Rolling Resistance And Tire/Road Noise On Rubberized Asphalt Pavement In Poland

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ABSTRACT: *The paper presents results of tire/road noise and rolling resistance measurements performed on stone-matrix asphalt (SMA) that contains rubberized asphalt developed and produced by the refinery in Poland. Bituminous binder was modified with polymer and additive of crumb rubber. The first observations of asphalt mixture with the new kind of modified bitumen used on the field section are presented. Rolling resistance of passenger car tires was measured by test trailer R^2 Mk.2. Tire/road noise was measured by Tiresonic Mk.4 trailer using Close Proximity Method. Measurements were performed for 50 and 80 km/h and the results obtained on test and reference sections covered with conventional SMA 11 were compared.*

KEYWORDS: *rubberized asphalt, rolling resistance, tire/road noise, measurements, road pavement*

1. Introduction

Modifications of the bituminous binder enhance asphalt mixture performance, especially its resistance to: permanent deformation, fatigue and thermal cracking (Caltrans, 2003), (Dantas-Neto *et al.*, 2006), (Gaweł *et al.*, 2011), (Iwański and Chomicz-Kowalska, 2015). In the case of course wearing, modification of bitumen reduces surface maintenance costs and in some cases allows to increase skid resistance and decrease noise levels. The most popular modifications of the bitumen - which can change its rheological properties are polymer or crumb rubber (CR) modifications. It is also possible to use at the same time the crumb rubber from scrap tires and polymer such as SBS copolymer during one process of binder modification (Caltrans, 2003), (Król *et al.,* 2013a). New high performance bitumen, modified by SBS and CR, was developed and it is in continuous production in Gdańsk refinery. This special new type of bitumen modified with SBS and CR together corresponds to rubberized asphalt binder (RA) according to the American classification. In Poland this bitumen is referred to as polymer-rubber modified bitumen 45/80-55 CR (PmB 45/80-55 CR) according to the European Standard for modified bitumen PN-EN 14023 (2011).

High performance and attractive price of the new rubberized asphalt binder developed in Gdańsk allow it to be widely used in Poland for wearing courses made either of stone mastics asphalt (SMA) or asphalt concrete (AC). From the end of 2012 to the middle of 2014 over 120 km of wearing courses in Poland were paved with PmB 45/80-55 CR. The conducted research covers modified bitumens such as polymer and polymer-rubber modified bitumens produced on an industrial scale and available in continuous sale in Poland. The properties of both polymer modified bitumen and polymer-rubber modified bitumen are constant and warranted by the refinery. Rubber modified bitumen, produced by small companies or selected contractors, was omitted in this research program.

The first part of this paper presents the properties of the new bitumen, as well as the performance of asphalt mixture made with this type of bitumen in laboratory. The second part presents the assessment of rolling resistance and noise properties of SMA wearing course made with polymer-rubber modified bitumen laid and compacted on National Road No 20 in Kościerzyna.

2. Description of the pavements with rubberized asphalt

2.1. *Production of polymer-rubber modified bitumen at the refinery*

There are two processes of crumb rubber asphalt modification: a dry process and a wet process. Among them the wet process gives more benefits. In the dry process, the crumb rubber is mixed directly with aggregates in the mixer to produce a rubber modified asphalt mixture. In the wet process the crumb rubber and bitumen are mixed completely to form modified bitumen, which is later mixed with aggregates in the mixer at the mixing plant. Crumb rubber is added to binder at the temperature of 180 °C. During this process rubber partially dissolves, swells and devulcanizes, what results in bitumen modification. In the wet process 5 to 25% (by weight of bitumen) of crumb rubber is added to modify the bitumen. The process needs special equipment for bitumen modification. In some cases non-dissolved CR particles in bitumen lead to phase separation, particularly when the blends are stored at high temperatures. As a result, the swollen CR particles are considered to settle down quickly due to initial higher density than the bitumen phase (Navaro *et al.,* 2004). On the other hand, migration of the CR particles to the top of the storage container due to a reduced density after swelling has also been reported in some research studies (Ghaly, 2008), (Pérez-Lepe *et al.* 2007). These different mechanisms lead to an unstable condition which results in a rubberised blend with varied properties after the storage, so called thermostability problem. To eliminate the thermostability problem of crumb rubber modified bitumen Gdańsk refinery introduced application of the finest crumb rubber, as well as reduction of the rubber content together with an addition of traditional SBS polymers in order to compensate for the reduced amount of rubber. This technological process is called „*terminal blend*" (Caltrans, 2003), (Hicks *et al.,* 2010), (Król *et al*., 2013a) and can be classified as a mix of rubber and polymer technology, in which benefits from traditional polymer modification as well as crumb rubber modifications are merged (Czajkowski & Kędzierska, 2013). This process also allows to reduce the amount of added polymers with respect to the standard polymer modified bitumens.

New polymer-rubber modified bitumen 45/80-55 CR fulfils all requirements set for PmB 45/80-55 bitumen according to the European Standard for Polymer Modified Bitumen (PN-EN 14023, 2011).

2.2. *Results of laboratory testing of materials and mixtures*

Two types of bitumen were selected for introduction of new rubberized bitumen properties: polymer-rubber modified bitumen 45/80-55 CR and as reference - polymer modified bitumen 45/80-55. Standard properties of bitumens used in this study, which were obtained at Warsaw University of Technology by Król *et al*. (2012), are shown in Table 1. It can be seen that the properties of polymer modified and polymer-rubber modified bitumen are rather similar.

Table 1. *Standard properties of bitumen according to PN-EN 14023 (2011) for polymer modified bitumen (Król et al., 2012)*

Property	Unit	45/80-55	45/80-55 CR
Penetration at 25 °C,	0.1 mm	49	46
Softening point by R&B,	°C	60.6	62.2
Force ductility at 5 °C,	J/cm2	8.3	7.8

Flash point,	°C	>235	>235
Fraass breaking temperature,	°C	-15	-16
Elastic recovery at 25 °C,	%	74	72
Penetration index,	-	1.1	1.2
Stability – difference in R&B,	°C	1.2	1.2
Chang of mass,	%	0.06	0.09
Retained penetration at 25 °C after RTFOT,	%	68	67
Increase in softening point by R&B after RTFOT,	°C	6.6	7.6
Elastic recovery at 25 °C after RTFOT,	%	69	68

More differences can be observed in rheological properties at high and low temperatures. Based on the work prepared at Warsaw University of Technology by Król *et al.*, (2013b) it can be concluded that polymer-rubber modified bitumen 45/80-55 CR at high service temperature (60 °C) has indicated a three times higher viscosity than polymer modified bitumen 45/80-55, but during hot mix asphalt production viscosity of both bitumens demonstrated the same viscosity level of 0.5÷0.6 Pa·s at 150 °C. A comparison of flexural creep stiffness modulus from Bending Beam Rheometer (BBR) test at low temperatures: -6 °C, -12 °C, -18 °C and -24 °C shows clearly a lower stiffness of polymer-rubber modified bitumen for long time of loading and at -6 °C, -12 °C for short time of loading. For short time of loading at -18 °C and -24 °C the stiffness of polymer-rubber bitumen is still lower, however is very similar to the stiffness of polymer modified bitumen.

