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Revision of GPAV-2020-0274 " Low-Noise Pavement Technologies and Evaluation Techniques: A Literature Review"

Response to reviewers' comments.

We would like to thank the reviewers for their review of the paper and for their comments. All of the items have been taken into account and corrections have been made in the text (in red). You will find our response to each comment below.

Reviewer: 1

Comments to the Author

This paper in order to be framed as a literature review of low-noise pavements must which needs to be strong integrated.

The Authors introduce several aspects related to the theme of low-noise pavements: direct and indirect noise measurement techniques; predictive models of acoustic performances etc.

It would be useful to introduce a flow-chart associated with the presentation of the paper on page 3 - lines 3 to 13. This flow-chart would show the structure and articulation of the full paper.

- This has been added in Figure 1.

Pag. 7 - Paragraph 2.4

Line 19: The ISO standard indicated is incorrect.

Line 23: The ISO standard indicated is incorrect.

- Thank you for your remark, these have been corrected.

The paragraph must necessarily be expanded by inserting a more detailed description of the methods. In particular, ISO 13472-1: 2002 (extended surface or Adrienne method) seems not to be well presented in paragraph 2.4. Authors are invited to consider the following article:
F.G. Praticò et Al. (2014): A study on the dependence of PEMs acoustic properties on incidence angle, International Journal of Pavement Engineering, DOI: 10.1080/10298436.2014.943215

- The article has been reviewed and incorporated into section 2.4, along with more information.

Pag. 14 - Line 8

Attention: the relationship between MTD and MPD to which the Authors refer has specific application ranges.

Being a literature review, it is absolutely necessary that clarity be made on this question, see:
F.G. Praticò et Al. (2015): A study on the relationship between mean texture depth and mean profile depth of asphalt pavements. Construction and Building Materials 101 (2015) 72–79.
http://dx.doi.org/10.1016/j.conbuildmat.2015.10.021

- Thank you for this suggestion. This has been incorporated as follows:

" so long as the depth is below 1.5 mm (Praticò and Vaiana, 2015)."

Authors must also introduce and describe the ENDt (Expected pass-by Noise level Difference) indicator.
This is an indicator that estimates the sound level of a pavement in comparison with a reference pavement starting from the disaggregated measure of a surface texture profile by the Texture level: F.G. Praticò and P.G. Briante. Prediction of surface texture for better performance of friction courses. Construction and Building Materials 230 (2020) 116991.
https://doi.org/10.1016/j.conbuildmat.2019.116991

- Reference incorporated into the comment on NMAS-noise relation in Section 5.1.

Reviewer: 2

Comments to the Author
The manuscript is a review of the measurement methods of the tyre/road noise (in-situ and in laboratory), sound absorption coefficient, texture, air flow resistivity, water permeability, dynamic stiffness. The general characteristics of low-noise pavements (porous asphalt, double layer porous asphalt, semi-dense asphalt, crumb rubber modified asphalt, thin layer asphalt and poroelastic pavement) are presented. The assumptions of selected models that can be used in road traffic noise forecasting when designing low-noise pavemets are also discussed. In my opinion the author (authors) should present more detailed comparative analyses. Values presented in Table 2 and 3 are too general.

- We appreciate the comment but it is not clear how Table 2 and 3 should be more specific. The point of the tables is to generalize the information written in the paragraphs around them. Table 3 includes the affected noise mechanisms, advantages, disadvantages and estimated noise reduction based on the evaluation of several studies.

The manuscript lacked references to such pavements as: SMA LA, exposed aggregate cement concrete.

- One study with SMA LA was sound and added to Section 5.4:

  "A low noise version of SMA, known as SMA LA has been developed in Germany. A noise decrease of 2.5-4.0 dB by CPX is achieved compared to DAC by increasing the air voids content to 9-14% (Gardziejczyk et al., 2020). This air void content, similar to SDA, is clearly the factor in the low noise properties."

- Thank you for the suggestion of exposed aggregate cement concrete. This have been incorporated (along with the newer NGCS) as follows:

  "5.6 Low-Noise Cement Concrete Surfaces
  Portland cement concrete (PCC) pavements represent a small fraction of the pavements worldwide but are desirable in certain conditions. Generally, their higher rigidity and the surface grooves needed for ad-equate skid resistance (Kuemmel et al., 2000) mean that they are significantly more noisy than DAC (Pinay et al., 2020). Exposed-Aggregate Cement Concrete Pavement (EACCP) adds a modifier on top of the PCC after placement, which results in having exposed aggregates on the surface. Comparison studies have shown that this pavement is 1-5 dB quieter than PCC pavement (Samuels and Parnell, 2001; Zhang et al., 2014), but otherwise having noise performance similar to DAC (Samuels and Parnell, 2001). A quieter PCC pavement in development is the Next Generation Concrete Surface (NGCS), which modifies the surface grinding of the pavement in order to reduce the amount of air trapped between the tire and the non-porous concrete surface (Scofield, 2017). OBSI

measurements with other pavements showed that NGCS is up to 5 dB quieter that the conventional PCC pavement and 1.5-2 dB quitter than the 9.5 SMA in the comparison (Mogrovejo et al., 2014). More studies are needed to confirm the validity of these findings."

The author (authors) should be appreciated for providing a concise overview od the literature on low-noise pavements. However, the reviewer has doubts whether the manuscript in this layout can be published in the IJPE. A review of the literature in the scientific journal is included in the introduction. In the main part of the manuscript should present specific results, analyses and conclusions. In this manuscript, there is no comparative analysis, the conclusions are generally known to those dealing with low-noise pavements technology and testing parameters that determine the acoustic properties of road surfaces. Before publishing in IJPE, the manuscript needs to be rewritten and introducing more detailed comparative analyses of pavements and measurement methods. The title of the manuscript corresponds to the content, but is a review of literature without detailed analysis a scientific article ?

- The authors agree that comparisons are important for literature reviews. The comparative analysis is already found in the Tables, and also in the summary of each section in 2.5, 3.4, 4.6 and 5.7.

This manuscript, including a very good review of the literature (163 items), can be the basis for writing a technical book.

Reviewer: 3

Comments to the Author
The paper “Low-Noise Pavement Technologies and Evaluation Techniques: A Literature Review” has some merits but several points should be better addressed.

Specify better the objectives (in the abstract too).

- The objectives have been specified in the abstract as follows:

" This literature review, intended for pavement researchers and professionals, looks at low-noise asphalt pavement technologies and the techniques which can be used to evaluate them."

- And furthermore in the introduction as:

" This present literature review is intended to provide useful information to pavement researchers and professionals looking to research and implement low-noise pavements. It will focus on the noise as it relates to the pavement type, focusing on low-noise pavement technology, acoustical laboratory and field measurement methods, noise relevant non-acoustical parameters, along with the modelling done in this regard. The first two parts focus on various laboratory and field testing methods used to characterize acoustical properties of pavements. This is followed by low-noise pavement technology, as well as the evidence of mechanical and acoustical durability. The last part of the paper focuses on the modelling options available for prediction of acoustical performance. To summarize, this work provides researchers working in developing low-noise roads a current overview of the most successful low-noise pavements, the laboratory and field test methods for their evaluation and the models which can be used to further exploit them."

Highlight that if you want to measure how quiet is a pavement the best method is the CPX (cf. De Leon et al, 2020).

- The authors are not prepared to make this conclusion given the information were have put together. However, the conditions where each methods may be better suited have been described.

Section 2.4.: It seems important to point out the different level of precision and accuracy of the available methods (cf. Praticò et al, 2017).

- A generally valid ranking of the accuracy of the methods cannot be given. This would depend largely on the question to answer and the implementation of the method.

Low-noise pavement technologies depend on the way you design and construct them. You may wish to discuss the link between pavement characteristics (e.g., gradation) and pavement performance (e.g., texture and noise). To this end, the prediction of texture levels as a proxy of noise is crucial (Praticò and Briante, 2020; Teti et al, 2020). Please discuss.

- Thank you for these very recent references, they have been integrated in the text, including into the comment on NMAS-noise relation in Section 5.1:

"It was found that smaller aggregate sizes in porous pavements further reduce noise (Freitas, 2012; Praticò and Briante, 2020; Russell et al., 2010)."

Suggested references.

Praticò, F.G., Fedele, R., Vizzari, D. Significance and reliability of absorption spectra of quiet pavements (2017) Construction and Building Materials, 140, pp. 274-281. DOI: 10.1016/j.conbuildmat.2017.02.130

de León, G., Del Pizzo, A., Teti, L., Moro, A., Bianco, F., Fredianelli, L., Licitra, G.Evaluation of tyre/road noise and texture interaction on rubberised and conventional pavements using CPX and profiling measurements (2020) Road Materials and Pavement Design, DOI: 10.1080/14680629.2020.1735493

Praticò, F.G., Briante, P.G., Prediction of surface texture for better performance of friction courses (2020) Construction and Building Materials, 230, art. no. 116991, DOI: 10.1016/j.conbuildmat.2019.116991.

Luca Teti, Gonzalo de León, Alessandro Del Pizzo, Antonino Moro, Francesco Bianco, Luca Fredianelli, Gaetano Licitra,Modelling the acoustic performance of newly laid low-noise pavements, Construction and Building Materials, Volume 247, 2020, 118509, ISSN 0950-0618, https://doi.org/10.1016/j.conbuildmat.2020.118509.

Associate Editor: Loizos, Andreas

Thank you for these suggestions, they have been incorporated into the text.

Low-Noise Pavement Technologies and Evaluation Techniques: A Literature Review

Abstract

Traffic noise is the perpetual form of environmental pollution adversely affecting human health in the urban environment. From all the sources of contribution to road traffic induced noise, the tire/road contact is predominant at higher vehicle speeds and therefore a vital starting point to reduce noise at source. This literature review, intended for pavement researchers and professionals, looks at the continuously evolving low-noise asphalt pavement technologies and the techniques which can be used to evaluate them. Test methods for determining the acoustical properties of asphalt pavements are reviewed, in both the laboratory and the field environment. The Close-Proximity (CPX) method is the most commonly used field test for pavement acoustics, followed by the Statistical Pass-By (SPB) and On-Board Sound Intensity (OBSI) methods. While SPB seems to be the most comprehensive methods, the CPX can be conducted with fewer resources. Methods for measuring the pavement acoustical properties in the laboratory include the impedance tube for sound absorption and laboratory pavement noise simulators; with the larger drum methods being able to produce conditions similar to in-situ. Measurement methods for noise-relevant non-acoustical characteristics like surface texture, porosity and airflow resistivity were also reviewed. Optimizing surface texture at the macro-scale was found to be important in reducing tire/road noise. For pavement types, porous asphalt concrete (PAC) and its variants result in low-noise properties the most reliably, while having some drawbacks in durability and maintenance. Finally, various acoustical performance prediction models based on the pavement properties were discussed.

Keyword: Asphalt pavement, acoustical properties, sound absorption, laboratory testing, field testing, porous material, surface texture, modelling

1 Introduction

Road traffic noise has been a problem of the urban dwellers since the ancient times as residents complained about the carriages rattling over uneven pavements (Bijsterveld, 2014). However, only with the explosion of road traffic in the 20th century, regulations were developed for traffic noise emission control (Sandberg and Ejsmont, 2002). This problem has only worsened over time; greater demands on the road transport infrastructure – as a result of economic growth – have manifested themselves in an increase in the number and load of vehicles worldwide. A 2011 report by the World Health Organization (WHO) indicates that in the EU and Norway, traffic noise is the second biggest environmental problem adversely affecting health after air pollution (World Health Organization, 2011). Comparative burden studies suggest that, after particulate matter, noise is the second major cause of disability adjusted life years (DALYs) lost in Europe (World Health Organization, 2010). This new health evidence highlights the urgency of government agencies adopting more stringent noise standards.

Traffic noise refers to the sound generated during road transportation, which can be unpleasant to humans or harmful to their health. The European Commission has regulated road traffic noise via EU

Directive 2002/49/EC (EU Directive, 2002). WHO indicates that noise can disturb sleep, cause cardiovascular and psychophysiological problems, reduce performance as well as provoke annoyance and changes in social behaviour. Traffic noise alone is harming the health of almost every third person in the European Region according to WHO. One in five Europeans is regularly exposed to sound levels at night, that could significantly damage health (World Health Organization, 2011).

A study by the Swiss Federal Office for Spatial Development has documented the external costs of transport (Ecoplan and INFRAS, 2014). The study calculated the social, economic, environmental, accident and health-related effects of transport in Switzerland in 2010, indicating the substantial external cost of noise from road transport at almost CHF 1.5 billion (€1.37 billion). Research has shown that the newer vehicles on the market with Euro 6 engines are less polluting in emissions. However, other important parameters – noise among them – remain higher than acceptable limits. Furthermore, it was shown that there was no systematic dependence of the noise emissions on the Euro vehicle emission classes for each Swiss 10 heavy vehicle category (Poulikakos et al., 2013). The results indicated that more needs to be done in encouraging the development of infrastructure to reduce the noise at the tire/road interface. Furthermore, electric vehicles do emit less noise due to their engines (Pallas et al., 2016), and assuming wider uptake of electric vehicles, improvements on the vehicle side can be expected. This puts even more weight on the pavements, since the tire/road noise emissions will become even more dominant.

The interaction between tire and pavement generates sound that is dependent on the vehicle speed as well as the properties of the tire and pavement. At lower speeds (< 30 km/h for passenger cars, <75 km/h for heavy vehicles), engine noise is dominant whereas at higher speeds the tire/road noise dominates (Heutschi et al., 2018, 2016). The engine noise has been reduced over the years and more attention is being given to tire/road noise. To this end in recent years, low-noise tires have been developed with EU label that describes their acoustical properties as well as fuel consumption and skid resistance allowing the consumers to decide.

