parameters for acoustic optimisation of SDA. To do this, we created a multivariate model to predict acoustic performance from our dataset with 1327 drill core and 775 mixture analyses and linked acoustic data. The resulting predictor variables with high significance (p<0.01) are displayed in Figure 5 .

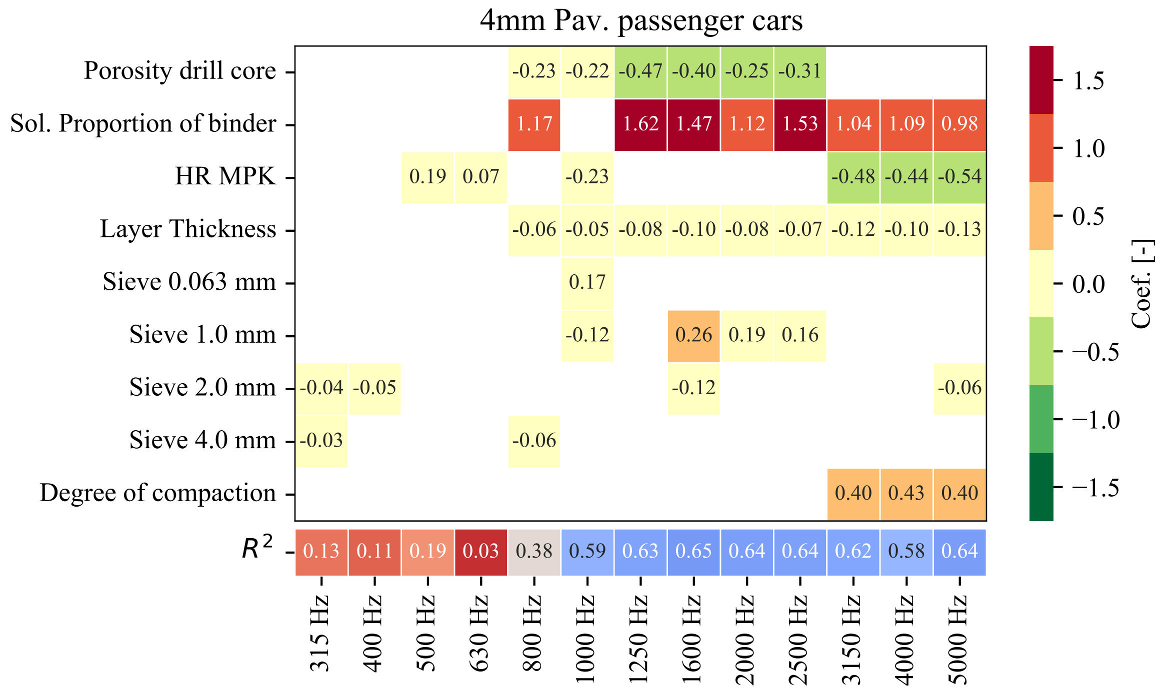


Figure 5: Predictor variables explaining acoustic performance with the coefficients from the multivariate model. Negative values indicate that noise emissions decrease with the variable.

Six of the 9 parameters relevant for acoustics are linked to mixture design (Proportion of binder, Void content in the mixture; Sieve 0.0063 mm, Sieve 1.0 mm, Sieve 2.0 mm, Sieve 4.0 mm), while three are related to construction of the top layer (Porosity drill core, Layer thickness, Degree of compaction). This selection of parameters also makes sense from a theoretical point of view, as most of the identified mixture and construction parameters are related to void content in the constructed layer. The importance of binder and fine particle fractions for acoustic optimisation of SDA can be explained by their direct influence on void content in the mixture and their role in blocking pore connections. Please note that in some cases collinearity between variables may lead to selections by the model that are difficult to directly relate to the variable. In order to be able to further investigate the multivariate relationships and to determine the acoustically optimal SDA mixture in Section 3.4, a separate Random Forest model with the 9 relevant parameters was developed. The established model was validated with an independent dataset in Figure 6 where measured noise reduction is plotted against model predictions.

With 90% of the total acoustic variance explained by the model, it predicts acoustic performance based on these 9 mixture and construction parameters with sufficient reliability. A further improvement of the model's prediction power may be achieved by testing and including additional variables that were not considered in the existing dataset, such as environmental factors at construction, material properties, compaction equipment and techniques amongst other possible influencing factors not covered so far.

