"Environmental Engineering" 10th International Conference
Vilnius Gediminas Technical University
Lithuania, 27–28 April 2017
http://enviro.vgtu.lt

eISSN 2029-7092 / eISBN 978-609-476-044-0
Article ID: enviro.2017.152
DOI: https://doi.org/10.3846/enviro.2017.152

Surface Type and Age Effects on Tyre/Road Noise Levels

Audrius Vaitkus[1], Viktoras Vorobjovas[2], Donatas Čygas[3], Tadas Andriejauskas[4], Faustina Tuminienė[5]

[1,2,4,5]Road Research Institute, Vilnius Gediminas Technical University, Vilnius, Lithuania
[3]Department of Roads, Vilnius Gediminas Technical University, Vilnius, Lithuania
E-mails: [1]audrius.vaitkus@vgtu.lt (corresponding author); [2]viktoras.vorobjovas@vgtu.lt; [3]donatas.cygas@vgtu.lt; [4]tadas.andriejauskas@vgtu.lt; [5]faustina.tuminiene@vgtu.lt

Abstract. Road surface characteristics are the core influencing factors for tyre/road noise generation mechanisms. Depending on the pavement wearing layer mixture composition, type surfaces have different acoustical properties. Acoustical parameters and acoustical behavior change over the time because of the effects of traffic and environmental conditions. Usually low noise pavements can be characterized with very good acoustical parameters but at the same time good acoustical properties deteriorates over the time. Paper presents the research study of surface type and age effects on tyre/road noise levels. Number of different age and different surface type pavements (conventional AC and SMA pavements, low noise SMA TM, TMOA and PA) were evaluated and compared in terms of acoustical performance. Analysis of CPX noise level measurement results are presented in the paper followed with the conclusions and recommendations of low noise pavement application for severe climate regions.

Keywords: tyre/road noise, low noise pavements, CPX measurements, acoustic ageing.

Conference topic: Roads and railways.

Introduction

Traffic noise is an increasing environmental problem which impacts are significantly underestimated. Exposure to excessive noise levels result a high risk to human health, with road traffic being the greatest contributor. Additionally, noise negatively affects some animal species and economies (EU annual socio-economic costs because of traffic noise are higher than 40 billion EUR and expected to increase 50% by 2050 (European Commission, 2011)). Therefore, huge efforts are needed to decrease noise pollution in EU Member States. Implementation of *Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to assessment and management of environmental noise* is one of the solutions, however implementation needs to be fostered and improved in terms of completeness, comparability and adaptation of highly effective solutions.

Noise barriers and noise walls are the most popular noise abatement solutions in road sector but at the same time their construction and maintenance is expensive, complicated and in some cases even not possible due to various restrictions. Alternatively, low noise road pavements are being more frequently developed and selected as a primary noise abatement solution. The most popular low noise pavements are porous asphalt, which significantly reduce traffic noise (depending on the asphalt mixture composition, noise reduction can be achieved up to (4-6 dBA) (Sandberg, Ejsmont 2002). However, porous asphalt pavements are sensitive to harsh climate conditions, especially high number of frost-thaw cycles and large temperature fluctuation ranges. Therefore, use of porous asphalt in Northern and Eastern European countries is not always feasible resulting research and development activities focused on traditional asphalt mixtures optimization for noise reduction. Optimization of regular dense asphalt AC and stone mastic asphalt SMA mixtures can lead to noise reduction by 2–4 dBA (). Modification of the mixtures is performed in combined way of optimizing mixture surface texture, increasing porosity and reducing mechanical impedance.

In recent years, Road Research Institute of Vilnius Gediminas Technical University was working on the development of low noise asphalt mixtures for Lithuanian and regional climate conditions (e.g. annual number of frost-thaw cycles in Lithuania is 60–80, and the temperature fluctuation range can be from –35 to 50 °C (Ratkevičius *et al.* 2013), what is considered as severe climate conditions for road infrastructure). Developed and optimized in laboratory (Vaitkus *et al.* 2016) low noise asphalt mixtures (SMA 5 TM, SMA 8 TM and TMOA 5) together with traditional asphalt mixtures (AC 11 VS, AC 8 PAS-H, SMA 8 S, SMA 11 S) and porous asphalt (PA 8) were successfully implemented in practice (Andriejauskas *et al.* 2016) for further testing under real traffic and climate conditions.

Because of low noise asphalt mixtures nature and composition specificity (they are characterized by increased porosity and optimized surface texture), their lifetime is a bit shorter than traditional dense graded asphalt mixtures. Additionally, acoustic ageing occurs and progresses faster than traditional asphalt mixtures. Acoustic ageing could be associated with the clogging of air voids or road surface texture variation of the initial state. This paper aims to analyze and compare acoustic ageing effects of developed low noise asphalt mixtures SMA 8 TM, SMA 5 TM, TMOA 5 and regular porous asphalt PA 8 using research and data from the constructed Test Road of Low Noise Pavements in Lithuania.