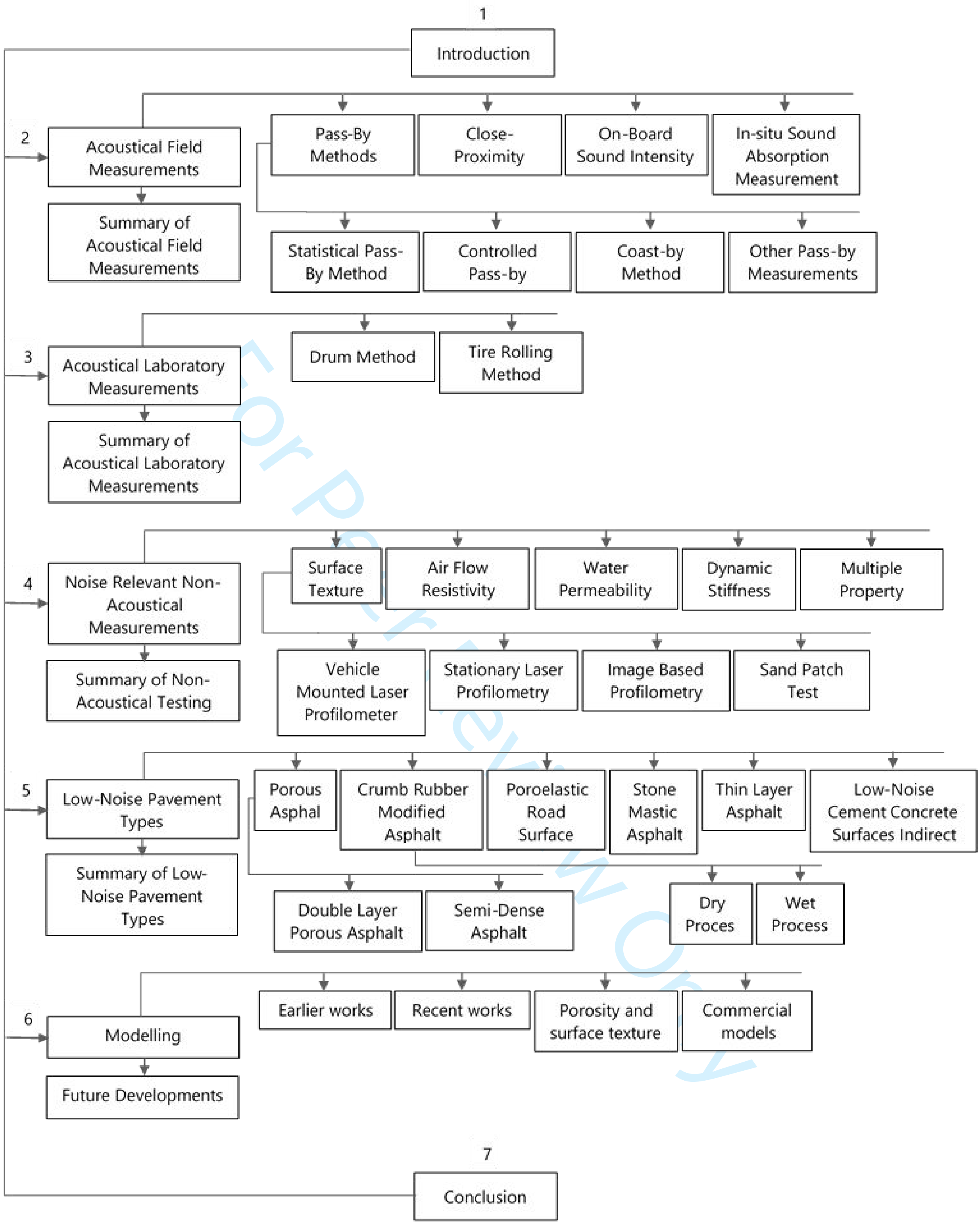
The tire/road sound generation mechanisms can be traced to the following: i) tread impact, ii) air pumping, iii) stick-slip and iv) stick-snap. In addition to these, three sound enhancement mechanisms can play a role: i) horn effect, ii) Helmholtz resonance and iii) pipe resonance (Ohiduzzaman et al., 2016; Sandberg and Ejsmont, 2002). While it is not the goal of this review to look at these mechanisms, they can be used to explain the performance of different pavement types. A summary of the pavement properties which have been found to affect these mechanisms is shown in Table 1. Although in most studies, the vibrations contribution to the generated noise is considered the dominant one (Sandberg and Ejsmont, 2002), models that incorporate the air pumping effect have shown that the contribution of the latter can be more significant than previously thought (Winroth et al., 2013).

Table 1 Summary of Noise Generation/Enhancement Mechanisms Affected by Pavement Properties (Ohiduzzaman et al., 2016; Sandberg and Ejsmont, 2002)

Noise Generation/Enhancement Mechanism	Pavement Property
Air pumping	Porosity and macrotexture
Stick-slip	Texture skewness
Tread impact	Surface macrotexture

Stick-snap	Surface microtexture
Horn effect	Porosity, sound absorption
Helmholtz resonance	Porosity and texture
Pipe effect	Porosity

This present literature review is intended to provide useful information to pavement researchers and professionals looking to research and implement the continuously evolving field of low-noise pavements. It focuses on the noise as it relates to the pavement type, focusing on low-noise pavement technology, acoustical laboratory and field measurement methods, noise relevant non-acoustical parameters, along with the noise prediction modelling (Figure 1). The first two parts focus on various laboratory and field testing methods used to characterize acoustical properties of pavements. This is followed by low-noise pavement technology, as well as the evidence of mechanical and acoustical durability. The last part of the paper focuses on the modelling options available for prediction of acoustical performance. To summarize, this work provides researchers working in developing low-noise roads a current overview of the most successful low-noise pavements, the laboratory and field test methods for their evaluation and the models which can be used to further exploit them.



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2 **Figure 1 Research Overview**

2 Acoustical Field Measurements

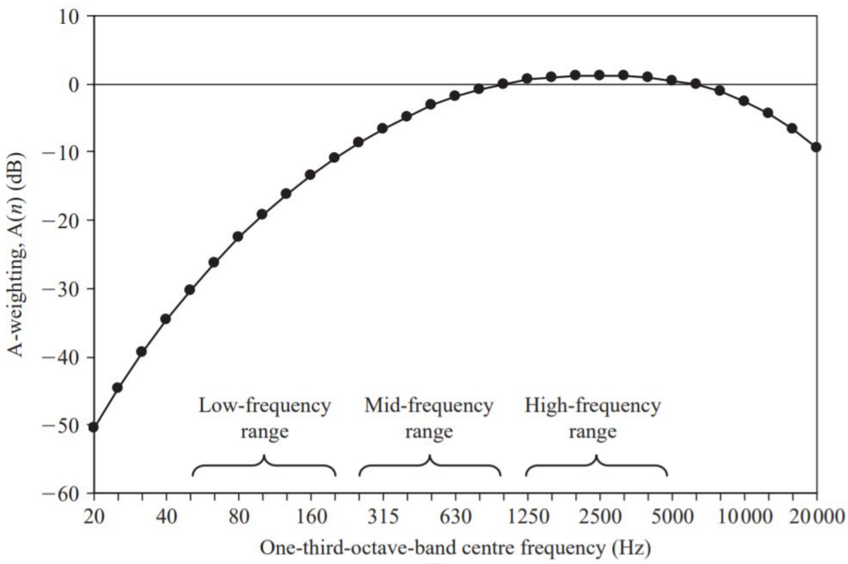

Figure 2 A-weighting Values Over the Range of Human Hearing Indicating the Low, Mid, and High Frequency Ranges (Hopkins, 2012)

Field tests are vital for noise assessment of low-noise pavements, but are also subject to the variability of the in-situ environment. Pavement noise levels can either be measured by moving on-board microphones or with non-moving microphones capturing vehicle pass-bys. These express the noise in terms of the A-weighted sound pressure level (SPL), which is weighted to account for the frequency-dependent sensitivity of human hearing and is expressed as dB(A) (Nilsson, 2007). Highest weights are applied in the 1–5 kHz range as shown in Figure 2. Additionally, the sound absorption of the asphalt can also be measured in the field.

2.1 Pass-By Methods

2.1.1 Statistical Pass-By Method (SPB)

The Statistical Pass-By (SPB) method is defined in the standard ISO 11819-1. The experimental set up is shown in Figure 3 (Angst et al., 2011); the tachometer for speed measurements and microphone for sound level measurements are installed on the roadside at 7.5 m from the centre of the lane at a height of 1.2 m. From a statistically significant number of individual vehicle passes, the maximum A-weighted sound pressure levels and the speed of the vehicles are measured. In this method, the type of vehicle (cars, dual-axle or multi-axle heavy vehicles) and the speed (high, medium and low) is mentioned in the results (Gardziejczyk, 2016; Remisova et al., 2014).

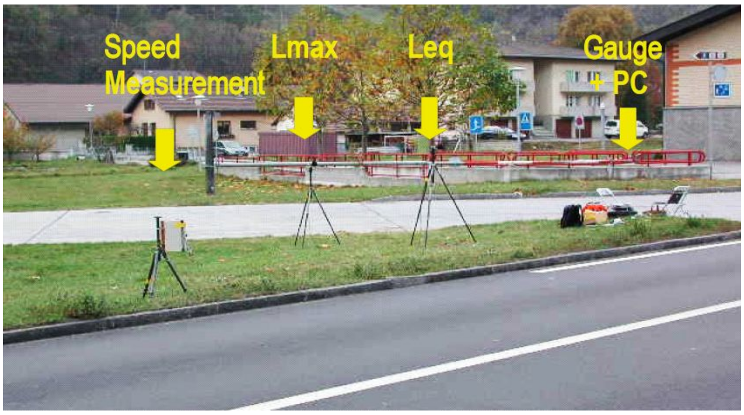

Figure 3 Experimental Setup of SPB (Angst et al., 2011)

Compared to the methods discussed subsequently, is that focus on tire noise generation, SPB measures total noise and contains also propagation effects. A big advantage of the SPB method lies in the fact that a typical vehicle fleet is considered and the evaluated sound pressure level is of direct relevance for residents living close to the road. The disadvantage of SPB is that it is quite time consuming for the same amount of data compared to the other methods here.

The Statistical Pass-By Index (SPBI) encompasses simultaneous measurement of noise level and speed of individual vehicles in the traffic stream. It quantifies the overall effects of a pavement surface type on traffic noise into one value (Simpson et al., 2014). Alabaster et al. (2012) used SPBI method to evaluate the traffic noise measurements in relationship with pavement durability.

2.1.2 Controlled Pass-by Method (CPB)

A variant pass-by method is the Controlled Pass-By (CPB) method. Here, there are a number of controlled and identified test vehicles, allowing monitoring of factors such as category, speed and load of vehicles, number of tests by each type of vehicle, type and the wearing of the tires, noise generated by the engine and the conditions of the surface (Freitas et al., 2009).

2.1.3 Coast-by Method

The "coast-by method" is performed with the vehicle engine off as described in ISO 13325. Most often, it is used to characterize the noise performance of tires. In contrast to SPB and CPB, this method does not include the effect of the pavement on the engine noise contribution. While it has been used to develop a semi-empirical model with regard to tire/road noise (Pieren et al., 2016), but is not as representative as the two aforementioned pass-by methods.

2.1.4 Other Pass-by Measurements

Two more "one off" acoustical pass-by tests were found in the literature. Herisanu and Bacria (2013) investigated the noise generated by vehicles on pavement using two hand-held analysers type 2250 Brüel & Kjær 2250 according to a Romanian standard (STAS 6161/3-82). Mavridou and Kehagia (2017) used a Noise Level Analyser using a single type 2237 Brüel & Kjær microphone positioned on the side of the road.

2.2 Close-Proximity Method (CPX)

The close-proximity method (CPX) specified by ISO 11819-2 aims to assess the traffic noise dominated by the contact between the tire and road surface. Figure 4 shows the typical setup of CPX (Bueno et al., 2014a), with a tire attached to a trailer with microphones, which measure the sound pressure emitted by the reference tire. The reference tires represent light vehicles by the ASTM F 2493 Standard Reference Test Tire (SRTT; P225/60R16) and heavy vehicles by the Avon AV4 (195R14C) (Anfosso-Lédée et al., 2016). Spectral information can be derived by an evaluation of the microphone signals in third octave bands. This method is recommended when traffic noise is dominated by tire/road noise (>40 km/h per ISO 11819-2).

Figure 4 Experimental Setup of CPX (Bueno et al., 2014a)

A newer CPX setup has improved the accuracy by adding an enclosure (semi-anechoic chamber) for the trailer, from a sound absorbing material. This reduces the effect of sound contamination from wind or external traffic (Eskandarsefat et al., 2018; Tian et al., 2013). The improved setup has been applied in several recent studies (Miljković and Radenberg, 2012; Świeczko-Żurek et al., 2017; Vázquez and Paje, 2016; Vuye et al., 2016).

CPX appears to be the most widely cited method to assess the tire/road interaction noise in the literature. An advantage of the CPX method is that it can monitor large distances of surface and geo-reference the sound spectra for every 5-10 m, to be able of obtain a more reliable mean value for the type of surface to be acoustically characterized. Furthermore, this method allows analysing the effect of pavement aging and identifying surface damage (potholes) or horizontal signs in urban environments (pedestrian crosses) (Paje et al., 2008). A downside to CPX compared to SPB for example, is that it does not consider the contribution of engine to the overall noise, which also affects people living in the proximity of the road.