Full performance grade tests according to Superpave (SHRP, 1995) procedure were conducted at Warsaw University of Technology (Król *et al.*, 2012). Results showed that 45/80-55 CR bitumen can be classified as PG 82-22 (Czajkowski & Kędzierska, 2013).

For the laboratory tests of asphalt mixtures two SMA 8 (maximum nominal grain is 8 mm) mixtures were prepared at Technical University of Gdańsk (TUG) (Judycki *et al.*, 2014), which comprised of granite grits 5/8, 2/5 mm, crushed sand 0/2 mm and limestone filler. Fat amine was used as adhesive agent. Cellulose fibres in the form of granules (0.5 % of bitumen mass) were used to prevent draining down of hot bitumen from aggregate grains. The bitumen content of each mixture used during laboratory tests was 7.0 % (by weight). The content of air voids in prepared mixtures was 2.6 %.

Rutting resistance test results (acc. to PN-EN 12697-22 (2008), method B) showed the possibility of designing rutting resistant mixtures using polymer-rubber modified bitumen. Results were similar to the rutting resistance of conventional SMA 8 mixture with polymer modified bitumen.

Based on water susceptibility test acc. to PN-EN 12697-21 (2012) both mixtures of SMA were classified as highly resistant to water and frost. Such classification was required by the Technical Requirement WT-2 (GDDKiA, 2010) and recommended by Jaskula and Judycki (2008).

Dynamic modulus was determined in Simple Performance Tester (SPT) according to standard proposed in NCHRP 9-29 project (Bonaquist, 2008) at TUG (Judycki *et al*., 2014). Master curves of tested mixtures are shown in Fig. 1. Three samples of each mixture were tested at three temperatures and frequency range from 25 Hz to 0.01 Hz.

Master curves obtained from SPT suggest that in temperature range from -10 ºC to +40 ºC the SMA 8 mixture with 45/80-55 CR bitumen has a slightly lower stiffness modulus than SMA 8 mixture with reference bitumen. However, the situation is opposite for temperatures lower than ca. -20 ºC. The SMA 8 mixtures with 45/80-55 CR bitumen may show a higher stiffness modulus than reference SMA 8 mixture in those conditions.

Results of Thermal Stress Restrained Specimen Test (TSRST) test acc. to PN-EN 12697-46 (2012) European Standard are presented in Fig. 2; where mean values of 3 samples are presented. The SMA 8 mixture with polymer-rubber modified bitumen 45/80-55 CR shows higher resistance to low temperature cracking.

Most of the laboratory test results were similar both for SMA 8 mixture with polymer-rubber modified bitumen 45/80-55 CR and conventional SMA 8 mixture with polymer modified bitumen 45/80-55. Nevertheless in the case of low temperature the SMA 8 mixture with crumb rubber modification shows slightly better performance, especially in TSRST test.

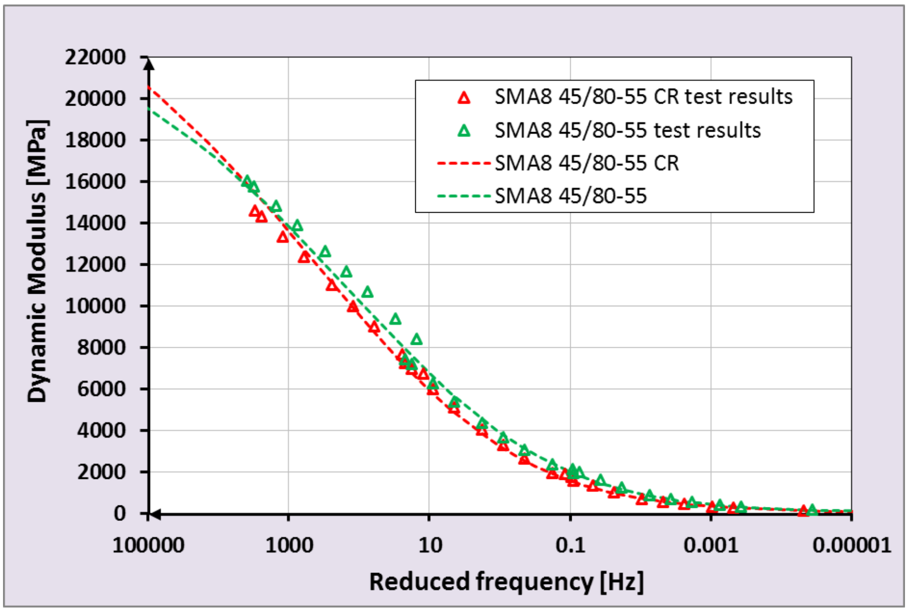

Figure 1. *Master curves of SMA 8 with polymer-rubber modified bitumen 45/80-55 CR and polymer modified bitumen 45/80-55; reference temperature of 20 ºC (Judycki et al. 2014)*

2.3. *Construction of the test pavements*

In July 2013 two test section were constructed on National Road No. 20 in Poland: a nearly 1 km long test section with SMA based on polymer-rubber modified bitumen and 6 km long reference section with conventional type of SMA mixture. The test section was located in Kościerzyna and constructed by a road construction company from Starogard Gdański. The scope of the test section construction corresponded well to the conception of the road rehabilitation project in terms of timing and length.

The rehabilitation was conducted as construction of two asphalt courses: 4 cm of AC 16 (maximum nominal grain is 16 mm) asphalt concrete binder/profile course and 4 cm of SMA 11 (maximum nominal grain is 11 mm) wearing course on existing pavement. Before placement of the asphalt overlay min. 2-3 cm of existing pavement was milled off to correct the road profile.

Properties of SMA 11 produced in the mixing plant are presented in Table 2. After compaction visual differences between the two test sections were not found. Also the pavement surface was found to be free of any surface failures (see Fig. 3).

