Long-term acoustical performance of low noise road surfaces in urban areas in Switzerland

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Summary

Acoustical measurements on 371 low-noise road surfaces, constructed over the last decade in urban areas in Switzerland, have shown that large initial noise reductions can be achieved. However, these surfaces change their noise-reducing characteristics over their lifetime as a function of age and wear. Information on the long-term acoustical performance of such road surfaces is currently not available. Such information is, however, of high importance for reliable cost-benefit analysis which serves as a crucial input for planning and decision making. This article aims to fill this gap by providing predictions for the acoustic long-term performance of these low-noise road surfaces. This study revealed that the ageing processes of road surfaces can in general be described by a logarithmic model depending on the surface age. It showed that the acoustic long-term performance of the 8 mm low void RS class is similar to the one of SMA 11 RS, even though considerable initial noise reductions were obtained. The acoustic long-term performances of 4 mm RS and 8 mm RS, however, are promising.

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1. Introduction

Low-noise road surfaces (RS) have become a popular and widely used measure in Switzerland to minimize road traffic noise at its source. New types of semi-dense RS and RS with small granulate sizes and very fine pores have been developed to prevent water and dirt from entering the pores and clogging the surface. Acoustical measurements on 371 low-noise RS constructed over the last decade in urban areas in Switzerland have shown that large initial noise reductions can be achieved. Nevertheless, as all conventional road surfaces, low-noise road surfaces become louder, i.e. there is a decrease in their initial noise reduction properties over their lifetime as a function of age and wear. Several efforts in maintaining long-term acoustical performance by preventing clogging of the pores, and thus inhibiting the ageing of low-noise RS, are targeted. For example, the study of [1] is investigating possible cleaning procedures for these fine porous low-noise RS. Nevertheless, there is still a lack of knowledge on the long-term acoustical performance of such RS. Such information is, however, of high importance for reliable cost-benefit analysis which serves as a crucial input for planning and decision making. The main objective of this article is to fill this gap by providing reliable predictions for the acoustic long-term performance of these low-noise road surfaces. In a first step, this article assesses the suitability of two easy to measure and often used factors to describe acoustical ageing of road surfaces: age and traffic load. Some efforts have been made in literature to evaluate different statistical models for describing acoustic ageing, unfortunately without yielding consistent conclusions [2][3]. However, a recent European study summarising data on acoustic ageing of RS concludes, that different models are needed to account for different road surface types and different climatic regions [4]. To contribute to the ongoing discussion, different statistical models were tested to predict long-term acoustical performance for the assessed low-noise RS types when applied in Swiss climatic conditions. We therefore compare long-term performance and ageing behaviour of the low-noise RS with the one obtained for conventional SMA 11 RS type. An attempt to explain in-class variability of acoustic ageing behaviour is made in a companion paper where the influence of environment- and traffic-related factors on acoustic ageing is investigated [6]. The study finally concludes by giving a brief outlook about the expected tendencies regarding acoustic long-term performance of such surfaces when applied in deviating climatic conditions.

2. Materials & Methods

2.1. Road Surfaces

The sample of RS (371 RS in total) consists of various products constructed by different road construction companies and can be divided into three main RS types: (1) those with maximum aggregate size of 4 mm and a medium to high void content (12 to 22%), (2) those with maximum aggregate size of 8 mm and a medium void content (10 to 16%) and (3) those with maximum aggregate size of 8 mm and a low void content (6 to 10%). An overview of RS types assessed in this study is presented together with their range in void content and product names in Table I.

Table I. Assessed road surface (RS) types.

RS Type	*Void*	*Product(s)*	*No. of RS*
Reference Surface	2-6%	SMA 11	328 (578 meas.)
4 mm	12-22%	Nanosoft, Sapaphone, Famsiphonogrip, SDA 4 B/C	196 (379 meas.)
8 mm	10-16%	ACMR 8 HR, SDA 8 B/C	48 (129 meas.)
8 mm low void	6-10%	ACMR 8, SDA 8 A	127 (270 meas.)