In addition to those mentioned above, a significant amount of literature was carried out using the CPX method, with a few noteworthy for their content. Mun and Cho (2009) developed and validated noise measuring procedures for evaluating light and heavy traffic on various pavement surfaces considering different vehicle speeds. Ho et al. (2013) investigated the tire-pavement noise level at five repaved road sections measured at 70 km/h, and evaluated the effect of tire rubber hardness on tire-pavement noise level. A round robin test on nine CPX systems from Austria, Belgium, Germany and the Netherlands conducted by Peeters et al. (2018) concluded that measurements of different teams were within acceptable variability.

2.3 On-Board Sound Intensity (OBSI)

The On-Board Sound Intensity (OBSI) method (Figure 5), initially developed by research led by Donavan at General Motors, is a near-field technique that measures tire/road noise in close proximity to the source (Donavan and Rymer, 2003; Rasmussen and Sohaney, 2012). Unlike the CPX method discussed above, instead of calculating the levels via measuring sound pressure by independent microphones, the OBSI measures tire/road noise using a phase-matched pair of microphones that are located in such a manner to isolate sound generated near the tire/road contact patch. The standard vehicle speed is 60 mph (96 km/h). The microphones are specifically tuned so that the tire/road interface can be focused on, and the background noise from other sources is limited (Wang et al., 2011).

The OBSI protocol is now standardized as per AASHTO TP 76 after subsequent refinement under Caltrans. The ASTM F 2493 SRTT (P225/60R16) is currently used as standard tire for OBSI measurements. However, in the past (2006 and 2007) the Goodyear Aquatred III (P205/70R15) tire has also been used for both OBSI and CPX testing. The tire was dropped from the test program as it is no longer in production and the test results between the two tires have been found to be highly correlated.

Some additional studies using OBSI are noteworthy. Pierce et al. (2009) studied the effect of studded tires on different pavement types and age using sound intensity measurements. Kohler et al. (2009) conducted a comparison of OBSI levels between different California asphalt pavements and existing PCC noise data. Ongel and Harvey (2010) measured the sound intensity levels at 800 Hz frequency band versus air-void content for different mix types. Donavan (2011) studied the additional sound attenuation of porous pavements over longer distances compared with dense pavements. Lu et al. (2011) evaluated the comparison of overall OBSI values for different mix types at different ages for first, second, and third survey years of different trial sections. Liao et al. (2014) developed a correlation of noise levels with pavement surface textures, surface porosity, stiffness, pavement roughness, ride quality with pavement surface texture and maximum aggregate size on the National Centre for Asphalt Technology (NCAT) test track. Donavan (2014) evaluated the noise reduction by overall wayside and OBSI levels of pavement pre-rehabilitation and after rehabilitation work. Additional sound attenuation porous pavements relative to nonporous pavements was also evaluated.

Figure 5 Experimental Setup of OBSI (Lu et al., 2011)

2.4 In-situ Sound Absorption Measurement

The sound absorption coefficient of pavements can be measured in-situ by different methods. These methods would use normal incidence (ISO 13472-2), or both oblique and normal incidence (ISO 13472-1) as a basis for measurement. In the normal incidence method, an impedance tube is mounted vertically with the open end resting on the pavement surface. As the necessary sealing at the interface between tube and pavement can only be achieved for non-porous surfaces, the method is not applicable for absorptive pavements.

The main procedure would be similar to the in-lab normal incidence impedance tube test (ISO 10534-2). However, correction factors are incorporated in computing the final absorption coefficient to compensate for uncertainties in the ISO 10534-2 procedure, varying external conditions and from pressure loss. Using these factors, the measured absorption, and system's measured internal damping, the absorption coefficient and the reflection factor can be calculated (ISO 13472-2). This method would not be helpful, if the oblique incidence measurement is required in an application (Praticò et al., 2015).

A more widely applicable method is the extended surface method or the Adrienne method (ISO 13472-1). For this purpose, a loudspeaker is installed at a height of 1.25 m and a microphone 0.25 m above the test surface. By evaluation of the impulse response and temporal separation of direct and reflected sound for an arbitrary angle of incidence, and using a geometrical spreading factor, the absorption coefficient and the reflection factor can be computed. This method can be used for normal incidence, although the Adrienne system is not equipped with a toll to fix the probe perpendicular to the pavement. In addition, some contract requirements mandate an incidence angle of 30˚ (Praticò et al., 2015). This measurement can also be carried out dynamically with the equipment mounted on a trailer travelling at up to 30 km/h (Morgan and Watts, 2003).

These methods might have advantages and disadvantages compared to each other. For example, the normal incidence method (ISO 13472-2) is considered to give a more accurate estimate of porosity compared to the Adrienne method (ISO 13472-1), in a study by Praticò et al. (2017). The precision in estimating the porosity of the pavement samples are considered to be increasing from ISO 13472-1 (extended surface method) to ISO 13472-2 (in-situ impedance tube) to ISO 10534-2 (in-lab impedance tube) in this study. However, whether or not this evaluation holds for the above methods as descriptors of the asphalt mixture quietness, needs more investigation.

Besides measuring sound pressure, the sound absorption property of a pavement can be determined by measuring the surface impedance (Li et al., 2015b). To this end a probe, which can measure sound pressure and sound particle velocity simultaneously (p-u sensors), is positioned at a height of 30 to 50 mm above the surface. The pavement is then exposed to sound that is generated by a loudspeaker and the complex ratio of pressure and velocity is evaluated. The impedance measurement can also be performed dynamically with a driving vehicle (Bianco et al., 2020; Tijs and Bree, 2009).

2.5 Summary of Acoustical Field Measurements

The measurement of noise generation in asphalt pavements in the field is fairly well developed with a number of commonly used method. CPX is the most commonly used method in this field, followed by OBSI. CPX has an advantage in being able to identify pavement damage. On the other hand, SPB/CPB can measure both the generation and propagation of total noise, which can directly be compared with road traffic noise models such as CNOSSOS-EU (Kephalopoulos et al., 2012) or the American TNM to predict sound pressure levels at resident's houses. While the pass-by method give more details, they are more time consuming than CPX and OBSI, and researchers would have to decide the best option based on their available resources. A relation between CPX and SPB data can be established in a first order approximation by a transfer filter that maps CPX third octave band levels onto SPB/CPB levels by a frequency dependent additive correction (Anfosso-Lédée et al., 2016; Cesbron and Klein, 2017). Sound absorption by the impedance tube is also an option in the field and is an important criteria in pavement acoustical properties, and where the researcher can choose from a number of methods.

3 Acoustical Laboratory Measurements

Various laboratory acoustical techniques have been developed to evaluate acoustical properties of pavements. These methods include impedance tube measurements of sound absorption and measuring noise levels from simulating tire/road noise generation on lab-made pavement samples.

3.1 Drum Method

There have been a number of 'drum tests' developed to measure the sound generations of pavements, with the TIPANOS being a relatively recent example (Figure 6). The test tire (axial tire tread) rotates over the cylindrical asphalt sample (100 mm diameter and 150 mm length), the smooth support tires at the bottom are used to prevent the asphalt sample from bending, and are supposed to generate negligible sound levels compared to the test tire. A microphone is placed between the test tire and the asphalt sample at a distance of 250 mm. The sound data is recorded for 10 s and the A-weighted SPL is computed from this. Three asphalt samples are prepared for the same mixture and the test is performed at 22°C. The sound from the background is tested in advance and then subtracted (Kocak and Kutay, 2012). The issue with the smaller drum tests is that, while practical to perform, they do not fully reflect in-situ reality due to the tire/drum interface being highly curved and the asphalt surface being mounted on a diameter similar to that of the test tire. Furthermore, the contact surface is on the side of a gyratory compacted sample, so the contact surface is perpendicular to the direction of compaction, where it is parallel in-situ. Finally, the speed attained is only about 15 km/h which is lower than the speed critical (Heutschi et al., 2016) for tire/road noise being dominant.

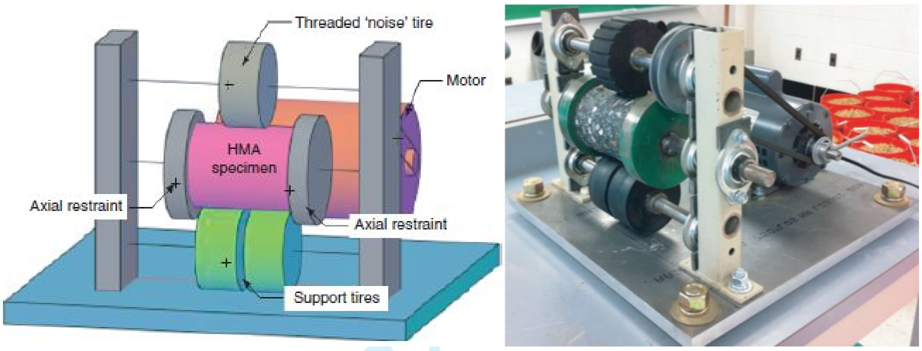

Figure 6 Experimental Setup of TIPANOS Drum Test (Kocak and Kutay, 2012)

Among the drum methods, larger drums are preferred to maintain a higher degree of pavement flatness, addressing the problem of the tire/road contact being unrealistic and are able to use standard treaded reference tires, such as the ASTM tires (Bernhard and McDaniel, 2005). The first of these larger tests are the drum facility developed at the Technical University of Gdansk (TUG), as presented in Figure 7, where a 5.4 m long, 0.2 m wide and 0.03 m thick pavement layer is placed around a 1.7 m diameter drum, and the noise is measure by CPX microphone conditions. This device is able to attain an impressive velocity of almost 100 km/h while (Sandberg et al., 2013; Wozniak et al., 2015), which is the highest speed attained for any drum test.

The Tire-Pavement Test Apparatus (TPTA) is a larger apparatus, which uses a series of 2.2 m long, 0.4 m wide and 0.08 m thick asphalt mixture arches (Figure 7). Six of these are placed around a 4.1 m diameter drum and do not seem to require as much ductility as the TUG test. The special compaction procedure do performed using Portland cement concrete melds and a steel roller supported on a loader performing the compaction. The melds and roller are heated to 55 and 75°C, respectively. An interchangeable tire travel along the surface and the noise is measured using OBSI microphone conditions, and the test can take several days to complete the noise measurements alone. While the samples sizes are larger, the top speed is only around 50 km/h (Kowalski et al., 2013). A promising new version of the TPTA by Han et al. (2000) has also been developed which addresses the difficulty in specimen preparation, with 12 samples of only 1 m length around the 4 m diameter drum. Additionally, it is able to achieve a speed of 70 km/h, with plans on increasing it to 100 km/h (Han et al., 2020).

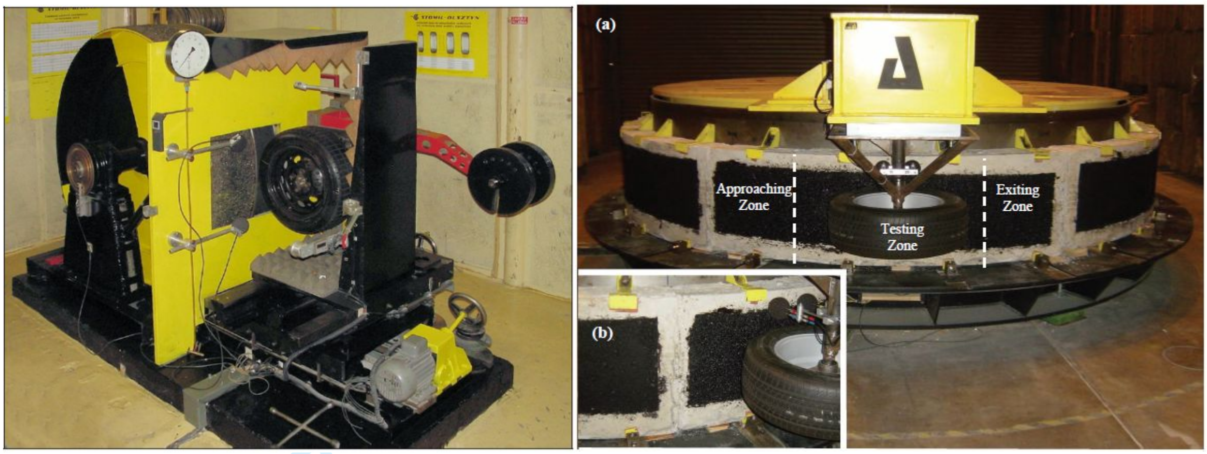

Figure 7 Left: Drum Facility at the Technical University of Gdansk (Sandberg et al., 2013); Right: Setup of Tire/road Test Apparatus (TPTA), where (a) Overview, (b) Setup of Microphones (Kowalski et al., 2013)

3.2 Tire Rolling Method

The Tire Rolling (TR) method was developed by the Pavement Research Centre of Chang'an University in China (Figure 8). The rolling rail is fixed with a pre-set angle that allows the tire to roll down from the top of the rail from a resting state. The tire is accelerated while rolling and impacts the surface of the asphalt sample (0.5 x 0.5 x 0.1 m) with a certain speed. It is assumed that negligible thermal energy is generated during the rolling of tire. The final speed of the tire is calculated on the basis of a free rolling down process. Two microphones are positioned beside the asphalt sample with a distance of 10 cm. The test is performed in a hemi-anechoic chamber to suppress reflections from walls and the ceiling. It should be noted that the speed (around 20 km/h) is lower than the speed where vehicle noise is dominant (Heutschi et al., 2016), so there is significant uncertainty in applying the data from this test to pavement models (Chen et al., 2019, 2018).