Acoustic ageing of asphalt pavements

Pavement degradation is one of the most important problems, that affects acoustical performance of low noise asphalt mixtures. However, pavement degradation impact on acoustical behavior is difficult to quantify. Low noise asphalt pavements should not only have good initial noise reduction but also need to retain good acoustical properties over the pavement lifetime. Pavement wear is a dynamic process caused by winter road maintenance actions, traffic impacts, environmental impacts and others. Therefore, the impact on acoustical properties is complex and depend on numerous parameters such as pavement surface type, porosity, wear level, climate impact level, etc. Because of these influencing factors pavement wears and noise reduction properties decrease. For some surfaces acoustic ageing is rather small and for other it may be drastic.

PA surfaces are the most common and popular low noise pavement solutions with 1.5–4 dBA higher noise level reduction compared with the SMA and AC pavements (Yu *et al.* 2014). However, the shorter lifetime leading to 50% higher life-cycle costs than traditional dense asphalt concrete wearing courses (Ongel, Harvey 2012) is the main disadvantage when selecting PA as a low noise pavement solution. According to Takahashi (2013) research in Japan, initial noise reduction of PA surfaces drops from 5 dB to 1 dB after 6 years of exploitation and requires surface cleaning actions. To extend the lifetime and increase noise reduction properties of porous asphalt (Hamzah *et al.* 2013), double layer porous asphalt layer was developed where the upper layer is constructed with a smaller size of maximum aggregate to protect surface texture from clogging while the bottom layer is constructed using larger size of maximum aggregate to ensure good acoustical absorption (Ahammed, Tighe 2011).

Acoustic properties of the road surfaces evolve with time and their respective noise emissions change over the years and pavement wear level. Increasing macrotexture contribute to increasing noise levels. Acoustical ageing starts even before significant pavement deterioration appears. Main factors contributing to acoustic ageing are: change of mega- and micro- textures because of worn out particles of increased stiffness (due to compaction of the traffic); polishing of microtexture; chemical effects of weather and crumbling of the surface; cracks; clogging (Sandberg, Ejsmont 2002).

Acoustic properties of dense road surfaces are mainly influenced by the road surface texture. For dense asphalt road surfaces, acoustic ageing is mainly a function of traffic load (especially of the number of heavy vehicles) leading to a disaggregation of the filler component in the surface texture. This was also confirmed by the HOSANNA project research (Schmerbek 2013): performed CPX measurements on different dense asphalt surfaces on highways driving 80 km/h showed that on the right driving lane acoustical regression is 0.5 dB/year and on the left driving lane it is 0.3 dB/year, meaning that the acoustic ageing is slower on the left driving lanes which has much smaller number of heavy vehicles. Irali *et al.* (2015) research shows that in traditional asphalt pavements, noise levels increase linearly with time and it is usually two times higher for cars than for heavy vehicles. Typically, smooth and medium-textured dense asphalt surfaces such as SMA and AC have increased noise levels for the first 1–2 years of exploitation, then stabilize until the end of the lifetime (when severe megatexture cracks and unevenness occur). Increase is mostly between 1 and 2 dB(A) and generally occurs at frequencies typical of air-displacement mechanisms (Sandberg, Ejsmont 2002).

Acoustical ageing for porous or semi-porous mixtures is different. Belgian research (Vuye *et al.* 2016) on the acoustical ageing of thin asphalt layers showed a linear relationship of the acoustic ageing effect on the noise reduction: noise increase of 0.02–0.14 dBA per month (based on SPB measurements) and 0.05–0.2 dBA per month (based on CPX measurements). Strong relationship between the acoustic ageing and raveling was found out for thin asphalt layers (Bergiers *et al.* 2014), which can be explained by the composition of the mixtures (aggregate grading and bitumen content) and the higher void content.

The acoustic properties of porous road surfaces are mainly influenced by the acoustic impedance and the surface texture, meaning that not only the traffic load influences the acoustic ageing but also clogging of the open pores (Maennel, Altreuther 2016). Dutch study (van Loon *et al.* 2015) analyzed the acoustic ageing factors of porous surfaces:

- Clogging of the lower layer and further of porous surface cause reduction of the thickness of the effective absorption layer and thus a shifting the absorption peaks to higher frequencies.
- Clogging of the top layer (either due to extensive dirt or compaction) amplifies aero-acoustic noise generation and thus increases levels at the mid and high frequency range.
- Surface texture degradation through aggregate loss amplifies texture induced vibration of the tyre structure and respective increase noise in the lower and mid frequency range.
- The aging effects of surfaces on heavy vehicles noise are not that different from light vehicles.