2.2. Acoustical performance

To assess the acoustical performance, we evaluated a large dataset of tyre/road noise measurements comprising of:

- 258 SPB (statistical pass-by) measurements carried out according to [7][8]
- 999 CPX (close proximity) measurements carried out according to [9], with sets of reference tyres which correspond to passenger cars (Standard Reference Test Tyre SRTT of dimensions 225/60R16) mounted in a closed two-wheeled trailer.

All measurements were carried out on urban roads where the speed limit is typically 50 km/h. In this study, the focus is laid on the noise reduction determined for passenger cars, due to the higher robustness of measurement results for this vehicle category.

2.3. Factors of ageing

Ageing of RS is mainly expressed as a function of the two easy to measure factors: age (i.e. number of years/winters a surface has been exposed to climatic stress) and by the number of vehicles passing by (accounting for the mechanical stress related to the traffic load [4]). Traffic load affects the RS via a decrease in surface texture and redensification of the pores in the surface [5].
Tyre wear, agricultural pollution or mechanical stress due to e.g. snow chains are also important factors contributing to the ageing processes of low-noise RS (see also [6]). However, these factors are specific contributors within certain locations and do not generally influence the ageing processes of low-noise RS classes. Thus, these factors can be neglected in this study.
A multivariate analysis was carried out to assess the suitability of these two factors for predicting acoustic long-term performance of RS.

2.4. Acoustic Reference

Usually, the acoustic properties of a road surface in Switzerland are expressed as deviation to the standard national emission model StL-86+ [10]. To allow interpretation of acoustical performance away from national models, an alternative and internationally more practical reference was chosen. Therefore, all measurements are referenced to the mean acoustical properties of aged but intact SMA 11 RS, a surface type which is widely used in Europe and elsewhere (see Table I).

2.5. Testing ageing models

Several studies investigated the ageing of pavements by testing several statistical models (e.g. [2], [4], [11], [12]). However, in most of the studies specific RS types were tested and modelled without showing it in a broader framework of RS classes. In this study, several available specific road types were grouped in three RS classes (see Table I).
Different statistical models were tested for each class of RS (see Sect 2.1). A linear, exponential and logarithmic model was fitted to the four classes of dataset (including the reference pavement SMA 11). The χ^2 is indicated in Table II as a goodness of fit. The smaller the χ^2 value the better the fit. The accuracy of the model is determined by the prediction band from the 83.3% confidence interval.

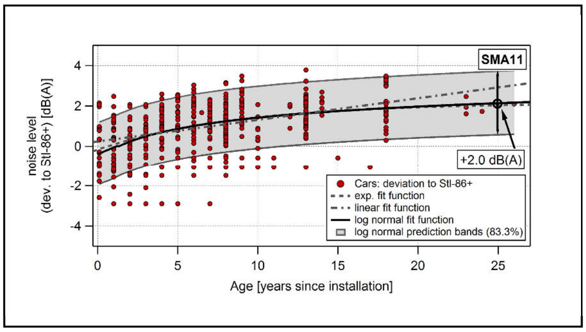

Figure 1: Acoustical ageing of the road surface SMA 11 referenced to the Stl-86+ model (See Sect. 2.2). An exponential (exp.), linear and logarithmic (log normal) fit function was applied to the data with a life expectancy of the road surface of 25 years.

In opposition to [3] and [4] who showed linear models for several RS of the type OPA and SMA, 27 years of measured road acoustic properties of 578 measurements of the SMA 11 in Switzerland (see Figure 1) show either an inverse exponential or a logarithmic decrease in the acoustic properties but not a linear decrease. The best model for the SMA 11 was found to be the logarithmic model, shown in Figure 1. It has the lowest χ^2 value of all the tested models, although, being close to the χ^2 value of the inverse exponential model. The logarithmic model is expressed as:

$$\text{noise level}(\text{age}) = y_0 + A\exp\left\{-\left[\frac{\ln(\text{age}/x_0)}{width}\right]^2\right\}, \qquad (1)$$

where y_0, A, x_0 and *width* are RS class specific constants, and age is given in years after installation of the RS.