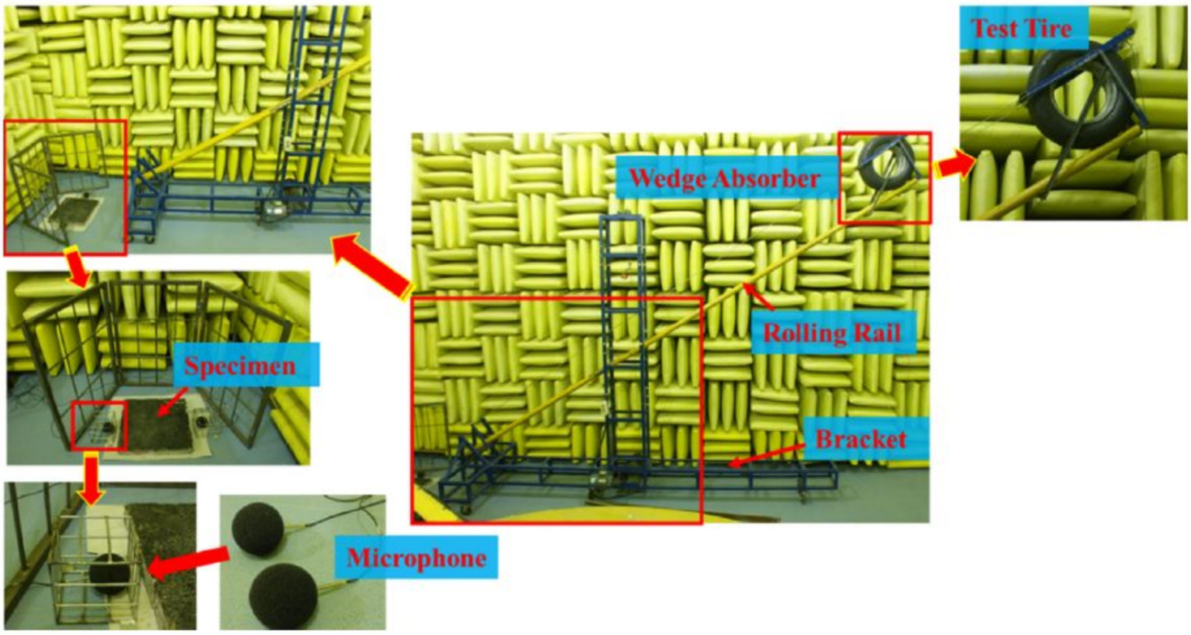

Figure 8 Experimental Setup of Tire-Rolling Method (Chen et al., 2018)

3.3 Impedance Tube Method for Sound Absorption

Figure 9 Experimental Setup of Sound Absorption by Impedance Tube (Vaitkus et al., 2017)

The sound absorption coefficient is defined as the ratio of energy absorbed by a material to the energy incident upon its surface. The measurement process for normal sound incidence has been specified in ISO 10534-2. As shown in Figure 9, a rigid tube is used for testing, in which one end of the tube has a sample holder and the other end is connected to a loudspeaker. Two microphones are inserted on either side of loudspeaker in the tube. The incident sinusoidal sound wave is generated by the loudspeaker and is reflected from the test sample. The superposition of incident and reflected waves, i.e. the standing wave pattern, is evaluated by the microphone. From the maximum and minimum sound pressure amplitudes, i.e. the standing wave ratio, the sound absorption coefficient of the material is determined.

3.4 Summary of Acoustic Laboratory Measurements

Sound absorption by the impedance tube is the most commonly used method to evaluate the acoustical properties of pavements due to its simplicity and the importance of sound absorption in pavement noise. However, the absorption property is only one of several aspects that determines the acoustical properties of a pavement. There have been a number of laboratory noise measurement techniques developed by various researchers, usually involving a tire rolling on an asphalt mixture for multiple cycles. The drum method is the most popular of these, but the smaller versions do not represent field conditions very accurately. Larger drum tests are also used and are more accurate, but also take much more resources in implementing, with the TPTA taking several days and significant resources.

4 Noise Relevant Non-Acoustical Measurements

In addition to the previously stated methods, there a number of noise relevant non-acoustical parameters that can be measured and used to estimate the acoustical properties of pavements. These parameters include surface texture, air flow and water permeability, along with a method combining a number of non-acoustical parameters. These parameters are also used as input to models that give an assessment of the noise reduction properties of a certain asphalt mixture (see Section 5). The test methods to acquire these parameters and relate them to acoustical properties will be discussed.

One otherwise important parameter is static porosity, or air void content (Martin and Putman, 2016). This is crucial for asphalt mixture acoustic properties, and nearly all other mixture properties.

Therefore, it is a base requirement for any asphalt mixture testing or research, and its testing is widespread enough not to be discussed in this review.

4.1 Surface Texture

Based on previous research and the guidelines in ISO 13473-1, the surface macrotexture (texture wavelength 0.5-50 mm) of the asphalt pavement surface layer, correlates with the acoustical properties of the pavement, making it an practical indicator for noise assessment. This relationship has been adopted to a number of pavement noise characterization techniques based on measuring the surface profile. However, the macrotexture-noise relationship changes within the macrotexture defined bandwidth, as a lower texture amplitude at wavelengths 2-8 mm has been correlated to higher noise emission at higher frequency (200-5000 Hz), while lower texture amplitude at 16-160 mm has been correlated to lower noise emission at lower frequencies below 800 Hz (De León et al., 2020; Del Pizzo et al., 2020; Losa et al., 2010). This trend seems to hold for low speeds as well as high speeds as shown in Figure 10 (Losa et al., 2010).

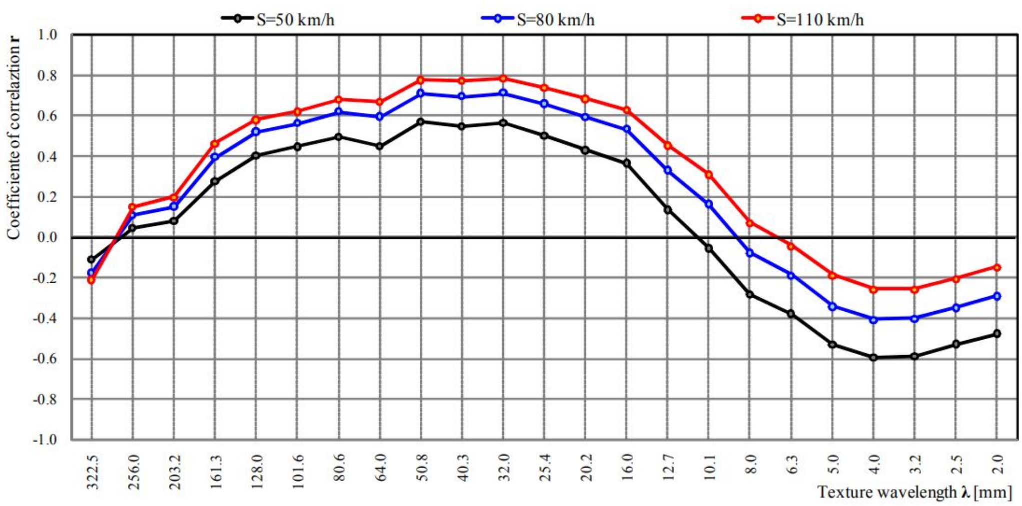

Figure 10 Correlation Coefficient (r) between CPX Noise Levels and Texture Wavelength (λ) for Three Speeds (S) (Losa et al., 2010)

The mean profile depth (MPD) is frequently used to describe the surface texture and is defined by ISO 13473-2, as the average depth of the surface over a 100 mm baseline. The correlation of noise with the MPD has given mixed results. For porous pavements, higher air voids will lead to higher MPD values, and indicate better acoustical properties (Sohaney and Rasmussen, 2013). However, dense pavements may have the opposite (Vázquez et al., 2020) or no MPD-noise correlation (Bueno et al., 2014b), so the parameter should only be used when in the context of having other data available. Surface texture can further be correlated to noise levels through the parameter texture skewness (ISO 13473-2). This can result in a positive or negative texture (Figure 11), with a negative texture indicating more deep valleys and less vibration-induced noise (Angst et al., 2016), although some have found no correlation with noise levels (McDaniel et al., 2014).

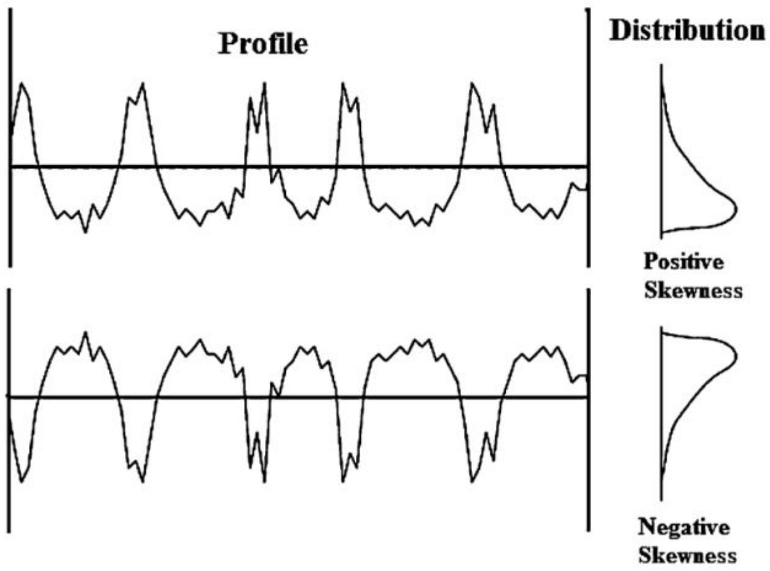

Figure 11 Example of Positive/Negative Skewness (Menezes et al., 2013)

4.1.1 Vehicle Mounted Laser Profilometer

Laser profilometers can be mounted on vehicles to measure the texture on long stretches of highway and determines the texture level based on (ISO 13473-2). An example is the Dynamic Laser Profilometer (Figure 12) at the Belgian Road Research Centre (BRRC), where a laser using a high sampling frequency and small beam diameter is mounted on a vehicle (Vuye et al., 2016). It can attain a vertical resolution of 1 μm in a 64 mm measurement range with an 80 km/h reference speed. The Laser DynamicPG-LA^{2}IC (Paje et al., 2013) a similar device (Figure 12), which adds a synchronized GPS location to the measurements.

Figure 12 Left: BRRC Dynamic Laser Profilometer (Vuye et al., 2016); Right: LaserDynamicPG-LA^{2}IC (Paje et al., 2013)

4.1.2 Stationary Laser Profilometry

Figure 13 Ames Engineering 9400HD 3D Laser Texture Scanner in Lab and In-situ

Stationary Laser Profilometry (SLP) can also be employed to determine the texture of a road. A laser scanner can be mounted on top of an in-situ pavement surface (Bueno et al., 2011) or laboratory produced asphalt samples. The scan then produces a profile of the surface from which the texture level (in dB), MPD and skewness can be derived according to ISO 13473-2. Newer models such as the Ames Engineering 9400HD (Figure 13) can attain resolutions of around 0.005 mm vertically, 0.006 mm along the length of the scan and 0.02 mm for the width (Poulikakos et al., 2019). Although this method can scan smaller wavelengths and areas than the vehicle mounted versions, it is able to scan more accurately and add the microtexture to the data.

4.1.3 Image Based Profilometry

The 2D Image Texture Analysis Method (2D-ITAM) can also be employed to determine the range and distribution of surface texture. The image of a sliced asphalt mixture sample is acquired with a 3D matrix from optical scanning, and is converted to a greyscale image represented by a 2D matrix. Due to the distance between the scanner and the sample, the areas of background and air voids in the image are close to black. Therefore, they can be removed from the image. By evaluating the remaining parts, i.e. the areas of asphalt/binder mastic and aggregate, the edge of mixture can be clarified. It is then possible to determine the surface profile of the sample (Chen et al., 2015). While this method is less practical than SLP, it may be useful in research where the clogging of porous asphalt field samples are also of interest (see Section 5.1).

4.1.4 Sand Patch Test

The Sand Patch Test (EN 13036-1) is a basic test to determine the macrotexture of pavements. As shown in Figure 14, the test is based on the volume of material on the surface and the area it covers. The quotient between the volume and the area is the mean texture depth (MTD), which can then be used to estimate the MPD (Eskandarsefat et al., 2018) so long as the depth is below 1.5 mm (Praticò and Vaiana, 2015).

Figure 14 Procedure of Sand Patch Test (Eskandarsefat et al., 2018)

4.2 Air Flow Resistivity

Air flow resistance is a non-acoustical parameter which is an important predictor of sound absorption in porous materials (Allard and Atalla, 2009). In the case of asphalt, it can be used as a descriptor of the tire/road air pumping noise generation (Beckenbauer et al., 2008). Flow resistance is the ratio of the static pressure difference across a porous material sample to the steady air flow velocity passing through the sample (Kleiner and Tichy, 2014). Flow resistance is expressed in Ns/m^3 or Pa s/m or per unit thickness of the material, in which case it is called flow resistivity, with units Ns/m^4 or Pa s/m^2.

Flow resistance can be measured using several types of equipment, as explained in ISO 9053-1. Most literature is focused on the laboratory measurements, however, some studies have performed in-situ air flow resistance measurements of porous pavements (Altreuther et al., 2008). In the laboratory, the air pressure difference is measured at the two ends of the material sample (diameter >95 mm) using a micro-manometer. The air flow velocity is measured using a flow meter. It is often recommended that the measurements are repeated for different asphalt samples due to the random distribution of the aggregates and pores (Kleiner and Tichy, 2014).