3.3. Determining acoustically optimal parameter ranges

In a third step, the acoustically optimal parameter ranges and target values for the important mixture and construction parameters are derived by further studying the bivariate relationships with acoustic performance. The optimal parameter ranges can be explored in the thumbnail graphs in Figure 7,

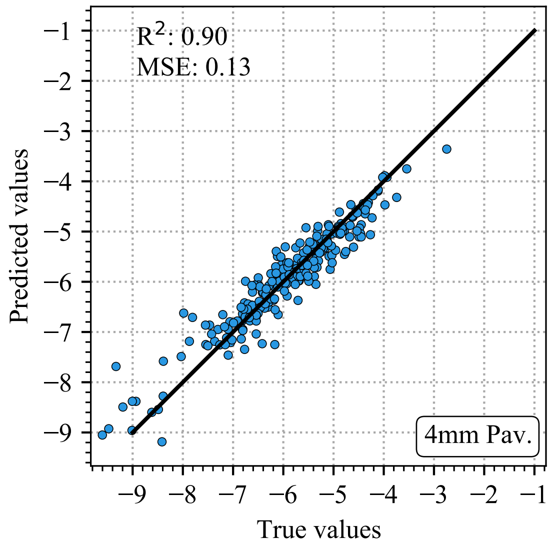


Figure 6: Model validation - predicted vs. measured values

where the mean and standard deviation of the influencing variables are plotted against statistical acoustic performance measured on 136 SDA road surfaces.

In the left upper graph in Figure 7 is shown how mixture void content influences acoustic performance with negative values in dB indicating the expected noise reduction compared to a conventional dense road surface (DAC 11 / SMA 11). Some important findings can be derived from this figure: noise reduction does not continuously improve with void content in the mixture. There appear to be several performance gaps: With a steep increase in acoustic performance just above 13 %, this trend continues until about 17 %, at which point only marginal further increases in performance are possible. Similarly, the optimal ranges for the other parameters were derived which are listed below each graph. The target values are derived using the neural network model so that the multivariate relationships between the parameters can be accounted for.

Summarising the analysis for Sieve 0.0063 mm, Sieve 0.5 mm, Sieve 1.0 mm and Sieve 2.0 mm, the relationships clearly show that from a certain amount of fine particles the acoustic performance decreases abruptly. This may be due to an increase in blocking of the pores' connections to the surface by these fine particles in the case a certain critical level of this parameter is reached. For SDA with maximum aggregate size 4 mm, these critical values seem to be around 10 % for the filler fraction (Sieve 0.063 mm), around 16 % for the 0.5 mm fraction, around 20 % for the 1.0 mm fraction and around 27 % for the 2.0 mm sand fraction. Please note that for mixtures with other maximum aggregate sizes, separate limit need to be derived. On the side of the construction related parameters, degree of compaction seems to have its optimum around 100% regarding acoustic performance when newly constructed. While under-compaction can improve the acoustic performance of an SDA when new, it brings significant negative effects on the acoustic durability of the road surface. As our data show, under-compaction (< 98%) and severe over-compaction (> 102%) should be avoided.

When investigating bivariate relationships in a multivariate and complex setting, one should keep in mind that reaching a certain target value does not automatically mean guaranteed acoustic performance, as other relevant parameters or a combination of them can lead to failure. This phenomenon is also evident from the bivariate graphs, where a parameter value within the optimal range can often reach a wider span of acoustic performance, depending on the contribution of the other relevant parameters. On the other hand, it is also very likely that the optimal range of certain parameters can be extended if another influencing parameter compensates for this, with the mixture still resulting in an acoustically effective road surface. In the underlying research report [7], we give