According to the different ageing mechanisms, it can be observed that the ageing of porous road surfaces usually does not follow a linear trend over time (Fig. 1). After some initial level increase, the sound pressure level consolidates for a long time. In this period the road surface remains in a metastable equilibrium between clogging and self-cleaning (Maennel, Altreuther 2016).

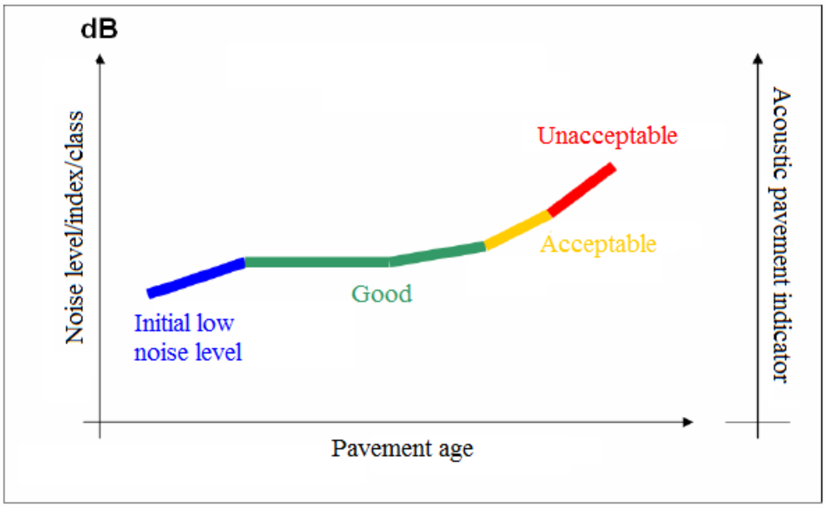

Fig. 1. Acoustic ageing of porous surfaces (Sandberg, Ejsmont 2002)

Another study in Denmark showed that an open-graded mix on a highway (high speed) could give a noise reduction of 3 to 4 dBA over its lifetime while a similar mix placed on an urban road (low speed) with an initial noise reduction of 3 dBA lost its noise reducing properties in only two years due to clogging of the pores (Kragh *et al.* 2013).

Analyzed literature indicated the need to investigate the acoustical behavior of the developed optimized low noise asphalt mixtures SMA 5 TM, SMA 8 TM, TMOA 5 for severe climate conditions. Knowledge on the acoustic ageing (either linear or non-linear regression curves) are important for mixtures application (conditions, locations, lifetime, etc.) and further development directions. Regional and country variables need to be included in the mixtures installation procedures.

Experimental research

Experimental research on the acoustic ageing of optimized low noise asphalt mixtures SMA 5 TM, SMA 8 TM, TMOA 5 and traditional porous asphalt PA 8 were performed in Test Road of Low Noise Pavements in Lithuania. Research activities were performed by Road Research Institute of Vilnius Gediminas Technical University.

Test Road of Low Noise Pavements

Based on the laboratory research, testing results and estimations that developed low noise asphalt mixtures for regional climate conditions should reduce noise by 2–4 dBA (Vaitkus *et al.* 2014), it was decided to construct test sections and perform further research of low noise pavements. The aim is to increase the level of living quality of population by testing low noise pavements in real traffic and environmental conditions, evaluating noise reduction characteristics dependent on asphalt mixture type and duration and level of exploitation.

Test Road of Low Noise Pavements was constructed in September, 2015 on a highway of national significance. Highway A2 Vilnius–Panevėžys is a two lane dual carriageway road which connects two large cities – Vilnius and Panevėžys. Test Road was constructed on a right side of the highway in the direction to Panevėžys at 56.07–57.57 km. Average annual daily traffic (AADT) in different parts of this highway varies from 7000 to 10000 vehicles per day. Speed limit is 110 km/h.

Test Road is 1.5 km in length and consists of 9 short sections where asphalt wearing layer was constructed using different asphalt mixtures. Those mixtures include 3 noise reducing asphalt mixtures (TMOA 5, SMA 5 TM, SMA 8 TM) developed by VGTU RRI for Lithuanian climate conditions, 1 porous asphalt mixture (PA 8), 1 special pavement and 4 traditional asphalt mixtures (SMA 8 S, SMA 11 S, AC 11 VS, AC 8 PAS-H). Main characteristics of the sections are presented in Table 1. Road surface texture of traditional porous, optimized low noise sections are illustrated in Figure 2. From the figure it is clearly seen the differences between traditional asphalt mixtures and mixtures with noise reduction properties. One group of mixtures have higher porosity (PA 8 and SMA 8 TM) for better noise absorption and decrease of air pumping mechanisms. Other group can be characterized by optimized negative' surface texture with small maximum aggregate size (TMOA 5 and SMA 5 TM) for tyre vibrational mechanisms reduction.