The flow resistivity can be used to predict the complex wave number and characteristic impedance of the material, both as a function of frequency (Allard and Atalla, 2009). This is often done using empirical formulas for example as in Delany and Bazley (1970). Using the calculated values for impedance, the absorption coefficient of the material can be calculated for different frequencies. This method is based on the assumption of normal incidence of the acoustic wave. Other authors have suggested different approaches (Dunn and Davern, 1986; Komatsu, 2008; Mechel, 1975; Miki, 1990). One limit of estimating sound absorption from air flow resistivity is that the empirical expressions of Delany and Bazley have been developed based on a sample set of highly porous materials with porosities of 90-99% (Vigran, 2014). Since even porous asphalt is only around 20% porosity, using these expressions for asphalt mixtures might not be accurate enough.

4.3 Water Permeability

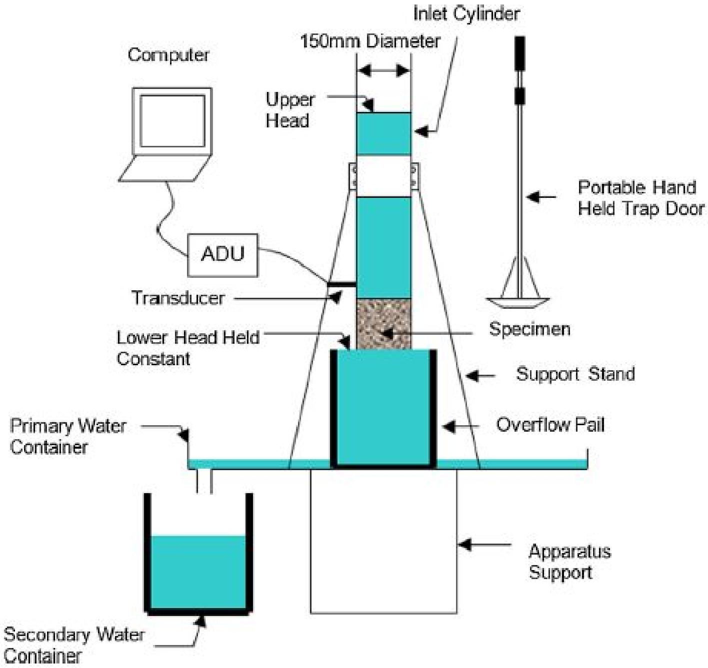

Figure 15 Diagram of Falling-Head Measuring Method (Chu and Fwa, 2019)

The falling-head method is developed to measure the permeability of porous asphalt (Figure 15). A head of water is allowed to flow through a 150 mm diameter asphalt samples. The variation in the upstream water level is collected to calculate the flow rate. The permeability coefficient is calculated based on the flow rate and the hydraulic gradient. This also allows the measurement of at placement permeability and also the effects of clogging by adding a clogging material to the top of the sample. The higher the permeability, the less clogged the permeable asphalt would be, and thus, the better the low-noise properties of the porous asphalt would be retained (Chu and Fwa, 2019). The limitation of this method is that in can only be used on permeable samples.

4.4 Dynamic Stiffness

The dynamic stiffness test has been used to measure vibration properties of pavements (Vázquez and Paje, 2016). The set-up consists of a vibration exciter, an amplifier and an impedance head and a multi-analyser system to perform the measurements (Figure 16). The vibration exciter is placed upside down, with the impedance head is in contact with the ground through a circular plate fixed to the surface. Sweep signals between 10 Hz and 7 kHz are used for the excitation of the samples. The dynamic stiffness is determined by means of the ratio between force and motion signals and presented as a function of the vibration frequency. It can be performed in-situ or on cored/ laboratory prepared samples. The higher stiffness can be an indicator of more sound generated by the pavement through the vibration mechanism (Vázquez et al., 2016).

Figure 16 In-situ measurements of the dynamic stiffness of pavements (Vázquez et al., 2016)

4.5 Multiple Property Indirect Noise Testing

Angst et al. (2012) proposed the IMPACT (Investigation Machine for Pavement Acoustic Durability) method aims to estimate the acoustic durability of low-noise pavements based on the testing of several non-acoustical parameters on the same laboratory asphalt sample (Figure 17). The tire moves back and forth to simulate the tire/road interaction. It is possible to adjust several different parameters, including temperature, wheel spin, wheel load, rolling cycle, type and pressure of tires. The asphalt sample with good longitudinal evenness, especially after loading, is necessary for the test. The driving speed (3.4 km/h) and duration of load cycle (2s) follow the process of the wheel track rutting test (EN 12697-22), but is significantly slower than a normal vehicle. A hood covering is used to keep a constant temperature, and noise levels are calculated using the SPERoN model (see Section 6.4) rather than direct measurements. SPERoN uses various input parameters of the road surface, such as air flow resistance, macrotexture, mechanical impedance and sound absorption. As with the laboratory acoustical methods, the laboratory tire velocity is much smaller than during field noise generation, but a number of parameters not dependent on the velocity are nevertheless attained.

Figure 17 Experimental Setup of IMPACT (Angst et al., 2012)

4.6 Summary of Non-Acoustical Testing

Texture profiling, specifically when analysed by different texture wavelengths by laser scanning, have been correlated with noise characteristics of asphalt pavements, and can be done on either lab or field samples. Airflow resistivity measurement is another important method which can provide information on the acoustical properties.

5 Low-Noise Pavement Types

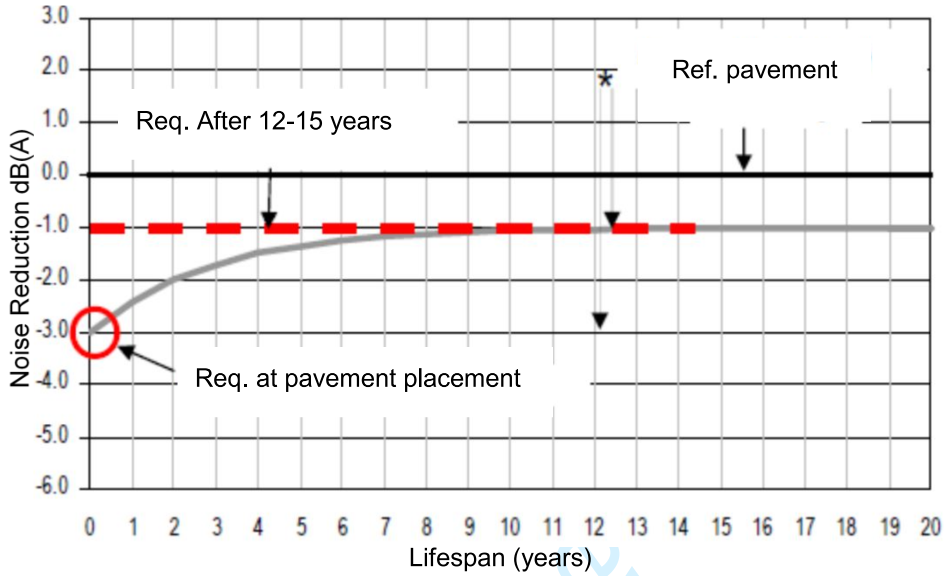

Figure 18 Pavement Noise Requirements in Switzerland (Bühlmann et al., 2017)

The exponential increase in urban vehicle traffic in the 19th and 20th centuries resulted in the development of new pavement types and the consideration of their dust resuspension and acoustical properties. In the 19th century, some US roads were made from wooden blocks to replace noisier cobblestones. The early 20th century saw the introduction of more durable asphalt pavements, which were was also a major improvement on cobblestone in terms of noise. From late 20th century onward, a number of asphalt pavements have been developed that have had "low-noise" as a feature (Sandberg and Ejsmont, 2002). Low-noise pavements are typically defined as achieving -3 dB(A) relative to a reference dense mixture. The reference dense mixture was defined by a recent EU project as dense asphalt concrete (DAC) 0/11 or stone mastic asphalt (SMA) 0/11 (Anfosso-Lédée et al., 2016). Some places like Switzerland extend this definition to maintain a minimum -1dB(A) after 12-15 years of service life (Bühlmann et al., 2017) as shown in Figure 18. The following section will discuss the various pavement types used with the objective of reducing the noise.

5.1 Porous Asphalt

Porous asphalt concrete (PAC) or open graded asphalt concrete (OGAC) is the most common type of low-noise pavement. While the aggregate structures of dense asphalt pavements are designed to pack as many voids as possible, porous asphalt consists of gap graded aggregate structures that allow a high amount of voids space (>20%) to form in the layer while still maintaining stone to stone contact and stability in the remaining aggregate. Besides having better acoustical properties, they are designed for better storm water management (Chu and Fwa, 2019), improving skid resistance during severe rain and allowing underground aquifers to be more efficiently refilled. PAC is limited by certain weaknesses however, as the mechanical performance is generally weaker.

Table 2 Reduction in SPL of Single Layer PAC Compared to Dense Asphalt in Selected Studies

Author	Noise Reduction dB(A)	Ref. Surface	Test Method
Simpson et al., 2014	5	DAC	SPB
Donavan, 2014	7-11.5	DAC	OBSI
Lu et al., 2011	2.3	DAC	OBSI
Russel et al., 2010	3.5	DAC (1/2 inch HMA)	OBSI
Shimeno et al., 2010	3	DAC	CPX
Ongel and Harvey, 2010	3-3.2	DAC	OBSI
Pierce et al., 2009	3-5	DAC	OBSI
Freitas et al., 2009	2.9-3-6	DAC	CPB

Numerous researchers have shown the low-noise properties of PAC. Field measurements of noise on roads have shown porous asphalt to be significantly better in acoustical properties compared to dense asphalt pavements, including with CPX (Li et al., 2015a; Pierce et al., 2009; Shimeno et al., 2010), SPB (Freitas et al., 2009; Simpson et al., 2014) and OBSI (Donavan, 2011, 2014; Liao et al., 2014; Lu et al., 2010b, 2011; Ongel and Harvey, 2010; Russell et al., 2010). The noise reduction has also been shown when comparing porous and dense concrete pavements (Tian et al., 2013). This has been quantified by a number of studies (Table 2), normally at around 3-3.5 dB lower compared to DAC, but it should be noted that this all depends on the many variables ranging from the pavement properties to field conditions.

The improvement in the acoustical properties of porous pavements can be linked to their sound absorption characteristics (Chu et al., 2017). Many works have shown that the sound absorption is higher in PAC than in DAC (Guo et al., 2012; Li et al., 2015a; Luo et al., 2015; Vaitkus et al., 2017), resulting in less tire/road noise being reflected to the surrounding environment. Additional noise mechanisms reduced by increased porosity are the air pumping, horn and pipe effects (Sandberg, 2009). These properties does not only depend on the volume of air voids, but rather by the interconnected voids (Knabben et al., 2016).

In addition to physical measurements, the noise reduction potential of PAC has also been found in psychoacoustic listening experiments that measured the effects on short-term noise annoyance (Freitas et al., 2012; Mendonça et al., 2013). This may also be related to the fact that the spectral centre of gravity of the sound is shifted to lower bands with PAC (Bendtsen et al., 2009), by about 200 Hz in one study (Donavan, 2014). This is in line with increased acoustic absorption found at higher frequencies (Li et al., 2015a; Luo et al., 2015; Ongel and Harvey, 2010). It was found that smaller aggregate sizes in porous pavements further reduce noise (Freitas, 2012; Praticò and Briante, 2020; Russell et al., 2010). Furthermore, during periods where the road is wet, for which pavement noise increases (Raimundo et al., 2010), porous asphalt has also been shown to have reduced noise due to superior water drainage properties (Freitas et al., 2009).

The main weakness of porous asphalt is its durability and mechanical performance, particularly with durability. Porous asphalt has been shown to be weaker that dense asphalt in terms of indirect tensile strength (Vaitkus et al., 2017), in terms of ravelling (Bergiers et al., 2014) and sometimes a lower stiffness modulus (McDaniel et al., 2014). This is due to the aggregate structure having more voids and less contact points within the asphalt matrix, resulting in higher loads for a given contact point. On the other hand, the rutting resistance of PAC is higher due to the predominance of stone to stone contact taking the loading compared to the more plastic-like binder (Wu et al., 2020).

The moisture resistance of the asphalt mixture has also shown to be worse (Vaitkus et al., 2017) and more water can stay in the porous asphalt, especially when clogging becomes an issue. Additionally, the higher pore volume exposes more surface area of the binder to water and temperature resulting in more of the binder being aged. These weaknesses require porous asphalt mixtures to have more resilient binders, such as those with polymer modification (Luo et al., 2015). The binder content is also critical due to binder drainage issues, which results in less effective binder in the mixture (Afonso et al., 2017; Hamzah et al., 2012).

Additionally, it is susceptible to clogging (increased maintenance cost), which can lead to a significant reduction of noise and skid resistance properties. Studies have shown that the noise reduction advantage of porous asphalt relative to dense asphalt decreases over time (Bendtsen et al., 2009; Kohler et al., 2009; Paje et al., 2009; Pierce et al., 2009), sometimes to having the same performance (Alabaster et al., 2012; Chu et al., 2017), as shown in Figure 19. The open aggregate structure of porous asphalt allows material from the outside environment to enter, filling the pores that allow for noise reduction and drainage, without improving the mechanical performance (Gardziejczyk, 2016). This can be remedied by maintenance strategies such as power washing through the pores (Hamzah et al., 2013), but adds an additional cost consideration for road authorities.