The prediction range of each statistical model applied to the RS classes is limited by their life expectancy [13]. Thus, for the SMA 11 RS type the end of lifetime value (EOLV) for the road acoustic property was determined at 2.0±1.5 dB(A) to the national emission model StL86+ (see Figure 1) at 25 years lifetime.

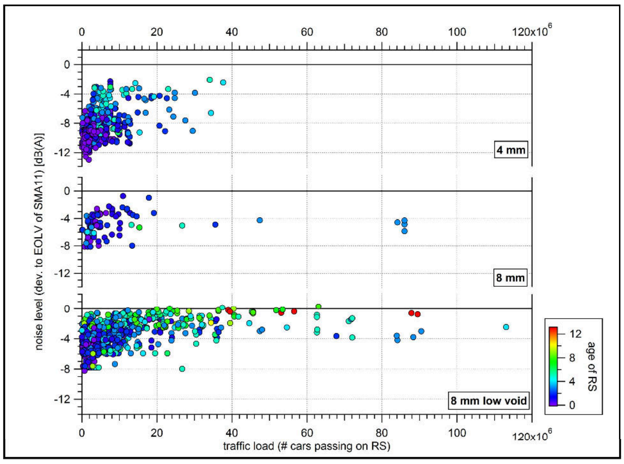

Figure 2: Noise level referenced to the EOLV of SMA 11 to the traffic load (number of vehicles passing on the RS). The points are colour coded to show the age of the RS in years after installation.

It is expected that for all RS classes the same model must be applied. Nevertheless, in Sect. 3.2 all the different models are tested for each RS class.

3. Results and discussions

3.1. Main factors describing acoustic ageing

The change of the noise reducing abilities of RS due to ageing of the pavement is mainly characterised by two factors: surface age and traffic load. To illustrate the influence of both factors, Figure 2 shows the noise reduction referenced to the EOLV of SMA 11 RS (see Sect. 2.5) as a function of the traffic load. The age of the RS (summarizing the environmental factors) is indicated by the colour coding of the points in Figure 2. In general, there is a clear trend between the traffic load and the noise reducing abilities of the RS. While the traffic load is increasing, the noise reducing abilities of the RS are decreasing. Nevertheless, it has to be mentioned that the traffic load correlates with the age of the RS. At higher traffic loads, though, a trend of an increase in noise levels for a particular traffic load with an increase in age of RS can be seen.

A multivariate analysis showed that in general for all the RS, the surface age is a stronger descriptor (highly significant partial coefficients of 0.24, 0.34 and 0.41) of acoustic ageing compared to the traffic load (highly significant partial coefficients between 0.18, 0.21 and 0.27). Therefore, only the influence of the factor age will be investigated in more detail in the following analysis.

3.2. Model representing best acoustic ageing

Figure 3 shows the SMA 11, 4 mm, 8 mm and 8 mm low void RS acoustic properties referenced to the EOLV of the SMA 11 at 25 years lifetime. A linear, inverse exponential and logarithmic statistical model was applied to the time-resolved data of the 4 mm, 8 mm and 8 mm low void classes.

Figure 3 shows the SMA 11, 4 mm, 8 mm and 8 mm low void RS acoustic properties referenced to the EOLV of the SMA 11 at 25 years lifetime.
A linear, inverse exponential and logarithmic statistical model was applied to the time-resolved data of the 4 mm, 8 mm and 8 mm low void classes.