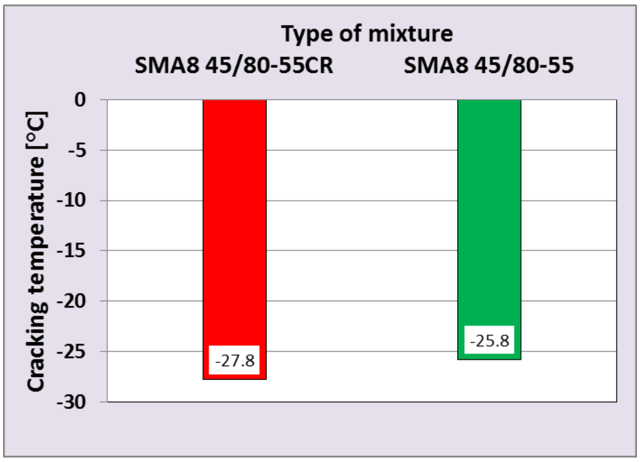

Figure 2. *Results of TSRST test (Judycki et al., 2014); mean value of 3 samples*

Table 2. *Properties of SMA 11 with polymer-rubber modified bitumen 45/80-55 CR and conventional polymer modified bitumen 45/80-55 used on test sections; mean values of 2 tests*

Properties	Value		WT-2 requirements
	SMA 11 45/80-55 CR	SMA 11 45/80-55	
Water sensitivity	96.2 %	93.6 %	ITSR $_{90}$
Rutting resistance, small device, method B in air, 60 °C, 10 000 cycles WTS $_{AIR}$, [mm/1000 cycles] PRD $_{AIR}$	 0.06 7.4 %	 0.07 7.5 %	 WTS $_{AIR\ 0.3}$ PRD $_{AIR-TBR}$
Bitumen content in layer	6.5 %	6.6 %	$B_{min\ 6.4}$
Air Voids content in layer	2.6 %	2.7 %	2.0 - 5.0
Compaction factor in layer (percent of Marshall density at 50 blows per site of sample)	99.0 %	99.8 %	≥ 97

Abbreviations:

PRD $_{AIR}$ - the proportional rut depth for the material under test at N cycles using a small size device in air,

WTS $_{AIR}$ - the wheel-tracking slope, calculated as the average rate at which the rut depth increases with repeated passes of a loaded wheel of a small size device model B in air,

ITSR – indirect tensile strength ratio, calculated as the ratio of the indirect tensile strength of wet (water conditioned) specimens to that of dry specimens, expressed in percent,

B_{min} – minimum binder content, expressed in percent.

Asphalt mixtures were designed according to WT-2 requirements (GDDKiA, 2010), European Standards PN-EN 13108-5 (2008) and the recommendations developed during the laboratory stage (with some exceptions in the cases of the maximum size of the aggregate and totally different source of aggregate). The particle size distribution curve of the SMA 11 mix is presented in Figure 4.

Figure 3. *Building of the test SMA 11 section with polymer-rubber modified bitumen in wearing course*

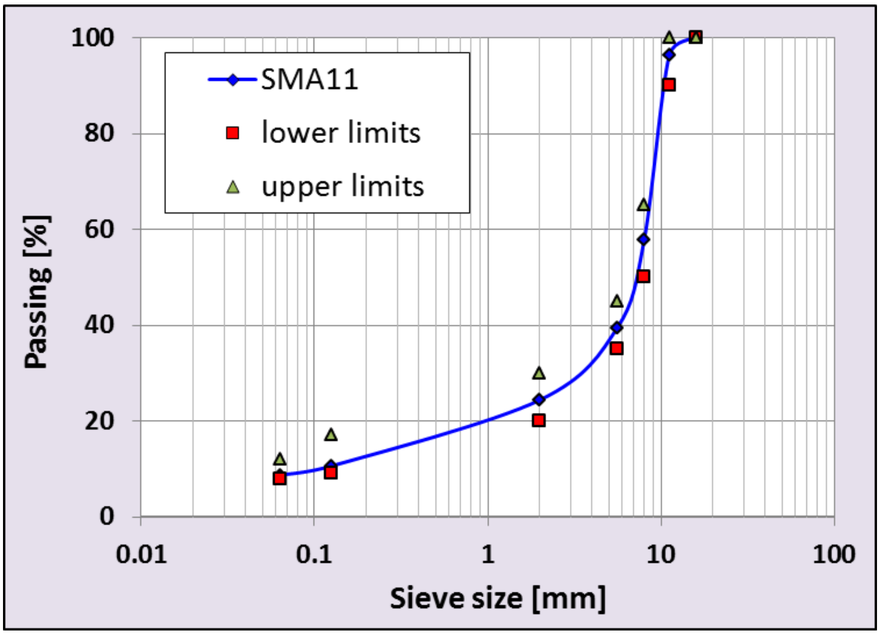

Figure 4. *Particle size distribution curve of aggregate mixture used to produce the tested SMA 11*

3. Test sections and test tires

3.1. *Test section on the road DK20 Korne-Kościerzyna*

Road DK20 is a moderately trafficked national road leading from Gdynia towards Stargard Szczeciński. As it was mentioned above, in 2013 part of the road was rebuilt. From km 257+700 to km 258+500 Stone Mastic Asphalt SMA 11 based on polymer-rubber modified bitumen manufactured by Lotos was laid. From km 251+700 to km 257+700 Stone Mastic Asphalt SMA 11 with binder of polymer modified bitumen PmB 45/80-55 was used. As this two road sections are adjacent and located in very similar surroundings it is very convenient to use them as test sections (with SMA 11 based on polymer modified bitumen as reference). The test section with rubberized asphalt was named **SMA 11-R** and the reference test section **SMA 11-P**.

In Fig. 5 the view on test section with polymer-rubber modified bitumen is presented. In Fig. 6 the texture of both sections is visually compared. Tests performed by the mobile laser profilometer installed on rolling resistance test trailer (see Chapter 5.1) one year after laying the surface indicated that averaged MPD for the test section SMA 11-R was 0.58 mm, while for the SMA 11-P section it was 0.70 mm.

Figure 5. *Test section SMA 11-R as seen west direction*

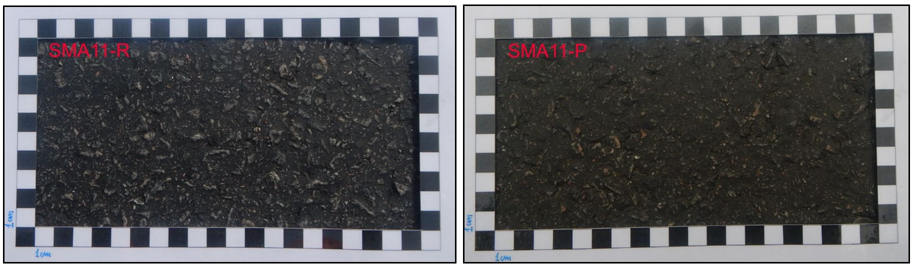

Figure 6. *Texture of test section SMA 11-R (on left) and texture of reference section SMA 11-P (on right)*

3.2. *Test tires*

Several passenger car tires were used during the experiments. A description of tires is presented in Table 3. The tire set contained tires that are considered as reference tires in standard ISO/DIS 11819-3 (AAV4, SRTT), informal reference tires for rolling resistance measurements (AAV4, SRTT, MCPR), winter tires (T1066, T1071, T1072), summer tires (T1080, T1081, T1082, T1093) and tires specially designed for electric cars (T1083, T1095). Such a diversity of tire types ensures that the results are representative for existing traffic.