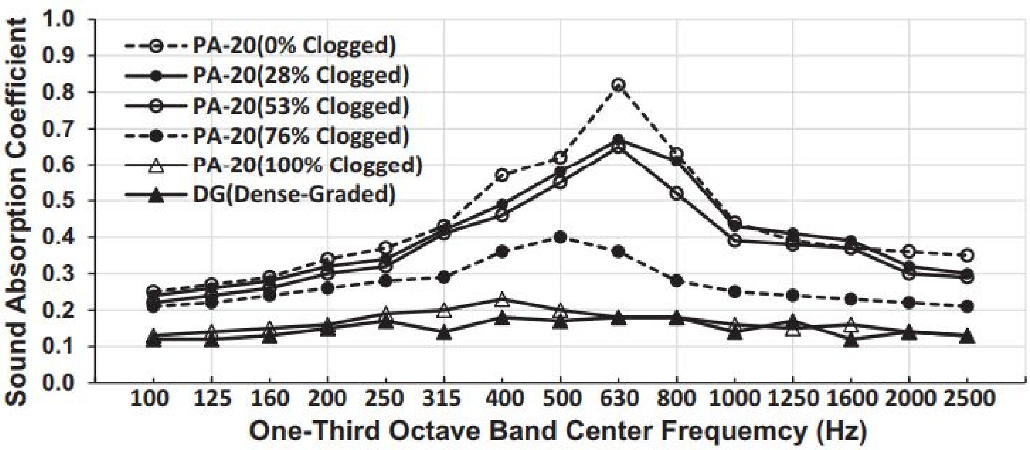

Figure 19 Effect of Clogging on the Sound Absorption of PAC and DAC, both with 16 mm Max Aggregate Size (Chu et al., 2017)

5.1.1 Double Layer Porous Asphalt

Double layer of porous asphalt or two-layer porous asphalt (DPAC) leverages the ability to place two different mixes in order to improve on the properties of the single homogenous layer PAC. In all cited cases, this refers to a lower layer with a larger maximum aggregate size and an upper layer with a smaller aggregate size (Morgan, 2008). In theory, the smaller stones in the upper layer provide a better driving surface than if the configuration was the other way around, as well as have smaller openings for potentially clogging debris.

The main advantage of the DPAC design is the ability to retain noise reduction properties over time by resisting clogging (Hamzah et al., 2013). One study found DPAC to generate less noise at placement (-5 dB) compared to regular PAC (Sandberg and Mioduszewski, 2012). This has been confirmed through the improved absorption properties of the double layer pavements with the same thickness (Chu and Fwa, 2019). Some studies have had contradictory findings however, as one model found better noise reduction in the single layer PAC (Liu et al., 2016), although the model pore structure was somewhat crude. Also, an experimental study found that the double layer had more issues with clogging (Chu and Fwa, 2019). This may be dependent on the properties of the mixture constituents, but the major part of studies conclude that DPAC is better in both noise and clogging over the single layer variant. The double layer may also be more cost intensive in terms of having to have to make and place multiple mixtures, although this would depend on the available equipment.

5.1.2 Semi-Dense Asphalt

Semi-Dense Asphalt (SDA) is based on the same concept as PAC, with the same gap graded aggregate skeleton. In order to improve the mechanical properties compared to PAC, the target air voids are reduced to 12-16 %. The gradation also typically uses a smaller 4 or 8 mm maximum aggregate size (Poulikakos et al., 2019). In Spain and in Switzerland (SN 640 436) especially, it is commonly placed for low-noise purposes (Steiner et al., 2018).

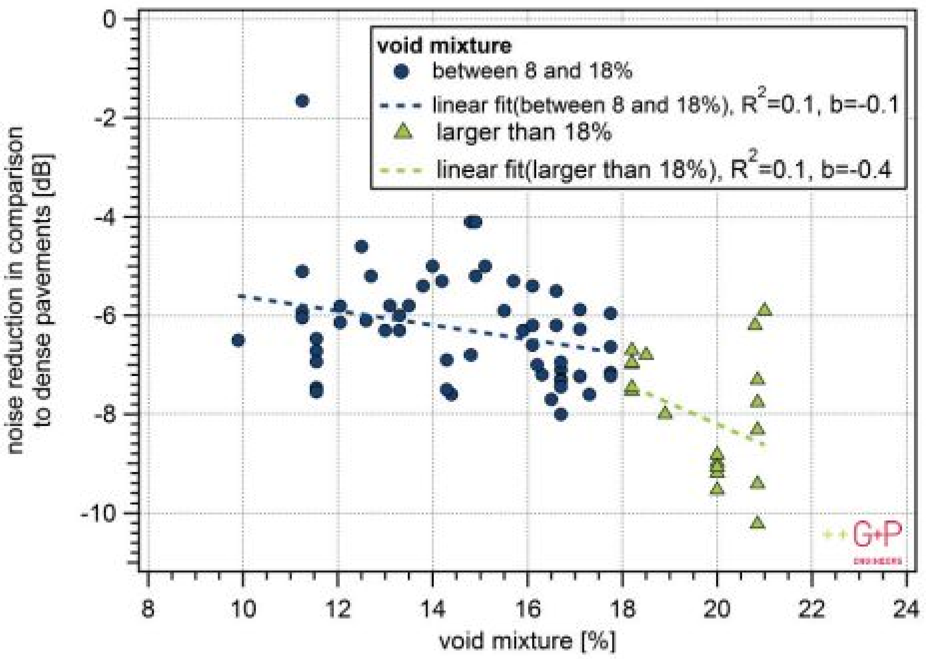

Figure 20 Relationship between Noise Reduction and Air Voids for SDA (left) and PAC (right) with 8 mm Max Aggregate Size (Bühlmann and Hammer, 2017)

SDA has been found to produce less noise than dense asphalt pavement, which has been attributed to its higher porosity and improved sound absorption characteristics (Li et al., 2015a; Losa et al., 2013; Poulikakos et al., 2019). The maximum sound absorption of SDA occurs at lower frequencies compared to PAC (Chu et al., 2017), but has a higher amplitude overall (Bühlmann and Hammer, 2017). As with PAC, the low-noise performance of SDA decreases over time (Beltzung and Balmer, 2020) with weathering and clogging of voids and the connections between them (Figure 20). It has been demonstrated that lowering the content of sand and fines in the SDA mix design are critical for noise reduction longevity (Bühlmann and Hammer, 2017).

The modulus of SDA was found to be only somewhat lower than for dense asphalt (Pérez et al., 2010). With gradation, SDA with a 4 mm maximum aggregate size was found to have better acoustical properties than one with 8 mm (Angst et al., 2016), as well as better homogeneity. The noise reduction of SDA is less pronounced with decreasing depth in the tire tread (Angst et al., 2011).

5.2 Crumb Rubber Modified Asphalt

Due to the prevalence of end-of-life tires, the incorporation of crumb rubber (CR) into asphalt has been practiced as early as the 19th century (Mashaan et al., 2014). The rubber is processed to reduce the particle size and sometimes treated or pre-swelled (Figure 21). The incorporation can be done during the asphalt mixing in what is known as the dry process or pre-mixed with the asphalt binder in the wet process. The rubber modification provides a method to valorise tire waste and potentially improve the mechanical performance of asphalt mixtures. Many studies have also looked at the way CR influences noise performance in DAC.

Figure 21 Crumb Rubber from Recycled Tires (Sandberg et al., 2011)

5.2.1 Dry Process

The dry process of CR asphalt mixtures includes the addition of rubber during the mixing phase with the aggregates and binder. One study using the CPX method (Paje et al., 2010) reported a reduction of 2 dB relative to DAC. Another study, using a Romanian method (pass-by), found a 1-6 dB reduction of CR modified DAC compared to the reference DAC (Herisanu and Bacria, 2013). However, it should be mentioned that the aforementioned studies did not record the air void content of each mixture, which could have contributed to these results. A different study with OBSI found CR asphalt as somewhat more noisy (Pierce et al., 2009), and other CPX studies have found no significant difference (Eskandarsefat et al., 2018). The former study limited the rubber content to only 0.5% of the mixture mass. Therefore, it is possible that there is some optimal CR content to achieve acoustical and mechanical performance.

The main noise reducing mechanism of dry process CR pavements is the lower macrotexture, affecting the air pumping and tread impact mechanisms. The addition of rubber was found to reduce the megatexture (IRI) (Pierce et al., 2009) and macrotexture (MPD) (Paje et al., 2010). A study measuring the macrotexture and microtexture found that both of these decreased with rubber addition (Eskandarsefat et al., 2018). It has also been shown that the initial noise reduction of rubberized mixtures tend to disappear after a few years of service life (Lu et al., 2010b, 2011), this is primarily due to clogging or changes in surface texture. On the other hand, the pavement can also be noisier if it is made overly sticky by the CR addition, enhancing the snapping mechanism after the tire makes contact with the pavement (Ongel and Harvey, 2010).

The Indirect Tensile Strength (ITS) and Indirect Tensile Strength Ratio (ITSR) of 1% CR modified mixtures using the dry process was found by some to not be very different from the control mixtures (Eskandarsefat et al., 2018), although another study found it significantly lower at a 2.5% aggregate replacement rate (Mikhailenko et al., 2020). The modulus of the CR mixture was found to decrease at lower temperature/frequencies (Mahmoudi et al., 2020). However, the rutting resistance (Cao, 2007) and fatigue resistance (Moreno-Navarro et al., 2016) of the dry process mixtures was found to improve in comparison to non-modified mixtures. A significant economic concern about working with the dry process is the crumb rubber reducing the effective binder content by absorption (Eskandarsefat et al., 2018), requiring more to be added in compensation.

5.2.2 Wet Process

The noise performance for mixtures with CR modified binder – also known as the "wet process" (usually at 5-10% by weight of the binder) – showed mixed results. It has been shown by some that rubber addition to the binder can help increase the sound absorption of the asphalt relative to mixtures with straight run binder (Freitas and Inácio, 2009; Kocak and Kutay, 2012; Lu et al., 2010a; Paje et al., 2013; Vázquez et al., 2016), while other studies found negligible differences (Knabben et al., 2016; Ongel and Harvey, 2010). The macrotexture MPD (Paje et al., 2013; Vázquez et al., 2016) of the mixture with rubber modification was found to decrease with CR modified binder.

In terms of SPL, some studies have shown the reduction of noise with wet CR mixtures by CPX (Świeczko-Żurek et al., 2017) and by TIPANOS model measurements (Kocak and Kutay, 2012). Long-term studies have found that this initial noise reduction decreases over a period of 3 years from 1.8 to 1.3 dB (Vázquez et al., 2016). But several other studies have found that rubber modified asphalt binder mixtures do not significantly reduce the SPL compared to PmB mixtures CPX (Bueno et al., 2014a; Freitas, 2012; Paje et al., 2010).

Although the noise performance is not clear, the wet process has been shown to improve the asphalt mixture modulus at high temperatures (Kocak and Kutay, 2012) and increase the dynamic stiffness (Vázquez et al., 2016), indicating resistance to permanent deformation but possibly indicating more noise from tread impact. This is followed by improved performance in mixture rutting resistance (Shirini and Imaninasab, 2016; Świeczko-Żurek et al., 2017). On the negative side, the stiffness modulus at temperatures below 0°C has been found to be lower compared to conventional dense mixtures (Gallego et al., 2007; Qiu et al., 2011). The indirect tensile strength performance results have been found somewhat lower with CR binder (Knabben et al., 2016), with the tensile strength ratio (TSR) results being mixed, some finding improvement (Qiu et al., 2011), while others report reduction with CR (Kim et al., 2014). The CR addition by wet process was found to improve the fatigue performance of the mixtures (Gallego et al., 2007; Kim et al., 2014).

5.3 Poroelastic Road Surface

Poroelastic Road Surface (PERS) is a non-asphalt based composite road surface originally developed in Sweden at the end of the 1970s, and later developed further in Japan, Sweden and the Netherlands in the 21st century (Sandberg et al., 2013). It consists of a hard aggregate with a low maximum size of 4 mm, a high rubber content of around 15-40% and a polyurethane binder (Figure 22). It is also porous with a voids content of 20-35% (Mioduszewski et al., 2018). Previous versions used very high rubber contents of over 70% and proved unsuccessful because of poor ravelling, sub-layer bonding and skid resistance (Goubert et al., 2019).

Noise measurements similar to the CPX method at the Technical University of Gdansk showed a 9-10 dB reduction in PERS compared to a dense graded 12mm asphalt mixture, especially at frequencies of 1000-2000 Hz (Sandberg et al., 2013). Noise reduction of 7-12 dB were reported in other studies (Skov et al., 2015). Significant increase in sound absorption in PERS was also found (Sandberg et al., 2013). The noise reduction comes from the porosity and also the texture, as PERS has a relatively low

MPD macrotexture provided by the smaller aggregates, while having a higher microtexture to ensure skid resistance (Skov et al., 2015). The high elasticity may also dampen the tread impact mechanism.