Such scope in variation of different pavement types is needed to perform long-term comparative monitoring of road surface characteristics, noise reduction properties, functional properties, resistance to climate conditions and durability between the different pavement types under real traffic and climate conditions. Construction of the Test Road of Low Noise Pavements is important for the whole region as there were no earlier experience of developing and testing low noise pavements for regional climate conditions. The results as well as optimized low noise asphalt mixtures will be valuable and transferable to other region countries.

Table 1. Main characteristics of the Test Road of Low Noise Pavements

Pavement type	Layer thickness [cm]	Section length [m]	Pavement width [m]
PA 8	4.0	100	11.25–11.60
SMA 8 S	3.0	175	8.55–8.75
SMA 11 S	3.0	175	8.55–8.75
AC 11 VS	3.0	175	8.55–8.75
AC 8 PAS-H	2.5	175	8.55–8.75
TMOA 5	2.5	175	8.55–8.75
SMA 8 TM	2.5	175	11.25–11.60
SMA 5 TM	2.5	175	11.25–11.60
Special pavement	2.5	175	11.25–11.60

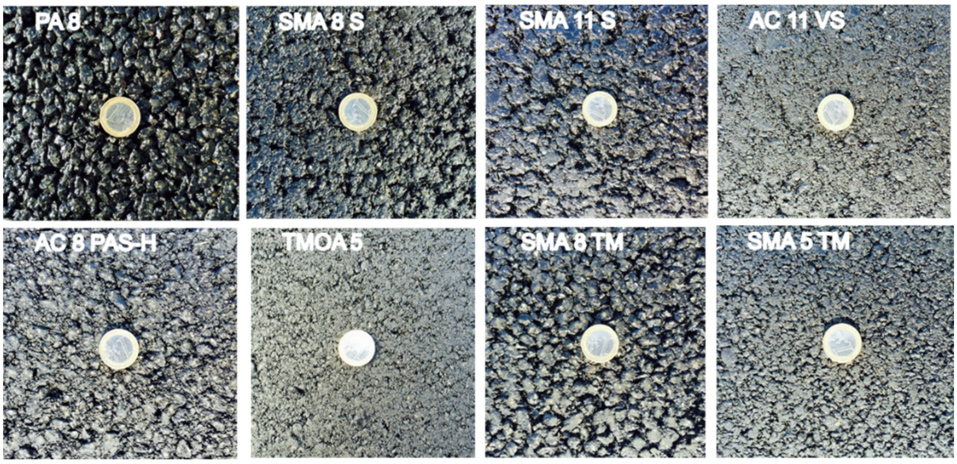

Fig. 2. Road surface texture view of the Test Road of Low Noise Pavements sections

In this paper, acoustic ageing will be further assessed and analyzed only for the mixtures with noise reduction properties (PA 8, SMA 5 TM, SMA 8 TM, TMOA 5).

Methodology

To analyze different low noise asphalt mixtures' acoustic ageing, periodical tyre/road noise level measurements were performed in the Test Road of Low Noise Pavements. Measurements were performed 6 times (right after implementation; 1 month after implementation, before the winter season; in spring when average daily temperature is higher than 5ºC; when average daily temperature is 10–15 °C; before the second winter season) using CPX method (ISO/DIS 11819-2). This method is based on test tyre rolling on the road or the test track surface with measuring microphones located close to the tyre surface. CPX trailer (Fig. 3) is towed by a light vehicle. Trailer has two measurement wheels which are covered with the trailer case to isolate microphones from unwanted outside sound sources, wind or traffic influence. Parallel to the CPX measurements, driving speed, road section length, GPS coordinates, air and road surface temperature are measured too.

Fig. 3. CPX noise level measurement trailer (left – closed; right – opened)

CPX noise level measurements on both traffic lanes were performed at two different speeds: 50 and 80 km/h. Such measurement speeds were selected with a purpose to accurately determine road surface influence on noise generation mechanisms depending on the driving speed and road category (low speed roads/urban streets and high speed roads).

Two sets of measurement tyres to represent passenger cars and heavy duty vehicles were used. For passenger car representation standard reference test tyres (SRTT) are used and for heavy duty vehicle representation – Avon Supervan AV4 tyres (AAV4).

Results and interpretation

Tyre/road noise level measurements showed that after one year of exploitation porous asphalt PA 8 pavement section retains its initial acoustical properties. According to the CPX noise level results presented in Figure 4 it can be seen that initial CPX noise level was lower on the right traffic lane approximately by 1.5 dBA compared to the left traffic lane. Additional tests that were performed in the Test Road, showed that it was probably caused by the inhomogeneity in construction phase – left traffic lane was over compacted resulting lower air void content. It was also noticed that the trend of acoustical behavior is opposite to the trends found in literature, CPX noise levels after one year of exploitation have reduced for SRTT tyres by approx. 0.5 dBA (both for 50 and 80 km/h on both traffic lanes) and for AAV4 tyres by approx. 1.0 dBA (both for 50 and 80 km/h on both traffic lanes). Highest CPX noise levels for SRTT tyres were measured after 7–8 months after exploitation. However, after 7–8 months of exploitation, high increase of CPX noise levels was measured only for light vehicles, therefore it can be assumed that after the winter (use of studded tyres) road surface texture was roughened resulting higher increase in vibrational noise generation mechanisms for passenger tyres than for heavy vehicle tyres. Since the driving speed is quite high in the Test Road, possibility of clogging of the pores after one year of exploitation is minor and was also confirmed by visual assessment.