Table 3. *Test tires used in the experiments*

Tire Symbol	Manufacturer	Type	Size
T1063 *(AAV4)*	AVON	SUPERVAN AV4	195R14C 106/104N
T1064 *(MCPR)*	MICHELIN	PRIMACY HP	225/60R16 98V
T1077 *(SRTT)*	UNIROYAL	TIGER PAW (M+S)	P225/60R16 97S
T1066	WANLI	S-1200 (M+S)	195/60R15 88H
T1071	VREDESTEIN	QUATRAC 3 (M+S)	195/60R15 88V
T1072	YOKOHAMA	Wdrive (M+S)	195/50R15 88T
T1080	MICHELIN	ENERGY SAVER X GREEN	215/55R17 94H
T1081	DUNLOP	SPORT BLURESPONSE	195/65R15 91H
T1082	MICHELIN	ENERGY SAVER + Extra Load X GREEN	195/65R15 95T
T1083	MICHELIN	ENERGY EV GREEN	195/55R16 91Q
T1093	NOKIAN	HAKKA GREEN	195/65R15 95T
T1095	DUNLOP	ENASAVE 2030	175/55R15 77V

4. Tire/road noise measurements on rubberized asphalt

Road measurements of tire/road noise may be performed with different methods, the most popular being: Statistical Pass-By (SPB), Controlled Pass-By (CPB), Coast-By (CB), On-Board Sound Intensity (OBSI) and Close Proximity Method (CPX). At the Technical University of Gdańsk the CPX method is mainly used for evaluation of road pavements. The method is fully described in (ISO/DIS 11819-2, 2012). It is based on measurements with microphones mounted close to the tire/road interface. The method may be carried out with an ordinary car or with a specially designed trailer. TUG utilizes trailers for execution of CPX measurements.

4.1. *Test equipment*

TUG has built its first trailer of Tiresonic series in 1979. Since then three new generations of trailers were developed. At present trailer Tiresonic Mk.4 is in use -

see Fig. 7. The interior of the trailer (after opening the protection chamber) is presented in Fig. 8. The trailer may be driven with maximal speed of 130 km/h and is constructed in such a way that it may be used on ordinary roads without any special disturbances to normal traffic. The exchange of the test wheel is very fast (about 3 minutes) and the trailer is not impairing the turning circle of the towing car. Data acquisition and evaluation is performed by B&K system PULSE.

Figure 7. *Trailer Tiresonic Mk.4 designed and built by TUG for CPX measurements.*

A part of the results presented in this article was obtained by SINTEF, Norway working together with TUG within the LEO project (LEO, 2013) aiming to select road pavements and tires optimal for electric vehicles. Within this project numerous tires, including tires specially designed for electric cars (like T1083, T1095), and road pavements, including innovative poroelastic road surfaces, were tested (Swieczko-Zurek *et al.*, 2014). SINTEF uses a CPX trailer of different construction, which was built by the company M+P Consulting Engineers in the Netherlands (see Fig. 9).

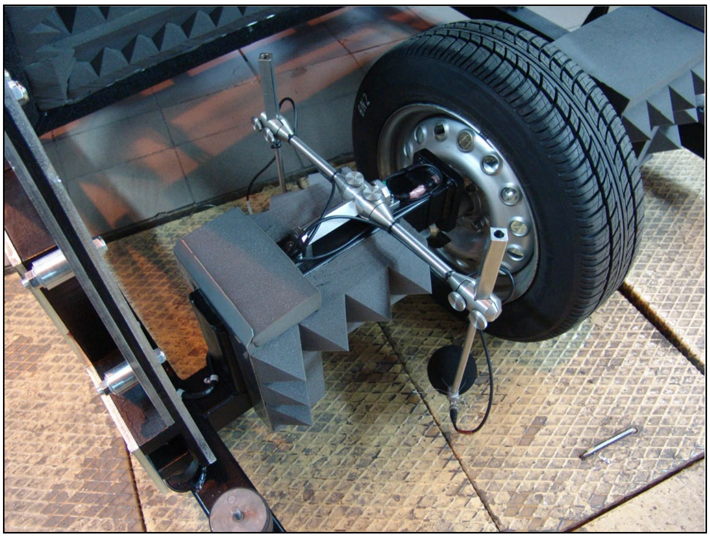

Figure 8. *Interior of the Tiresonic Mk.4 trailer*

Figure 9. *CPX test trailer used by SINTEF, Norway*

4.2. ***Test results***

The CPX measurements were performed by TUG in August 2014 when the surface was 13 months old. The measurements were performed in the right wheel track at speeds 50 and 80 km/h. The measuring conditions were adjusted according to (ISO/DIS 11819-2, 2012), that is tire load was 3200 N and capped inflation pressure 200 kPa. A-weighted Sound Pressure Levels obtained during measurements are presented in Fig. 10. The levels measured on SMA-R and SMA-P test sections are very similar, but with a slight tendency for SMA with polymer-rubber modified bitumen to be less noisy (in average by 0.2 dB). Comparison of noise spectra (see Fig. 11) indicates that the difference is caused by low frequencies (below 800 Hz) that are usually mostly related to the surface megatexture (Sandberg & Ejsmont, 2002). Megatexture is the deviation of a road surface from a true planar surface with the characteristic dimensions (wavelengths) along the surface of 50 mm to 500 mm.

As it was mentioned above, both test sections were tested also by SINTEF, however, using different tires. Measurements performed by SINTEF indicate a higher difference between SMA 11-R and SMA 11-P. The difference was always favourable for rubberized asphalt - see Fig. 12 and Fig. 13. Also in the case of measurements performed by SINTEF, the difference in noise spectra was most visible in the low frequency range, up to 800 Hz - see Fig. 14.