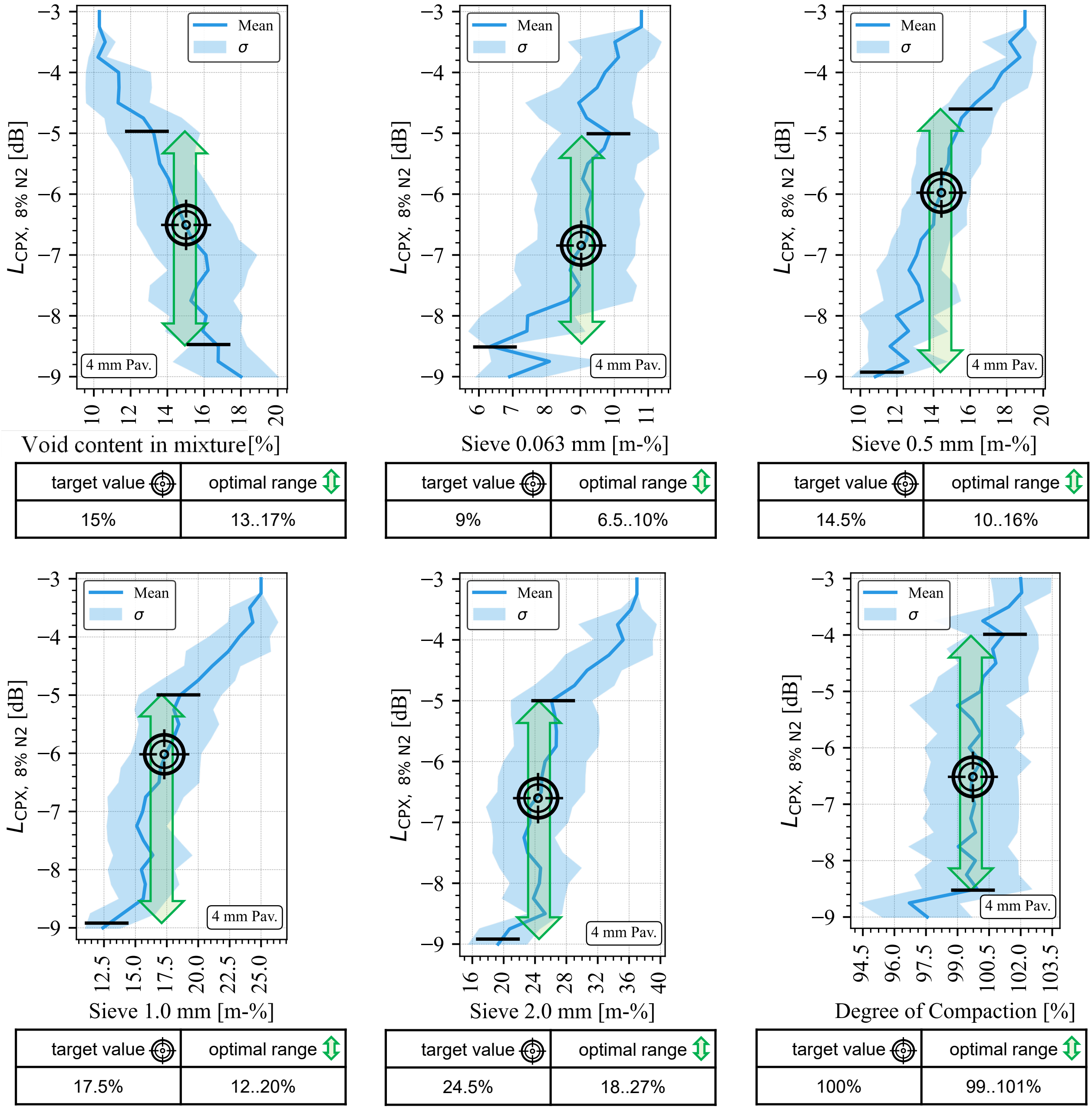


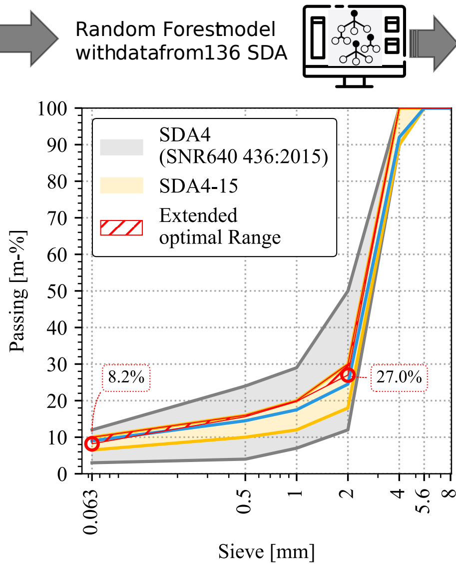
Figure 7: Analysis of bivariate relationships between relevant mixture/construction parameters and acoustic performance to determine optimal target mixture values and optimal parameter ranges.