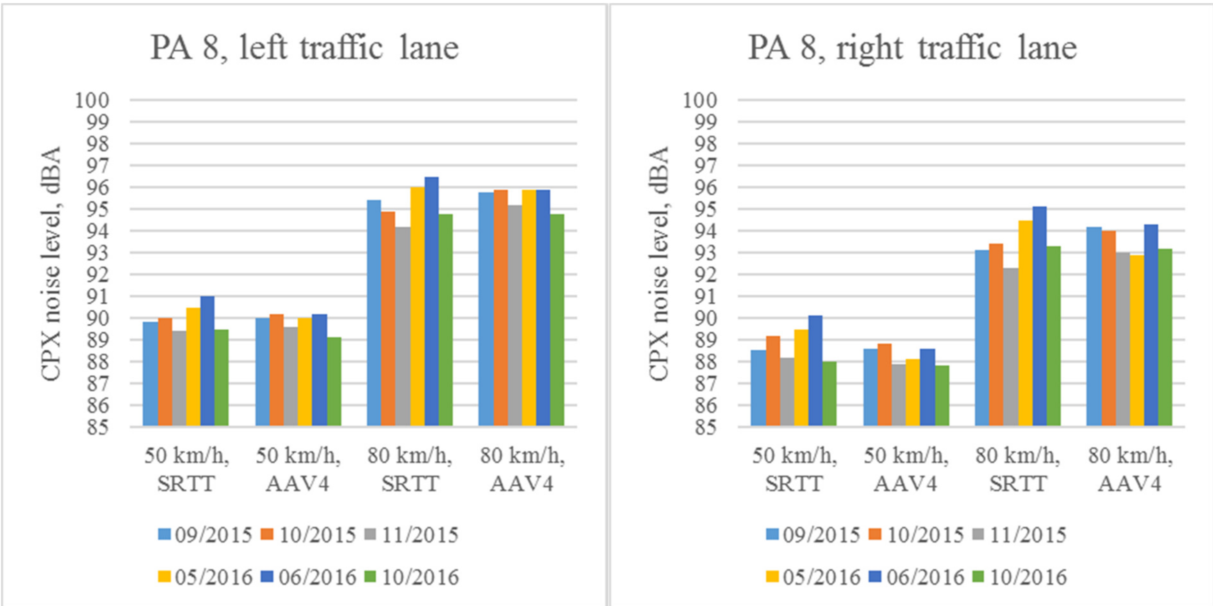

Fig. 4. CPX noise level change of porous asphalt PA 8 pavement sections on the Test Road

For the optimized low noise asphalt mixture SMA 5 TM (Fig. 5), initial CPX noise level was measured lower on the left traffic lane – difference between the lanes approx. 2 dBA. Noise levels drastically increased right after the first 1–2 months of exploitation: increased by approx. 3 dBA for SRTT and AAV4 tyres at 50 km/h and 4–5 dBA for SRTT and AAV4 tyres at 80 km/h on the left traffic lane; 2.5 dBA for SRTT tyres at 50 and 80 km/h and only 1.5 dBA for AAV4 tyres at 50 and 80 km/h on the right traffic lane. Differently than PA 8, better acoustical properties were measured with SRTT tyres. This can be related with the mixture design focused on light vehicles' noise reduction. Even if the noise levels increased during the exploitation, lower CPX noise levels were still measured for SRTT tyres.

For the optimized low noise asphalt mixtures SMA 8 TM (Fig. 6), initial CPX noise level was measured lower on the right traffic lane – difference between the lanes approx. 2.5–3.0 dBA. Initial difference between the traffic lanes could be associated with the inhomogeneous construction – left traffic lane was over compacted resulting 3% lower air void content. When monitoring CPX noise level changes over the time, it was noticed that on the left lane noise levels remained approximately the same or even decreased, whilst on the right traffic lane there was an increase, especially for SRTT tyres (after 8–9 months of exploitation, noise levels increased approx. by 4 dBA at 50 and 80 km/h).