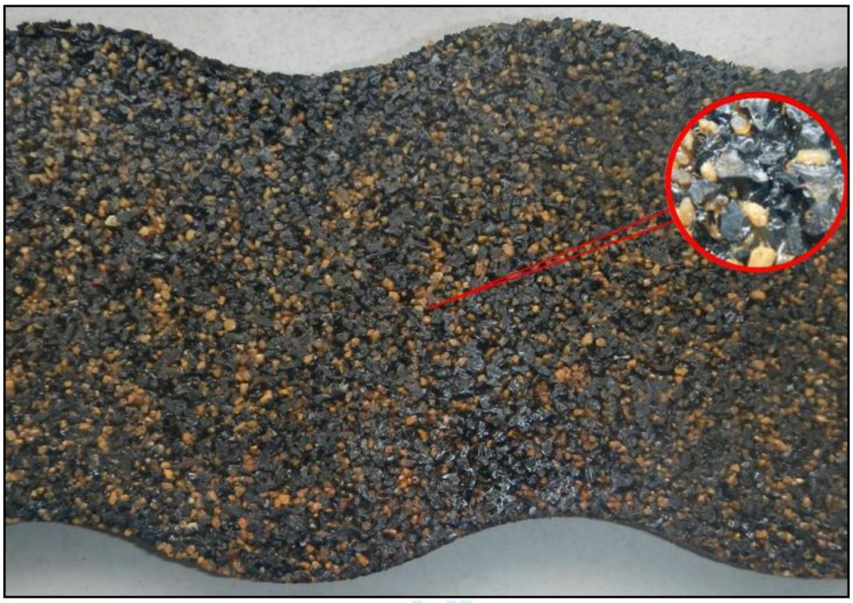

Figure 22 Poroelastic Road Surface (PERS) (Sandberg et al., 2013)

PERS does provide challenges in terms of resistance to rutting, meaning it is important for the non-rubber aggregates and binder to be as hard as possible. As a tradeoff however, the skid resistance is higher due to the softer nature of PERS as well as the higher voids content. The ravelling resistance results were comparable to dense asphalt (Sandberg et al., 2013). Another challenge in using PERS is the lack of bonding to the lower layers, where the experience has been mixed in this regard (Goubert et al., 2019).

5.4 Stone Mastic Asphalt

Stone Mastic Asphalt (SMA) is a high binder content, usually low maximum aggregate size (below 12.5 mm), gap-graded asphalt mixture used to provide a high friction (high microtexture) surface layer for the pavement (Figure 23). It was developed in Germany in the 1960s and is often used as the pavement surface for high traffic areas where a quality surface layer is important (Morgan et al., 2006).

In terms of noise emission, SMAs have been found by numerous studies to perform about the same as dense surfaces in terms of amplitude (Kocak and Kutay, 2012; Kragh et al., 2012; Miljković and Radenberg, 2012), wavelength (Rasmussen and Sohaney, 2012). Sound absorption was found to be similar to dense asphalt as well (Vaitkus et al., 2017). This is likely why it is recommended as a reference pavement alongside DAC (Anfosso-Lédée et al., 2016). However, there were studies that found some noise reduction with SMA compared to dense asphalt (Maeck and Bergiers, 2016; Simpson et al., 2014) but others also found it to be significantly more noisy than porous asphalt (Bergiers et al., 2014; Sandberg and Mioduszewski, 2012).

Due to the dense and impervious nature of SMA however, the noise performance decreases less over time compared to more porous pavements (Ho et al., 2013). One study found that the noise advantage of PAC over SMA is practically eliminated after 3 years of service due to higher clogging and deterioration (Gardziejczyk, 2016).

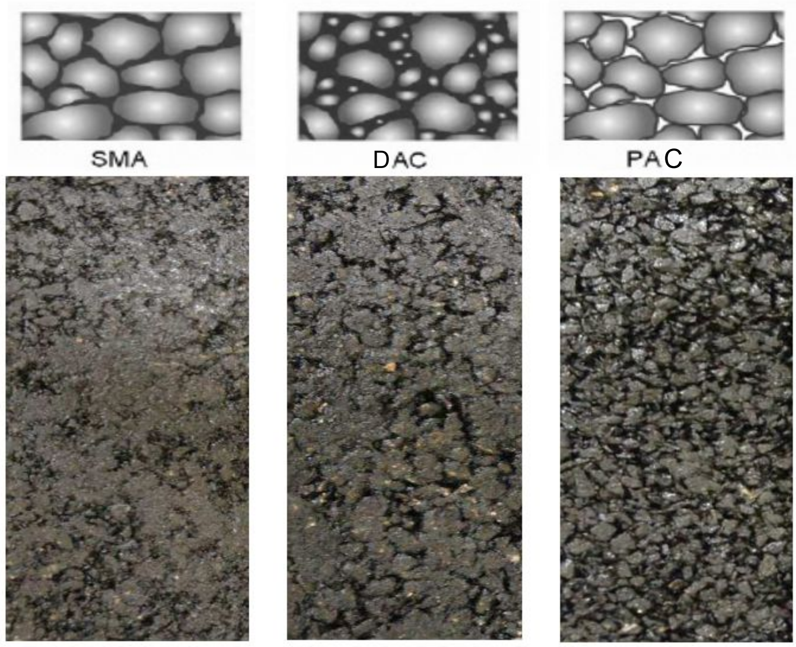

Figure 23 Examples of Pavement Surface for SMA, DAC and PAC (Remisova et al., 2014)

The MPD values of the SMA tends to be higher for pavements with similar aggregate size in terms of macrotexture (Kowalski et al., 2013; Remisova et al., 2014) and microtexture (Maeck and Bergiers, 2016). The mechanical properties of SMA have been found to be superior to porous and dense asphalt in terms of indirect tensile strength, moisture resistance and freeze thaw resistance (Vaitkus et al., 2017).

A low noise version of SMA, known as SMA LA has been developed in Germany. A noise decrease of 2.5-4.0 dB by CPX is achieved compared to DAC by increasing the air voids content to 9-14% (Gardziejczyk et al., 2020). This air void content, similar to SDA, is clearly the factor in the low noise properties.

5.5 Thin Layer Asphalt Pavements

Like in the case of stone mastic asphalt, there have been a number of thin asphalt layer (TAL) pavements, advertised as being low-noise (Vuye et al., 2016), including Beton Bitumineux Trés Mince (BBTM) and Ultra Thin Layer Asphalt Concrete (UTLAC). They also have a lower maximum aggregate size (below 12 mm) and higher binder content. As they are thin, they cannot be relied on to improve the pavement sound absorption properties significantly, but can alter the tire/road interaction properties. The main idea is to provide a high quality surface while not having to invest in a high volume of expensive high quality normal depth pavement (Sandberg et al., 2011).

Noise related studies on dense TAL pavements show that they tend to perform about the same as dense asphalt (Gardziejczyk, 2016; McDaniel et al., 2014). The sound absorption is also quite similar to dense asphalt except for higher frequencies of 1.25-1.6 kHz (McDaniel et al., 2014). The TAL that have shown to be better in acoustical properties than dense, were optimized with a higher air voids content (around 13-18%), where their optimized texture may play a role in improving the efficiency of the noise reduction (Sandberg et al., 2011; Vuye et al., 2016). The TAL friction properties are better, with higher MPD macrotexture (Maeck and Bergiers, 2016; Vuye et al., 2016) and lower rolling resistance (Sandberg et al., 2011). Similar to SMA, they show good mechanical performance but have not been shown to be effective as low-noise pavement solutions.

5.6 Low-Noise Cement Concrete Surfaces

Portland cement concrete (PCC) pavements represent a small fraction of the pavements worldwide but are desirable in certain conditions. Generally, their higher rigidity and the surface grooves needed for adequate skid resistance (Kuemmel et al., 2000) mean that they are significantly more noisy than DAC (Pinay et al., 2020). Exposed-Aggregate Cement Concrete Pavement (EACCP) adds a modifier on top of the PCC after placement, which results in having exposed aggregates on the surface. Comparison studies have shown that this pavement is 1-5 dB quieter than ordinary PCC pavement (Samuels and Parnell, 2001; Zhang et al., 2014), but otherwise having noise performance similar to DAC (Samuels and Parnell, 2001).

A quieter PCC pavement in development is the Next Generation Concrete Surface (NGCS), which modifies the surface grinding of the pavement in order to reduce the amount of air trapped between the tire and the non-porous concrete surface (Scofield, 2017). OBSI measurements with other pavements showed that NGCS is up to 5 dB quieter that the conventional PCC pavement and 1.5-2 dB quitter than the 9.5 SMA in the comparison (Mogrovejo et al., 2014). More studies are needed to confirm the validity of these findings.

5.7 Summary of Low-Noise Pavement Types

The principal findings with regard to low-noise pavement types are shown in Table 3. Among all the asphalt pavement types discussed, PAC has shown to have the best low-noise properties. This is due to the improved sound absorption properties and also the ability of the pavement surface to allow for air to penetrate. However, PAC has some weaknesses in moisture resistance and ravelling, which lower the overall service life. Additionally, clogging is an issue with this type of pavement, reducing its noise performance over time. Improvements in PAC design such as DPAC's can reduce the amount of clogging that occurs over time. SDA on the other hand, is better in mechanical performance than PAC, while being somewhat worse in terms of noise reduction and susceptibility to clogging. Smaller aggregate size can provide improved acoustical properties to porous pavements PAC or SDA.

The noise performance of asphalt mixtures with dry and wet process CR addition has shown varied results and will depend on the type of mixture and environmental conditions such as temperature and humidity. The noise performance may be improved if the rubber can lower the macrotexture. The main positives from the rubber modification come from the use of waste materials in the road, and some mechanical benefits with CR modified binder in terms of rutting and fatigue resistance.

Where PCC pavements are desired, the surface grinding in NGCS has shown to reduce the sound generation significantly. However, more studies are needed to confirm the validity of the initial findings and evaluate the performance over time.

In the case of non-porous asphalt pavements like SMA and TAL, while having good road friction properties, generally have the same acoustical properties as DAC. The cases where fine graded pavements do improve the acoustical properties are those where they have high porosity such as in the case of PERS. In the latter, the high porosity, along with the lower macrotexture and lower stiffness of the rubber modified mixture appear to reinforce each other in terms of lowering the pavement noise.

Table 3 Summary of Low-Noise Pavement Types

Asphalt Pavement Type	Noise Mechanism Reduced	Advantages	Disadvantages	Reduction in dB(A) Rel. to Ref. at t=0
Porous Asphalt Concrete (PAC)	Air pumping, Horn effect, Helmholtz resonance, Pipe effect	Very good levels of sound absorption and noise reduction Good drainage properties	Durability issues with strength, moisture resistance and ravelling, lowers service life Some clogging issues reducing noise improvement over time	2-12, but normally around 3-3.5
Double Layer Porous Asphalt Concrete (DPAC)	Air pumping, Horn effect, Helmholtz resonance, Pipe effect	Similar sound absorption and noise reduction to PAC Less clogging issues than for PAC	More complicated placement Same durability issues as PAC	Around 8
Semi-Dense Asphalt (SDA)	Air pumping, Horn effect, Helmholtz resonance, Pipe effect	Improved durability properties compared to PA Improved noise reduction compared to dense asphalt	Less noise reduction than PAC More clogging issues compared to PAC Durability issues with moisture resistance and ravelling	5-7, but less than PAC in similar conditions
Crumb Rubber – Dry	Air pumping, Tread impact	Use of recycled material Can improve some mechanical properties of asphalt such as resistance to fatigue	Generally has not been shown to provide noise reduction	0-2 dB, mostly no effect
Crumb Rubber – Wet	Not clear	Use of recycled material Improvement in rutting and fatigue resistance	Inconsistent results with noise reduction	Mostly no effect
Poroelastic (PERS)	Air pumping, Stick-slip, Tread impact, Stick-snap, Horn effect, Helmholtz resonance, Pipe effect	Superior noise reduction properties Good skid resistance	Can have high susceptibility to rutting Lack of adhesion to lower layer Ravelling issues	8-12
Stone Mastic	Stick-snap	Good skid resistance Good durability	Same noise and absorption properties as	Mostly no effect, 2.5-4

Asphalt (SMA)		Noise reduction with SMA LA	dense asphalt for normal SMA	dB for SMA LA
Thin Asphalt Layer (TAL)	Stick-snap	Good skid resistance	No significant noise improvement without higher air voids	Mostly no effect
Next Generation Concrete Surface (NGCS)	Air pumping, Horn effect, Helmholtz resonance, Pipe effect	Allows implementing PCC pavements with noise somewhat lower that conventional SMA.	Modest noise reduction compared to PAC Low amount of research	1.5-2 compared to SMA

6 Modelling

6.1 Earlier works

In order to help the building contractors including the acoustic performance in the design of low-noise pavements, different numerical models have been developed as a practical tool for predicting road traffic noise. Moreover, these models have played a main role for the understanding of the physical mechanisms governing tire/road noise. In this section, we review the most significant works and explain which factors are taken into account to describe the phenomena.

First, it is worth to mention the review recently carried out by Li et al. (2018) where more than 70 models were analysed from nearly 200 different publications. This effort covers early attempts that include the first air-pumping model developed by Hayden (1971) and based on monopole theory focusing on the noise generation at the leading edge of the tire contact patch where the tread is compressed. The review also commented on the investigations by Heckl (1986) of multiple tire/noise generation mechanisms such as tire vibration, air pumping, pavement texture impact, stick/slip and sound radiation from the tire. In addition, they observed that most of the early models focused only on passenger car tires. Due to the increased development of porous asphalt pavements and with it, new parameters that need to be considered, new models started including sound absorption and mechanical impedance as the relevant parameters. The authors divided their selection in 3 categories: deterministic models, statistical models, and hybrid models. It is explained that deterministic models usually require a large number of tire parameters, are limited to the frequency range of below 500 Hz and contain no experimental validation. The statistical models, including traditional regression models, are focused only on experimental correlations between noise levels and usually only use variables related to the pavement without the knowledge of the underlying mechanisms. Consequently, these models involve high labour cost but the obtained results show better accuracy. More recently, the tendency has shifted to the development of hybrid models. These combine the understanding of noise generation mechanisms through physics and computational fluid dynamics models with more precise experimental data consequence of the acceptance of on-board noise measurement techniques to obtain noise data for a longer duration with little environmental influence.