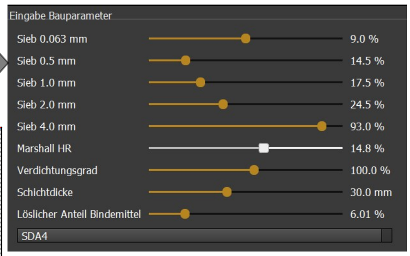
recommendations for a conditional optimal range for the sand content, under the condition that the filler content is kept low and visa versa (see also Figure 8) .

3.4. Resulting optimal mixture for high performance low-noise SDA

In the previous section we investigated the bivariate relationships and used a Random Forest model to determine the optimal parameter ranges and target values. With the model we combined the set of optimal target values into a target mixture design for high performance low-noise SDA for which the model predicted a noise reduction of -6.4 dB in comparison to a conventional dense asphalt pavement (DAC 11 / SMA 11). The statistically optimal mixture design is displayed together with predicted noise reductions for the mixtures at the upper and lower limit of the optimal range in Figure 8.

Name	current swiss standard SDA 4	optimal target values high performance SDA	optimum range SDA 4-15
Void content mixture	8..18	15%	13..17%
Sieve 0.063 mm	3..12	9%	6.5..10%
Sieve 0.5 mm	4..24	14.5%	10..16%
Sieve 1 mm	7..29	17.5%	12..20%
Sieve 2 mm	12..35	24.5%	18..27%
Sieve 4 mm	90..100	93%	90..100%
Acustic factor*	-	42	<45
Void content drillcore	8..18%	15%	13..17%
Degree of compaction	>=97%	100%	>99%
Binder content	>= 6.0 %	6.0%	>= 6.0 %





	optimal target values	optimum range upper limit	optimum range lower limit
Void content mixture (model prediction)	14.8%	12.8%	19.5%
Acoustic performace (model prediction)	-6.4 dB	-6.1 dB	-7.8 dB

Figure 8: Optimal mixture design for high performance low-noise SDA together with model estimates for mixture void content and acoustic performance.

4. CONCLUSIONS & RECOMMENDATIONS

In this paper we analysed a comprehensive dataset of 200 well documented SDA mixtures with mixture and drill core analyses and acoustic measurements to identify the statistically optimal mixture for high performance low-noise SDA for use on urban roads. Based on an analysis of their long-term performance, the following optimisation objective for SDA was derived: Choose a mixture design that guarantees connected pores in the constructed layer and an acoustic performance of at least -6 dB, while at the same time reducing void content to a minimum for improvement of acoustical and mechanical durability.

After identifying the 9 key mixture and construction parameters significantly influencing acoustic performance by multivariate statistics, we established and validated a Random Forest model to predict acoustic performance based on these key parameters. The model validation performed in this paper showed sufficient robustness of the model with 90% of the acoustic variance explained. Six of the important parameters are linked to mixture design: Binder content, Void content Mixture, Sieve 0.063 mm, Sieve 0.5 mm, Sieve 1.0 mm, Sieve 2.0 mm, Sieve 4.0 mm, while three parameters can be attributed to the construction process: Degree of compaction, Void content drill and Layer thickness. For each of these parameters, we determined optimal ranges and derived the optimal target mixture by considering their multivariate behaviour using the model. The void content of the acoustically optimal mixture is expected to be around 15 %. Evidence was found that the optimal range of certain parameters can be extended in the case another influencing parameter compensates for this: for example, an extended optimum range for the sand fraction can be applied, under the condition of a lower filler content. We plan to further investigate the multivariate relationship between the different parameters in future research to reveal more possibilities for conditional expansion of the optimal parameter ranges. It is also strongly recommended that additional variables be included in the model to further improve predictive accuracy; for example, a promising first step could be variables related to compaction equipment and methods.

Considering the evaluation of long-term performance presented in this paper we can expect a noise reduction for this new category of high performance low-noise SDA of at least -6 dB when newly constructed and of around -3 dB after 6 years, which is comparable to the noise reduction measured for PA on the high-speed road network. Based on current data, an acoustic and technical service life of about 10-15 years can be assumed for SDA 4, depending on the environmental and traffic strains and maintenance. Further research is needed on SDA mixtures with other maximum aggregate, which may require different optimal parameter ranges, but could provide welcome alternatives to SDA 4 with specific potential advantages regarding noise reduction or durability.

The development of an international standard - in addition to the existing standard for PA - based on the results presented here and other available research on SDA would be very welcome. Such a standard would certainly accelerate the widespread and successful application of high-performance, low-noise SDAs for use on urban roads, providing much-needed relief for noise-affected urban populations.

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