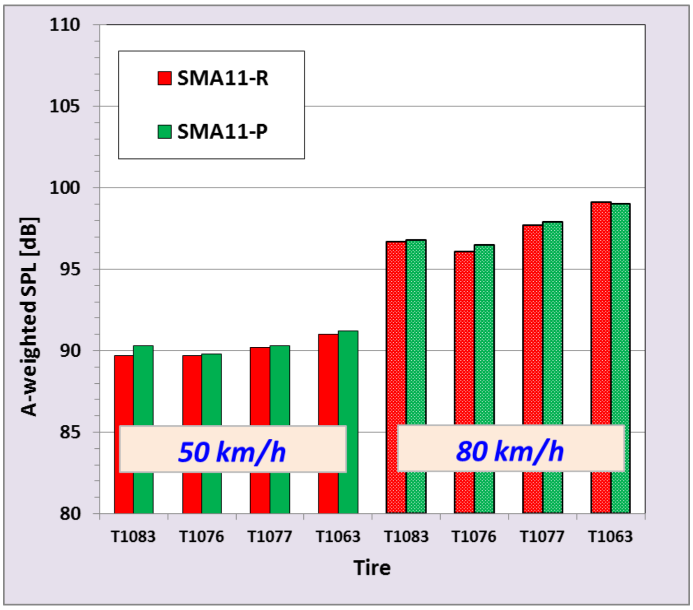

Figure 10. *Results of CPX measurements performed by TUG.*

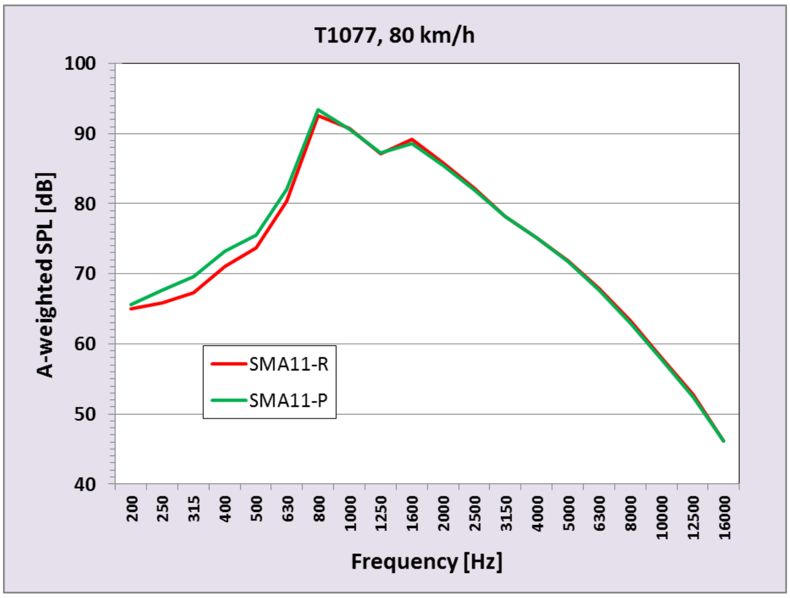

Figure 11. *Comparison of spectra obtained on test sections SMA 11-R and SMA 11-P by TUG*