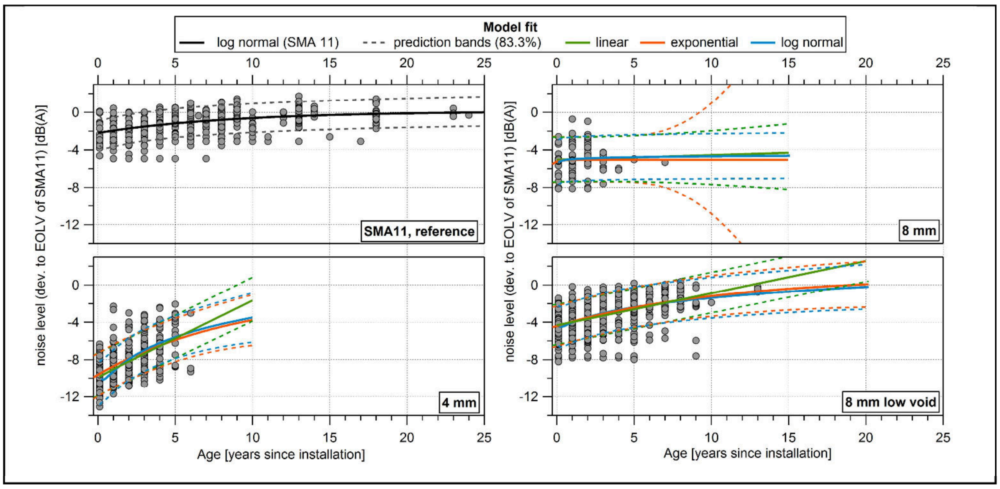

Figure 3: Acoustic ageing of the road surfaces SMA 11, 4 mm class, 8 mm class and 8 mm low void referenced to the acoustic properties of SMA 11 at 25 years age. A linear (green), exponential (orange) and a logarithmic (blue) model was applied to the data with their prediction bands of the 83.3% confidence interval (dashed lines).

The report of [13] suggests a life expectancy for 4 mm RS of 10 years. The analysis revealed that the 4 mm RS class indicates a faster ageing of the pavement in about the first 5 years, whereas it seems to stabilize after ~10 years of installation. The goodness of fit, χ^2 value (see Table II), indicates that the logarithmic model is the most appropriate one whereas the exponential regression model seems to describe the ageing of the road acoustic properties of the 4 mm class the weakest.

For the 8 mm RS [13] suggests a life expectancy of 15 years, however, only a small dataset is available with an age above 5 years of installation. Thus, with the dataset no clear trend can be observed concerning the ageing process of the road acoustic properties of the 8 mm RS class. Nevertheless, the goodness of fit indicates that the logarithmic model describes the data points the best compared to the linear and the exponential model. Due to the shortage of data, the prediction bands of the 83.3% confidence interval increase drastically after the age of 5 years of the RSs.

The 8 mm low void RS has a life expectancy of 20 years [13]. Up to about 5 years the linear, exponential as well as the logarithmic model seems to be able to represent the RS acoustic properties. However, after 5 years of installation the 8 mm low void surface seems to be better described with the logarithmic and exponential model. The goodness of fit values (χ^2) for all the RS classes (see Table II) indicate on average the logarithmic model as the best descriptor of the data. Physically it also makes sense to apply a model with a faster acoustical ageing rate in the initial years since: 1) In the initial years the pores may become clogged or their accessibility from the surface may be blocked, the result will be a fast loss of its initial sound absorption properties. 2) The further loss of acoustic effectiveness is likely to take place slower as changes to the road surface texture (due to mechanical stress) often take place more gradually [5].

Table II: Goodness of fit (χ^2) values of the linear, exponential and logarithmic models for all the road surface classes and reference surface SMA 11.

model	SMA 11	4mm	8mm	8mm low void
linear	600	1395	239	1701
exponential	584	1422	238	1691
logarithmic	583	1378	234	1696

Compared to the assessed low noise road surfaces, the reference surface, SMA 11, features a somewhat weaker acoustical ageing rate. Nevertheless, a logarithmic model with a faster acoustical ageing rate in the initial years is still valid. Therefore, the logarithmic model was chosen to apply for further analysis. This is in agreement with [2] who discussed that for some RS types other models than linear relationships may be more appropriate.