For the optimized low noise asphalt mixture TMOA 5 (Fig. 7), initial CPX noise level was measured lower on the left traffic lane – difference between the lanes approx. 1.0–1.5 dBA. After the first months of exploitation, noise levels increased on both lanes, but increase was again higher for SRTT tyres. After the first 2 months of exploitation (before the winter season) it wa measured extreme increase in CPX noise levels on the left lane. This happened because road surface was a bit humid during the measurements on the left traffic lane. After the winter season, it was recognized that noise levels tend to increase fof SRTT tyres and to remain at the same level for AAV4 tyres.

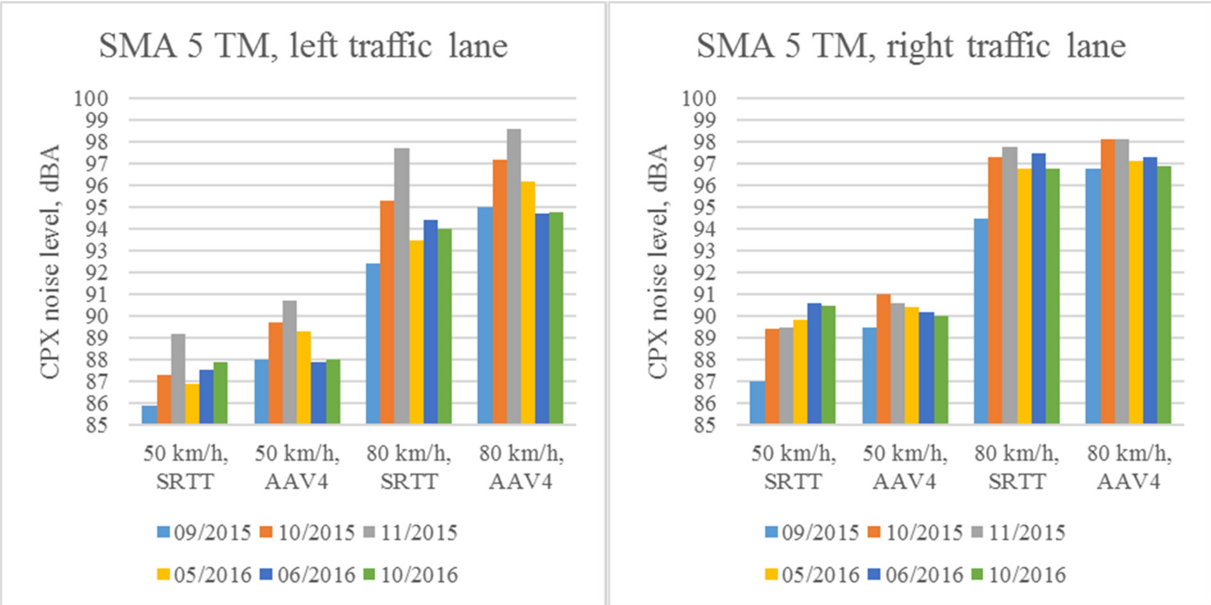

Fig. 5. CPX noise level change of porous asphalt SMA 5 TM pavement sections on the Test Road

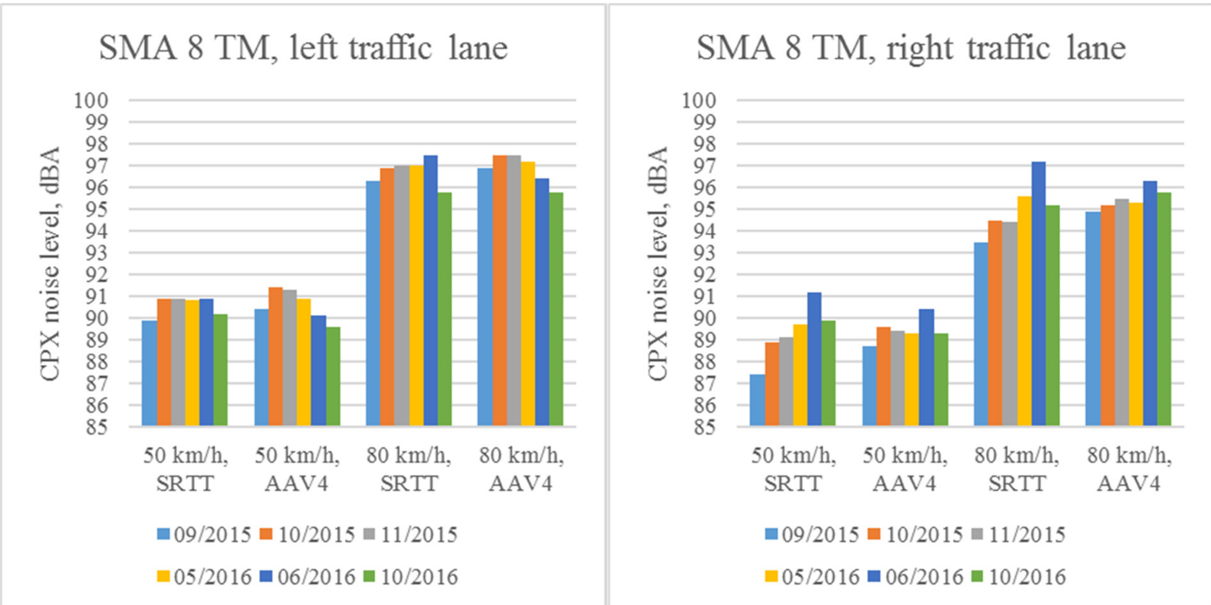

Fig. 6. CPX noise level change of porous asphalt SMA 8 TM pavement sections on the Test Road