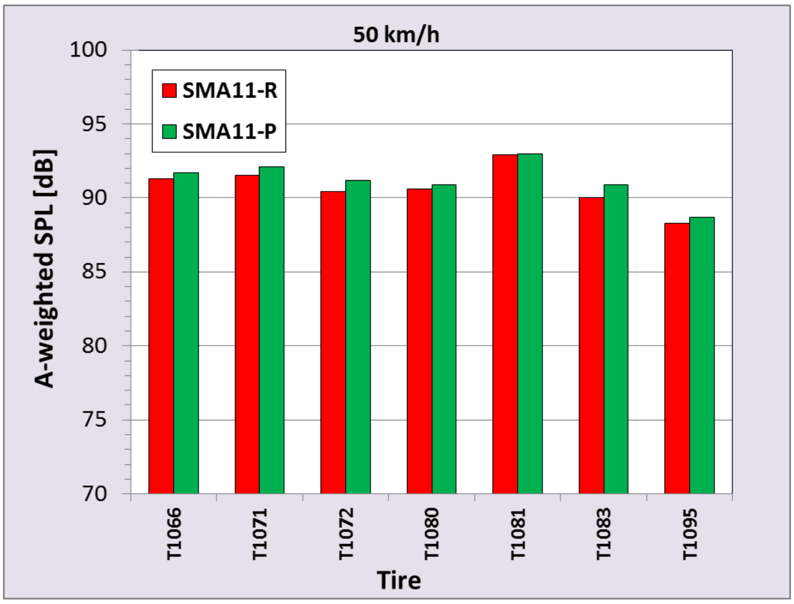

Figure 12. *Results of CPX measurements performed by SINTEF - 50 km/h*

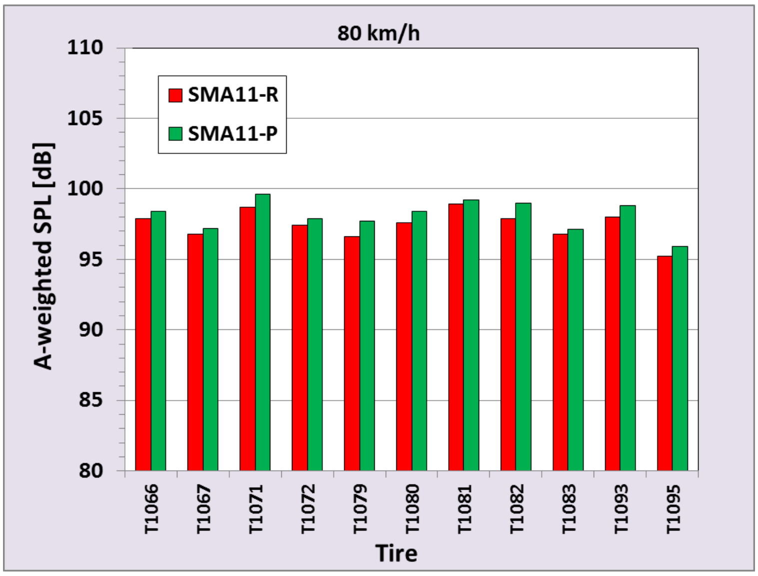

Figure 13. *Results of CPX measurements performed by SINTEF - 80 km/h*

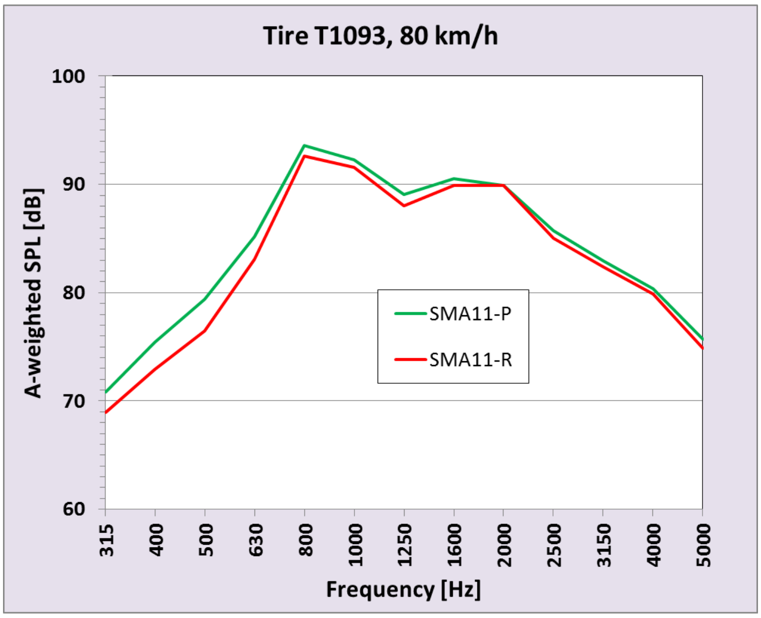

Figure 14. *Comparison of spectra obtained by SINTEF on test sections SMA 11-R and SMA 11-P*

5. Rolling resistance measurements on rubberized asphalt

Rolling resistance is one of the most important factors related to the tire/pavement interaction. In certain situations, rolling resistance may be responsible for up to 45 % of the vehicles energy consumption, although in most cases rolling resistance causes about 15-30 % of energy consumption (Ejsmont *at al.*, 2014), what is highly important from the economical point of view due to a rapid growth in road transport in Poland and in other countries in the region (Rys *et al.,* 2015). Rolling resistance is not easy to measure, especially in road conditions, as a relatively small rolling resistance force must be evaluated in a heavily loaded system. The typical Coefficient of Rolling Resistance C_{RR} (see equation 1) is in range of 0.006 - 0.014, thus passenger car tire loaded to 5 000 N will exhibit rolling resistance force close to 50 N. If the desired accuracy of measurements is 1%, the accuracy of the measuring system must be better than 0.5 N. Just for comparison, if the mass of the car wheel with the hub is 25 kg and the test vehicle accelerates/decelerates with acceleration of 0.02 m/s^2 (that is 0.002 g), the inertia force acting on the wheel would be 0.5 N introducing 1 % error to the result if not accounted for by hardware of software solutions.

$$C_{RR} = \frac{F_R}{L} \qquad [1]$$

Where:

C_{RR} = Coefficient of Rolling Resistance,
F_R = Rolling Resistance Force,
L = Tire Load.

5.1. *Test equipment*

Technical University of Gdańsk (TUG) has developed and built two trailers designed for rolling resistance measurements of passenger car tires. There are only a few trailers in the world that are intended for such measurements and the equipment of TUG is definitely the most busy one, making measurements all over Europe and in the USA. The first trailer was built in 2003 and it was designated as R^2. The second trailer was built in 2013 and designated as R^2 Mk.2. This trailer was used for measurements reported in this paper.

Both trailers use "*vertical arm principle*" described in Fig. 15. Rolling resistance force acting on the test wheel is transferred to the wheel hub located on a vertical swinging arm supported at the bottom end on the axle connected to the main frame of the trailer. The force acting on the arm produces momentum that deflects the arm in backward direction. The angle of deflection is measured by a laser system. To compensate for the influence of acceleration and longitudinal slope of the road surface a special counterbalance system is used. This system is patented by TUG. The trailer is loaded by a certain mass supported on a spring and shock absorber. At the front of the trailer there are two supporting self-aligning wheels. As the angle of the vertical arm deflection is measured in relation to the frame being the reference (not to true vertical direction), it is necessary to provide information about the frame tilt related to the pavement and horizontal plane. This task is accomplished with two laser sensors that measure distance from the pavement at the front and rear of the frame. The trailer is also equipped with a system evaluating road grade. Test trailer R^2 Mk.2 is presented in Fig. 16. In Fig. 17 details of the measuring system, after removal of the protective screen are visible. Vertical arm coupled to the counterbalance system ascertains that the influence of the road grade is always eliminated in 100% while the influence of acceleration is eliminated in about 95%. Also any would-be misalignments of the loading force are fully excluded.

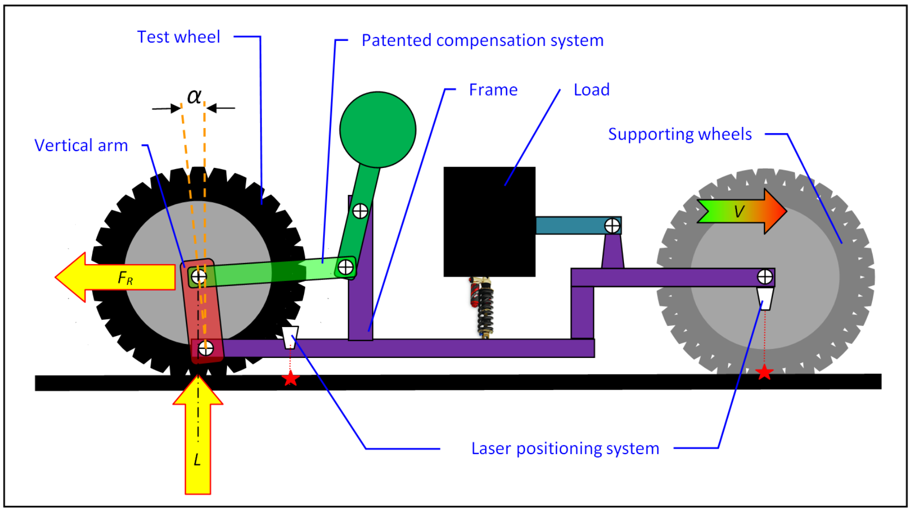

Figure 15. *Operation principle of the test trailer R^2 Mk.2*

6.2. *Test results*

Rolling resistance measurements were performed on test sections SMA 11-R and SMA 11-P on the 11th of September 2014. The air temperature during the measurements was 19 ºC and the road temperature was 20 - 25 ºC. The pavement was dry and clean. Each test section was tested in both directions (eastward and westward) and at least three valid runs for all tires at each direction were done after the tire warm-up period taking 20 minutes of driving with speed of 50 km/h. The results of measurements were corrected for temperature (to nominal air temperature of 25 ºC) and averaged. The averaged results are presented in Table 4 and in Fig. 18.