3.3. Acoustical long-term performance

Each RS class, 4 mm, 8 mm, 8 mm low void and SMA 11, is described with a given life expectancy according to [13]. Applying a valid model, the EOLV for the acoustic properties of each class can be retrieved. Figure 4 shows all three low-noise RS classes and the SMA 11 type together with their corresponding ageing model resulting in the EOLV referenced to the national model StL86+ as well as to the EOLV of the SMA 11.

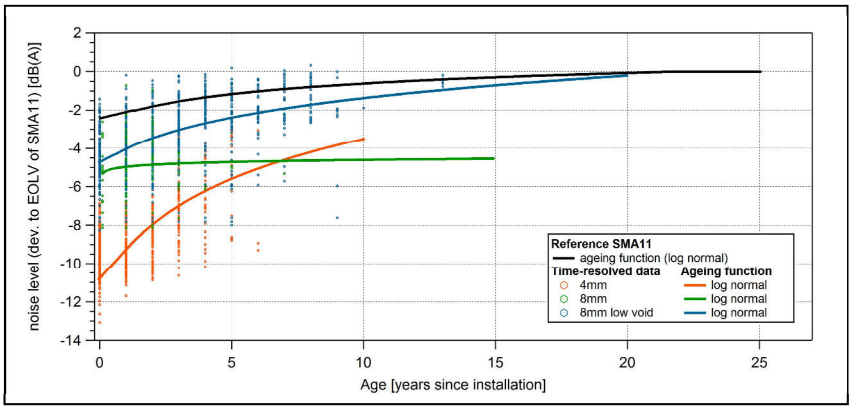

Figure 4: Acoustic ageing of the road surfaces SMA 11 (black), 4 mm class (orange), 8 mm class (green) and 8 mm low void (blue) referenced to the EOLV of SMA 11 at 25 years age. The logarithmic model fits are applied to the data ending at the respective life expectancy according to [13]. The EOLV for the 8mm class may contain large errors since only few data was available for this class.

The EOLV for the 4 mm RS class is determined at -3.5±2.6 dB(A). For the 8 mm and 8mm low void RS class EOLVs of -4.6±2.4 dB(A) and -0.2±2.4 dB(A) were determined respectively. All EOLVs are summarized in Table III.

It has to be noted that these large standard deviations are not only given by the missing data at higher ages but is also determined by the rather large variety of the initial noise level values at the time of installation of the RS.

As expected, the EOLV of the 8 mm low void RS class is higher compared to the EOLV of the 4 mm class. This can be attributed to the larger granulate sizes and the reduced void content in the RS.

The EOLV of the 8 mm surface class is likely to be overestimated at -4.6 dB(A). It is physically very unlikely to have such a low decrease in noise reducing abilities of only -0.8 dB(A) (EOLV minus the noise level at year of installation) over 20 years. It is expected that the true EOLV of the 8 mm RS class is at the upper end of the prediction band and thus smaller than the EOLV of the 4 mm RS class.

Given the fact that new standards are applied by many road building companies for the first time, the assessed datasets may contain a certain number of manufacturing errors. This may especially be the case for 4 mm RS. With increasing experience of the industry with the construction of low-noise road surfaces, such manufacturing errors may be considerably reduced in the near future. In addition, the road surfaces may in some cases be applied in unsuitable environmental or traffic conditions which may negatively influence its long-term acoustic performance (see also [6]). If both, production errors and unsuitable application areas are avoided in the future, EOLV may be somewhat lower and ideally approaching the lower prediction band presented in Table III.