6.2 Recent works

As a complement to that extensive review discussed above (Li et al., 2018), we need to describe some of the most significant modern models, which optimize the main design parameters affecting the sound generation (e.g. porosity and surface texture) and taking into account novel pavement designs (e.g. thin layers or double layer porous pavements). For the first time, in his work, Pinnington (2012) presented an algebraic model of a general surface to cover the full wavelength range for tire/road interaction (i.e. tires, radiation, friction and contact). He arranged different roughness orders of magnitude representing a size distribution of the particles by using measured road profile data in the range of about 100 m to 0.1 mm. This modelling is based on the physical structure and formation processes, and includes asymmetry between the upper and lower surfaces due to wear.

Some years earlier, Losa et al. (2010) described an empirical rolling noise prediction model based on dense asphalt surfaces with medium-low macrotexture levels. These texture levels are influencing sound generation mechanisms at high and low frequencies at different speeds and were used as predictors in a multivariate linear regression model. Similarly but focused on rigid pavements, Rasmussen (2009) identified the fundamental links between texture and noise level by measuring and modelling tire/road noise on various Portland cement concrete surfaces with different textures. Later on, Losa and Leandri (2012) also proposed a comprehensive model to predict sound absorption of porous asphalt. The novel approach relies on the use of specific parameters associated with the composition of the mix like aggregate shape and gradation, as well as volumetric composition. Moreover, the model is based on the Neithalath et al. (2005) microstructural formulation, which allows defining the internal structure of the mix that is required for the description of the acoustic field in a single pore, and predicting the sound absorption coefficient without flow measurements (Figure 24). Losa et al. (2013) combined their previous studies into a more complex statistical model to optimize the mixture design of low-noise pavements. The parameters used in the multivariate linear regression model include the air voids volume percentage, the gradation % passing 0.063 mm, the number of compaction gyrations and the fractal dimension of the aggregate gradation. These mixture characteristics were related to CPX measurements at different speeds. The model coefficients are affected by the speed variation and, therefore, were estimated by using the Levenberg–Marquardt optimization algorithm due to the non-linearity of the model. In this last work, the authors not only considered the dimensions of cavities at the pavement surface to reduce the sound generated by air pumping, but also the advantage of a surface texture with the negative profile to minimize the sound generated by tire vibration. This approach was done by introducing the two independent variables multivariate linear regression. Recently, Teti et al. (2020) have proposed two options to model the initial CPX levels of low-noise road surfaces using only parameters obtained during the design phase (e.g. grading curve, fractal dimension, asphalt binder content, air voids or voids in mineral aggregates). They have used ten low-noise road surfaces as a dataset to test and validate the models. Although this study provides promising correlations, it seems that further development would be required for open road surfaces to better reflect their sound absorption properties.

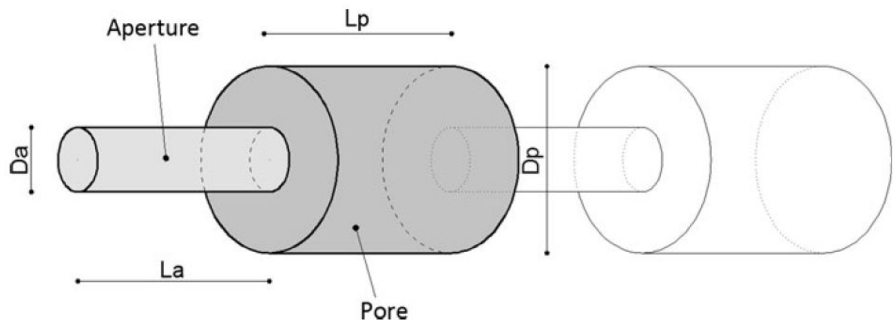

Figure 24 Geometric Model of the Pore Structure (Losa and Leandri, 2012)

6.3 Porosity and surface texture

Wang et al. (2016) tried to optimize the sound absorption for porous asphalt surfaces by investigating the influence of the pore structure. They implemented the Zwikker-Kosten model for rigid-framed porous materials and the transfer matrix method to predict the sound absorption coefficient considering the idealized pore structure parameters (pore radius, pore length, and porosity). They have observed that the microstructure of porous materials can significantly affect the thermoelastic damping and viscous losses. The results showed that an increase in pore radius can reduce sound absorption and an increase in pore length (as an indication of layer thickness) shifts the maximum absorption to lower frequencies. In an earlier study, Lui and Li (2004), a simplified model to investigate the propagation of sound in PAC showed that an increase in the thickness and porosity of a porous layer, or the use of a double layer of porous road pavement, reduces the horn effect.

In a more recent work, Liu et al. (2016) studied the effects of double layer porous asphalt pavements as a solution for noise reduction in urban streets. With numerical simulations they developed a pavement structure with alternate layers of fine and course aggregates to generate an air void structure acting as Helmholtz resonator. They closely investigated the influence of different variables such as the air void ratios of the single surface and the double surface as well as air void structure including the main and side air voids, the combinations of thicknesses for both porous surfaces within the structure and the texture of the pavement surface. Ding and Wang (2017) also considered the effect of texture in their analysis of the tire/road noise for PAC. They used a coupled modelling approach with finite element method–boundary element (FEM-BEM) analysis by first building a radial tire model, where the tire surface accelerations under the excitation from pavement texture were obtained from modal analysis. The radiated sound field due to the tire vibration was solved using BEM. They found that the noise variation due to different sound absorption coefficients of porous pavement is not as significant as the effect of surface texture.

In another recent work, Chen et al. (2018) established a prediction model correlating the tire/road noise level with the macrotexture and megatexture of PAC. In parallel, they proposed a micro-element model to calculate the sound absorption of the PAC permeable air voids (Figure 25). This model consists of units with one sphere and one capillary where the sphere simulates the air void while the capillary represents the interconnect channel between two air voids. This modelling conception has been successfully applied to ballast surfaces previously (Heutschi, 2009). According to the different mechanisms of pavement surface texture affecting tire/road noise, two indicators are proposed in the model: a low texture wavelength indicator (0.4–10 mm) and a high wavelength indicator (12.5–80 mm), which is consistent with the empirical results described in Section 4.1.

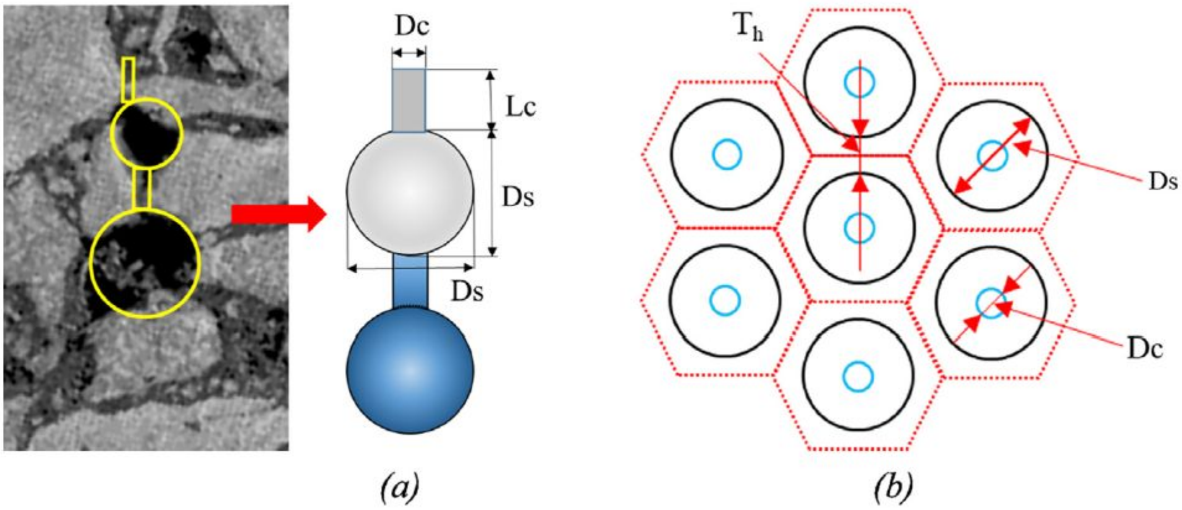

Figure 25 Sound Absorption Model of PAC: (a) Micro-Element Model and (b) Permutation and Combination of Micro-Element Models (Chen et al., 2018)

A semi-empirical study on the acoustic properties of an ultrathin porous pavement with high viscosity asphalt rubber binder as an innovative design of low-noise surfaces was conducted by Luong et al. (2014). In this work, a comparison between sound absorption data from experimental tests with an impedance tube and analytical simulation leads to an optimization of the intrinsic parameters of highly porous asphalt specimens (>25% air void content). A phenomenological approach is then adapted in porous pavements by considering the porous medium as a compressible fluid in which acoustic waves scatter and propagate, with an energetic degradation process due to viscous and thermal loss. Specifically, the prediction model used by Hamet and Bérengier allows determining absorption coefficient from viscous dissipation related to intrinsic parameters such as porosity, static airflow resistivity and tortuosity (Hamet and Bérengier, 1993). Besides the ones mentioned here, other models are also available (Allard and Atalla, 2009).

6.4 Commercial models

Many countries have developed prediction tools based on existing software models supported by integral databases of measurement data. For example, the German model SPERoN (Beckenbauer and Kuijpers, 2001) and the French model HyRoNE (Klein and Hamet, 2007) predicts the pass-by tire/road noise of a passenger car from intrinsic characteristics of the road surface. They have been implemented as user-friendly stand-alone applications. De Roo and Gerretsen (2000) describe the prediction model TRIAS (Tire/Road Interaction Acoustic Simulation). This includes multiple pavement parameters, such as texture depth, porosity, structure factor, flow resistance, and/or sound absorption. These parameters are measured experimentally or acquired from the supporting simulation model RODAS (ROad Design Acoustic Simulation), which generates the physical pavement characteristics from the material composition of the mixture (chipping size, binder content, and layer thickness) and analyses the texture spectrum. In parallel, another supporting submodel, TYDAS (TYre Design Acoustic Simulation) generates model inputs from known tire parameters. Specifically, the

Acoustic Optimization Tool (AOT) was developed for the general investigation and optimization of the acoustic performance of low-noise surfaces. The model was a deliverable within the IPG (Noise Innovation Program), which was established to help meet Dutch national targets for noise reduction from transport noise in a cost effective way (Kuijpers et al., 2007).

6.5 Future Developments

Although some models already include input data from new pavements designs (Bendtsen et al., 2009; Ongel et al., 2008; Reyes and Harvey, 2011), it seems clear that in the future, updated versions of the current models must be developed. These new models should include new parameters that take into account the specific details which will affect the well-known functional properties of road surfaces (e.g. incorporation of alternative materials such as waste materials or reduction of the layer thickness), the ageing effect (Bendtsen et al., 2009) as well as the arrival of modern vehicle fleets, tires and other future trends.

7 Conclusions

The current study presented a review of the acoustical properties of asphalt pavements, the methods of measuring them in the lab and in the field, noise related non-acoustical tests, along with modelling techniques for acoustical properties. The conclusions from this study are drawn as follows:

- The close-proximity method (CPX) is the most commonly used method for measuring tire/road noise in the field. On-Board Sound Intensity (OBSI) and Statistical Pass-By (SPB) are the other common methods.
- Compared with CPX and OBSI that focus on tire/road noise generation, SPB measures both the generation and propagation of tire/road noise along with the pavement influence on engine noise.
- Measuring sound absorption using an impedance tube is a common and relatively simple way to quantify the absorption properties of asphalt pavements in a lab and in-situ.
- There are several unique methods for simulating and measuring tire/road noise in a lab, although most produce conditions that are not representative of in-situ. The exceptions are the larger drum methods, which also require a significant amount of resources to implement. There is a need to develop a more easy to implement method, which can have more widespread use.
- Texture profiling, specifically of the macrotexture, has been correlated with acoustical properties of asphalt pavements. This detailed profiling can be done by laser profilometry. However, the correlation depends on the wavelength within the macrotexture of lower and higher texture level wavelengths.
- Among the various proposed low-noise pavements, porous asphalt (PAC) is the most consistently correlated with low-noise performance linked to its capabilities in sound absorption, especially at higher frequencies, and influence on air pumping, horn effect and pipe effect. Durability is the greatest challenge for PAC, along with their ability to maintain their porosity over time due to clogging, which can be mitigated with adequate maintenance and using double layer pavements (DPAC).

- The most reliable way of reducing pavement noise is increasing the porosity along with some improvement possible with texture optimization. The long term performance can be improved through layer optimization by DPAC. To produce better low-noise roads, more research is needed to improve the durability of PAC and its variants.
- Some noise reducing pavement solutions such as the use of crumb rubber by the dry process to affect the texture properties have not been shown to have an effect on the noise. It is likely that the content of rubber used in these trials would not be significant enough to have an effect.
- A significant quantity of crumb rubber, such as in non-asphalt based poroelastic road surfaces, has shown significant improvements, in combination with high porosity. This requires the use of epoxy binder to make up for the mechanical weaknesses of such a rubber content.
- There have been a number of models proposed which include low-noise properties of pavements, although these vary significantly. There needs to be more research and discussion to develop a more comprehensive and widely recognized model.

The work presented herewith shows that the field of low noise pavements, its measurem ent and modeling is a continuously evolving field, and a number of question remain unanswered. The summary presented and discussed in this paper was made in order to give an overview with advantages and disadvantages of the methods in order to provide a guide for pavement and acoustic professionals to improve on the state if the art.

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