Figure 16. *Trailer R^2 Mk.2 during measurements in Denmark*

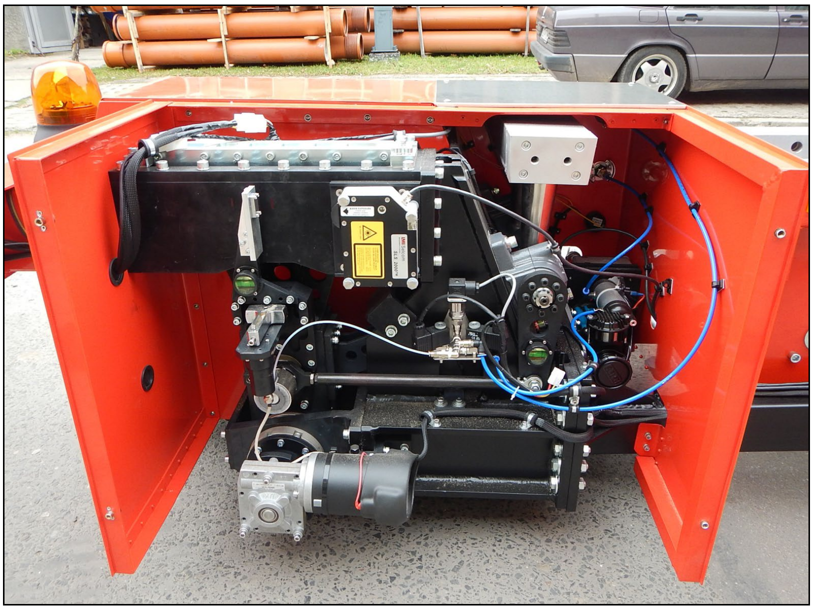

Figure 17. *Interior of the Trailer R^2 Mk.2*

Table 4. *Averaged Rolling Resistance Coefficients for tires tested on test sections SMA 11-R and SMA 11-P*

Tire	Speed [km/h]	Rolling Resistance Coefficient [-]	
		SMA 11-R	SMA 11-P
AAV4	50	0.0102	0.0102
MCPR	50	0.0086	0.0087
MCPR	80	0.0098	0.0099
SRTT	50	0.0064	0.0064

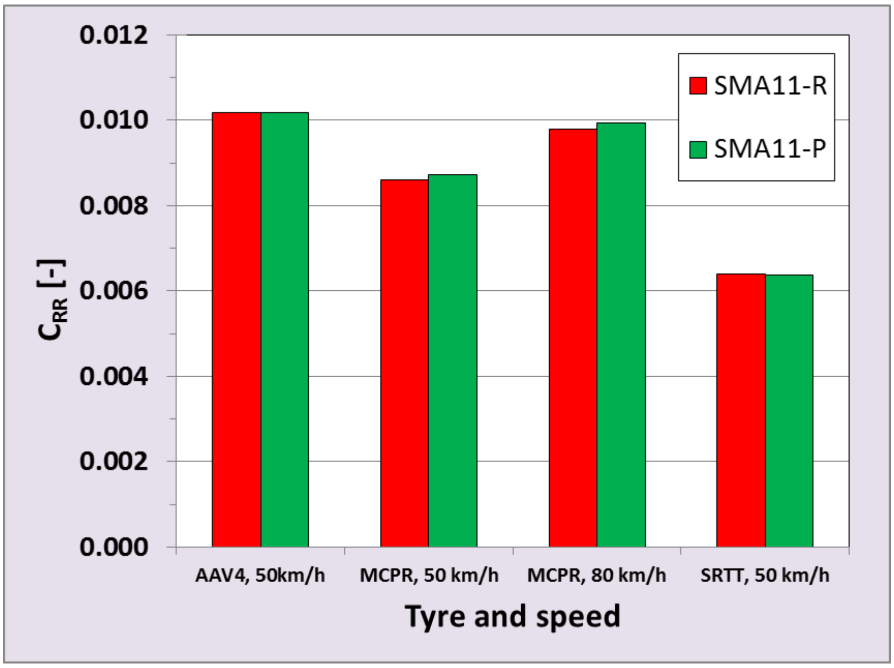

Figure 18. *Rolling resistance coefficients for SMA 11-R and SMA 11-P test sections*

The results presented above indicate that concerning rolling resistance there is no difference between the test section manufactured with polymer-rubber modified bitumen in comparison to the same type of mixture for the wearing course but produced with conventional polymer modified bitumen.

7. Conclusions

It was possible to manufacture at the refinery a new type of binder, polymer-rubber modified bitumen 45/80-55 CR which fulfils all requirements set for polymer modified bitumen PmB 45/80-55 according to the European Standard for Polymer Modified Bitumen PN-EN 14023 (2011).

After laboratory tests it can be said the rubberized asphalt mixture for wearing course (SMA) with polymer-rubber modified bitumen has similar physical and mechanical properties obtained at high and low temperature as a reference asphalt mixture (SMA) with polymer modified bitumen. Nevertheless, in the case of low temperature, the SMA mixture with crumb rubber and polymer modification shows slightly better performance, especially in TSRST test what should be more recognized even by other tests.

In the field, after compaction process finished, asphalt mixtures (SMA) with polymer-rubber and polymer modified bitumens demonstrate no visual differences between the two test sections. Also the pavement surface was found to be free of any surface failures on both sections.

Tire/road noise measured on SMA with polymer-rubber modified bitumen is marginally lower (that is without any practical significance) than on a corresponding SMA based on conventional polymer modified binder. The difference is in most cases between 0.2 dB and 1.2 dB, but it is consistent for all tested tires. Most of the noise reduction is due to the reduction of SPL in low frequency range.

Rolling resistance on SMA with polymer-rubber modified bitumen is the same like on SMA based on conventional polymer modified binder. The differences of results are within measuring errors.

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8. Bibliography

Bonaquist R. (2008), "Refining the Simple Performance Tester for Use in Routine Practice", *NCHRP Report 614*, Transportation Research Board, Washington D.C).

CALTRANS (2003), "Asphalt rubber usage guide", Materials Engineering and Testing Services-MS #5, January 2003, available at:

http://www.dot.ca.gov/hq/esc/Translab/ormt/pdf/Caltrans_Asphalt_Rubber_Usage_Guide.pdf (accessed 16 January 2016).

Czajkowski P., Kędzierska A. (2013), "Polymer-rubber modified bitumen MODBIT" (in Polish), quarterly *Asphalt Pavements* 1/2013 (in Polish - *Nawierzchnie Asfaltowe*), PSWNA Warsaw.

Dantas-Neto S. A., Farias M. M., Pais J.C & Pereira P.A.A. (2006), Dense Graded Hot Mixes using Asphalt-Rubber Binders with High Rubber Contents, Road Materials and Pavement Design, 7:1, 29-46, doi: 10.1080/14680629.2006.9690025

Ejsmont J., Świeczko-Żurek B., Ronowski G., Wilde W.J. (2014), "Rolling Resistance Measurements at the MnROAD Facility, Round 2", Research Project Final Report 2014-29, July 2014, Minnesota Department of Transportation, Research Services & Library, 395 John Ireland Boulevard, MS 330, St. Paul, Minnesota 55155-1899.