3.4. Expected tendencies for deviating climatic conditions

In section 3.3 estimates were given for the long-term acoustic performance of low-noise road surfaces when applied in Swiss climatic conditions. This section aims to give a brief outlook on the expected tendencies regarding acoustic long-term performance of such surfaces when applied in deviating climatic conditions. It is assumed that winter conditions are responsible for the major part of the climatic stress imposed on a RS. Table IV, gives an overview of climatic conditions in different cities. The yearly average number of frost days (*frosts*) gives an indication of the winters in the different countries influencing a RS acoustic ageing. A recent European study [4] discussed the influence of climatic zones on ageing of RS. They found that a specific RS type installed in Denmark (Copenhagen; DK) results in a stronger acoustic ageing process due to more frequent freezing/defrosting cycles compared to the same RS type installed in France (Paris; F) or

Table III: End of lifetime values (EOLV) of the road acoustic properties are indicated with the corresponding 83.3% prediction band per RS class referenced to national emission model StL-86+ and the EOLV of SMA 11 RS. Values in grey indicate the large model errors, which are likely due to the few available data for this class.

ref. to EOLV of ...[dB(A)]	SMA 11	4 mm			8mm			8 mm low void		
		lower	mean	upper	lower	mean	upper	lower	mean	mean
SMA 11	0.0±1.5	-6.1	-3.5	-0.9	-7.0	-4.6	-2.2	-2.6	-0.2	2.2
StL-86+	2.0±1.5	-4.1	-1.5	1.1	-5.0	-2.6	-0.2	-0.6	+1.8	4.2

Spain (Madrid; ES). Therefore, to give an estimate about a low-noise RS acoustic long-term performance elsewhere in the world, the climatic conditions need to be related to the ones of Zurich (CH) given in Table IV.

Table IV: Climatic conditions in different cities

Climate data (period from 1990 - 2015)			
Capital	T_{max} *[°C]*	T_{min} *[°C]*	*frosts [d]*
Amsterdam (NL)	14	7.5	35.6
Berlin (DE)	14	6.6	64.3
Copenhagen (DK)	12	6.1	62.7
Lisbon (PT)***	21.4	13.4	0.2
London (GB)*	8.2	7.4	39.0
Madrid (ES)	21.2	8.5	42.7
Oslo (NO)**	10.6	3.9	111.6
Paris (F)*	16	8.4	28.3
Rabat (MA)***	22.8	12.7	0.6
Stockholm (SE)	10.7	3.9	107.2
Tokyo (JP)***	20.3	13.7	3.8
Vienna (AU)	14.8	7.6	56.9
Zurich (CH)	13.3	6.8	58.6

* only data from 2003 – 2015, ** only data from 2005 – 2015
*** only data from 1997 – 2015
source: http://www.wetteronline.de/klimarechner/

4. Conclusions

This study elaborated the long-term acoustical performance of low-noise road surfaces (RS). These new types of semi-dense RS, and RS with small granulate sizes and very fine pores have been developed. They were classified into three RS classes 4 mm, 8 mm and 8 mm low void and their change in noise reducing abilities due to ageing of the RS were investigated.

Both, the surface age as well as the traffic load significantly influence the acoustic performance of a RS. However, in general, the surface age, i.e. the factor summarizing the environmental parameters, of the RS consistently resulted in a more significant influence than the traffic load. Of all the different statistical models tested, the log normal statistical model proved to be the best descriptor of acoustic performance as a function of the surface age.

Analysis yielded in the following predictions for the end of lifetime values (EOLV) of the assessed RS classes: -3.5 dB(A) for 4 mm RS, -4.6 dB(A) for 8 mm RS and -0.2 dB(A) for 8 mm low void RS. The presented values represent noise reductions relative to the EOLV of conventional SMA 11 RS. The acoustic long-term performance of the 8 mm low void RS class is similar to the one of SMA 11 RS, even though considerable initial noise reductions were obtained. The acoustic long-term performances of 4 mm RS and 8 mm RS, however, are promising. This becomes even more true when the average lifetime performance of these surfaces is considered. Nonetheless, it may be that the estimates contain large errors since few data was available for older RS, this is especially the case for the 8 mm RS class. In the case of the 4 mm RS class it is thought that the true EOLV may be somewhat lower if both, production errors and unsuitable application areas can be avoided. A first step is made in a companion study [6] which investigates such influences, ultimately aiming to provide critical information for the improvement of acoustic long-term performance of low-noise RS.

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