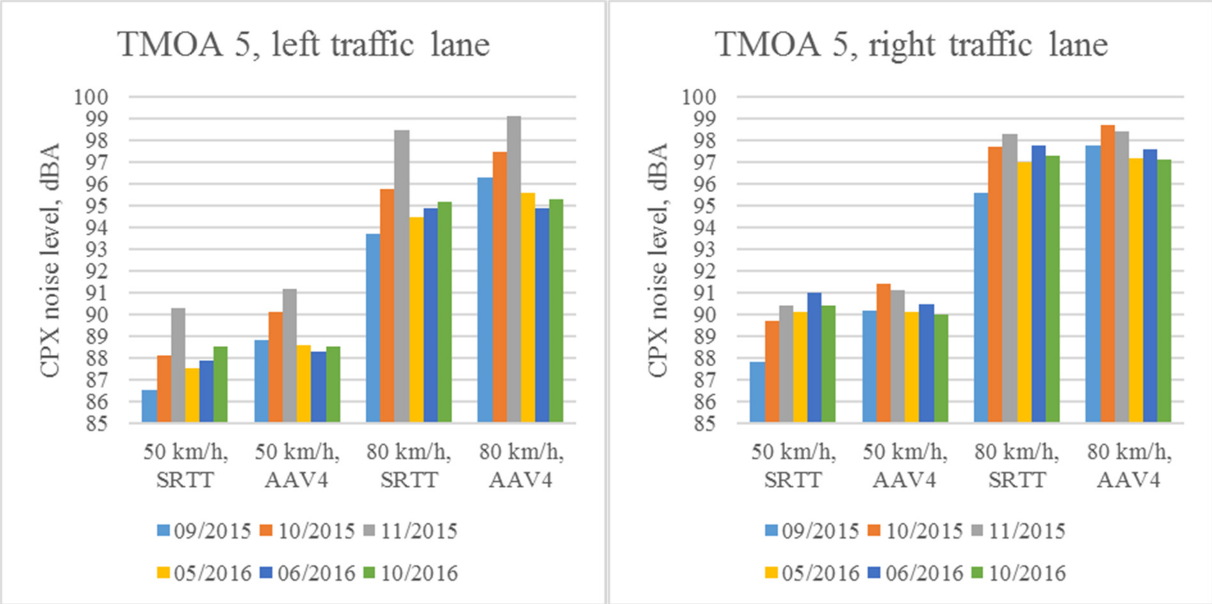

Fig. 7. CPX noise level change of porous asphalt TMOA 5 pavement sections on the Test Road

Conclusions

Road traffic noise is rapidly increasing environmental problem causing higher negative effects on human health, animals and economies. Therefore, holistic approach (combination of physical noise barriers, noise reducing road surfaces, control, monitoring and governance measures) of noise abatement and mitigation is needed.

Investigation of acoustical behavior of developed low noise asphalt mixtures (SMA 5 TM, SMA 8 TM, TMOA 5) for Lithuanian and regional climate conditions is relevant to gain understanding how developed mixtures react to real traffic and harsh climate conditions. Such knowledge is important when preparing low noise asphalt layers' implementation guidelines.

CPX noise level measurements were performed 6 times on the Test Road of Low Noise Pavements sections in the first year of mixtures exploitation. Based on the current results, it can be stated that developed low noise asphalt mixtures and porous asphalt mixture retain sufficiently high noise reduction properties.

Measurements have also showed that CPX noise levels tends to increase for passenger cars (SRTT tyres) and to decrease for heavy vehicles (AAV4 tyres). This can be related with the traffic loads and studded tyres impact on road surface texture. However, more periodic CPX noise level measurmenet data needed to confirm this relation.

Having in mind tendency of faster acoustic ageing of SMA 5 TM and TMOA 5 mixtures for SRTT tyres, it is recommended to use smaller aggregate size surface textured mixtures for roads with no or very low percentage of heavy traffic, which is the main catalyst for optimized surface texture deterioration and respective noise increase.

Based on the current noise level results it can be said that developed low nosie asphalt mixtures have similar or even better noise reduction properties than porous asphalt at the same time developed to maintain good stability and strength during the severe climate conditions. Further monitoring of acoustic and durability conditions of the low noise pavements is needed.

From the CPX noise level results, considerable differences between the traffic lanes were identified and might be associated with the construction issues. This raises the need of developing specific requirements for low noise pavement construction and quality assurance.

Funding

Construction of the Test Road of Low Noise Pavements and following research was initiated and funded by the Lithuanian Road Administration under the Ministry of Transport and Communications.

References

Ahammed, M. A.; Tighe, S. L. 2011. Acoustic absorption of conventional pavements, *International Journal of Pavement Research and Technology* 4(1): 41–47.

Andriejauskas, T.; Vaitkus, A.; Vorobjovas, V.; Čygas, D. 2016. Low noise pavement development for severe climate conditions, in *Proceedings of 45th International Congress and Exposition on Noise Control Engineering INTER-NOISE 2016*, 21–24 August 2016, Hamburg, Germany, 6995–7004.

Bergiers, A.; de Visscher, J.; Denolf, K.; Destree, A.; Vanhooreweder, B.; Vuye, C. 2014. Test sections to study the acoustical quality of thin noise reducing asphalt layers, in *Proceedings of the International Conference on Noise and Vibration Engineering (ISMA)*, 15–17 September 2014, Leuven, Belgium, 1707–1722.

European Commission. 2011. *Report from the Commission to the European Parliament and the Council: On the implementation of the Environmental Noise Directive in accordance with Article 11 of Directive 2002/49/EC. COM(2011) 321 final*. Brussels. 13 p.

Hamzah, M. O.; Abdullah, N. H.; Voskuilen, J. L. M.; van Bochove, G. 2013. Laboratory simulation of the clogging behaviour of single-layerand two-layer porous asphalt, *Road Materials and Pavement Design* 14(1): 107–125. https://doi.org/10.1080/14680629.2012.749803

Irali, F.; Gonzalez, M.; Tighe, S. L.; Simone, A. 2015. Temperature and aging effects on tire/pavement noise generation in Ontarian road pavements, in *Transportation Research Board 94th Annual Meeting 2015,* 11–15 January 2015, Washington DC, United States.

Kragh, J.; Andersen, B.; Pigasse, G. 2013. *Acoustic ageing of pavement, DVS-DRD joint research programme – Super Silent Traffic*. Vejdirektoratet.

Maennel, M.; Altreuther, B. 2016. Ageing of low noise road surfaces, in *Proceedings of 45th International Congress and Exposition on Noise Control Engineering INTER-NOISE 2016*, 21–24 August 2016, Hamburg, Germany, 6964–6972.

Ongel, A.; Harvey, J. 2012. Prediction of lifetime for different asphalt concrete mixes, *Road Materials and Pavement Design* 13(2): 203–217. https://doi.org/10.1080/14680629.2012.682382

Ratkevičius, T.; Laurinavičius, A.; Juknevičiūtė-Žilinskienė, L. 2013. Possibilities for the use of RWIS data in a building sector, *Procedia Engineering* 57: 938–944. https://doi.org/10.1016/j.proeng.2013.04.119

Sandberg, U.; Ejsmont, J. A. 2002. *Tyre/road noise reference book*. Informex, Kisa, Sweden. 640 p.

Schmerbek, R. 2013. *Schallmessungen in Bayern*. HOSANNA Final workshop. Planegg, Germany.

Takahashi, S. 2013. Comprehensive study on the porous asphalt effects on expressways in Japan: based on field data analysis in the last decade, *Road Materials and Pavement Design* 14(2): 239–255. https://doi.org/10.1080/14680629.2013.779298

Vaitkus, A.; Čygas, D.; Vorobjovas, V.; Andriejauskas, T. 2016. Traffic/road noise mitigation under modified asphalt pavements, *Transportation Research Procedia* 14: 2698–2703. https://doi.org/10.1016/j.trpro.2016.05.446

Vaitkus, A.; Vorobjovas, V.; Jagniatinskis, A.; Andriejauskas, T.; Fiks, B. 2014. Peculiarity of low noise pavement design under Lithuanian conditions, *The Baltic Journal of Road and Bridge Engineering* 9(3): 155–163 https://doi.org/10.3846/bjrbe.2014.20

Van Loon, R.; Tollenaar, C.; van Blokland, G. 2015. Mechanisms of acoustic aging of road surfaces, in *EuroNoise 2015*, 31 May – 3 June, Maastricht, the Netherlands.

Vuye, C.; Bergiers, A.; Vanhooreweder, B. 2016. The acoustical durability of thin noise reducing asphalt layers, *Coatings* 6(2): 21. https://doi.org/10.3390/coatings6020021

Yu, B.; Jiao, L.; Ni, F.; Yang, J. 2014. Long-term field performance of porous asphalt pavement in China, *Road Materials and Pavement Design* 16(1): 214–226. https://doi.org/10.1080/14680629.2014.944205