Gaweł I., Piłat J., Radziszewski P., Kowalski K.J., Król J. (2011), "*Rubber modified bitumen*" - chapter 4, Polymer modified Bitumen, Properties and characterization, Woodhead Publishing Limited.

General Directorate for National Roads and Motorways (GDDKiA) (2010), WT-2 "Asphalt pavement for national roads. Asphalt mixtures. Technical requirement". (In Polish). Warsaw.

Ghaly N.F. (2008), Effect of sulfur on the storage stability of tire rubber modified asphalt. World J Chem; 3(2):42–50.

Hicks R. G., Cheng D., Duffy T. (2010), Terminal Blend Rubberized Asphalt, Tech Report: 2010 – 102TM, California Pavement Preservation Center, Chico, California, p.82

ISO/DIS 11819-2 (2012), Acoustics — Method for measuring the influence of road surfaces on traffic noise - Part 2: Close-proximity method, International Organization for Standardization.

Iwański M., Chomicz-Kowalska A. (2013), Influence of synthetic fibres on the properties of asphalt concrete produced at reduced temperature - *Structure and Environment* No. 3/2013, vol. 5, The Journal published by the Kielce University of Technology, p. 21-26.

Jaskula P., Judycki J. (2008), "Verification of the criteria for evaluation of water and frost resistance of asphalt concrete". *I. J. Road Mater. and Pav. Des*. vol. X. no. 10.

Judycki J., Dołżycki B., Pszczoła M., Jaczewski M., Szydłowski C. (2014), "Testing and analysis of the SBS and rubber modified bitumen in asphalt mixtures" (Badania i analizy dotyczące zastosowania asfaltów modyfikowanych SBS oraz dodatkiem gumy do mieszanek mineralno-asfaltowych), (Unpublished Reaserch Report in Polish for Grupa Lotos S.A.), Gdansk University of Technology.

Król J., Radziszewski P., Sarnowski M., Czajkowski P., Kędzierska A., Chromiec A. (2013a), "Asphalt mixture with polymer-rubber modified bitumen for friction coarse", (Mieszanki mineralno-asfaltowe z lepiszczem polimerowo-gumowym do warstw ścieralnych) (In Polish), *Magazyn Autostrady* 5/2013, pp. 82-87.

Król J., Czajkowski P., Radziszewski P., Kowalski K.J., Sarnowski M. (2013b), "Viscoelastic Properties Of Polymer And Crumb Rubber Modified Bitumen. Laboratory And Field Investigation", International Scientific Conference, *Road Research And Administration*, Car 2013, Bucharest, 4-5th July.

Król J., Radziszewski P., Piłat J., Kowalski K.J., Sarnowski M. (2012), "Ocena wpływu zastosowania przyjaznych dla środowiska lepiszczy gumowo-asfaltowych produkowanych w technologii Grupy Lotos S.A. na właściwości drogowych mieszanek mineralno-asfaltowych (Unpublished Research Report in Polish for Grupa Lotos S.A.), Warsaw University of Technology.

LEO (2013), Low Emission Optimised tyres and road surfaces for electric and hybrid vehicles, Polish-Norwegian Research Programme CORE, project "LEO" No. 196195 /2013, web page: http://www.leo.mech.pg.gda.pl/

Navarro F.J, Partal P, Martinez-Boza FJ, Gallegos F. (2004), Thermo-rheological behaviour and storage stability of ground tyre rubber-modified bitumens. Fuel 14–15, October; 83.

Pérez-Lepe, A., Martínez-Boza, F. J. and Gallegos, C. (2007), High temperature stability of different polymer-modified bitumens: A rheological evaluation. J. Appl. Polym. Sci., 103: 1166–1174. doi:10.1002/app.25336.

PN-EN 12697-21 (2012), Bituminous mixtures. Test methods for hot mix asphalt. Indentation using plate specimens, Warsaw, Polish Standard – European Committee for Standardization (CEN).

PN-EN 12697-22 (2008), Bituminous mixtures. Test methods for hot mix asphalt. Wheel tracking, Warsaw, Polish Standard – European Committee for Standardization (CEN).

PN-EN 12697-46 (2012), Bituminous mixtures. Test methods for hot mix asphalt. Low temperature cracking and properties by uniaxial tension tests, Warsaw, Polish Standard – European Committee for Standardization (CEN).

PN-EN 13108-5 (2008), Bituminous mixtures - Material specifications - Part 5: Stone Mastic Asphalt, Warsaw, Polish Standard – European Committee for Standardization (CEN).

PN-EN 14023 (2011), *Bitumen and bituminous binders – Specification framework for polymer modified bitumens*, Warsaw, Polish Standard – European Committee for Standardization (CEN) .

Rys D., Judycki J., Jaskula P. (2015), Analysis of effect of overloaded vehicles on fatigue life of flexible pavements based on weigh in motion (WIM) data, *International Journal of Pavement Engineering*, DOI: 10.1080/10298436.2015.1019493

Sandberg U., Ejsmont J. (2002), *Tyre/Road Noise Reference Book*, Kisa, Sweden, INFORMEX.

SHRP (1995), "Superpave Binder Specification and Test Methods", Strategic Highway Research Program.

Swieczko-Zurek, B., Ejsmont, J., Motrycz, G. and Stryjek, P. (2014), "Risks related to car fire on innovative Poroelastic Road Surfaces—PERS", *Fire and Materials*, Vol. 39, Issue 2, March 2015, Pages: 95–108. doi:10.1002/fam.2231

CAPTIONS

Figure 1. *Master curves of SMA 8 with polymer-rubber modified bitumen 45/80-55CR and polymer modified bitumen 45/80-55; reference temperature of 20 °C (Judycki et al. 2014)*

Figure 2. *Results of TSRST test (Judycki et al., 2014)*

Figure 3. *Building of the test SMA 11 section with polymer-rubber modified bitumen in wearing course*

Figure 4. *Particle size distribution curve of aggregate mixture used to produce the tested SMA 11*

Figure 5. *Test section SMA 11-R as seen west direction*

Figure 6. *Texture of test section SMA 11-R (upper picture) and texture of reference section SMA 11-P (lower picture)*

Figure 7. *Trailer Tiresonic Mk.4 designed and built by TUG for CPX measurements*

Figure 8. *Interior of the Tiresonic Mk.4 trailer*

Figure 9. *CPX test trailer used by SINTEF, Norway*

Figure 10. *Results of CPX measurements performed by TUG*

Figure 11. *Comparison of spectra obtained on test sections SMA 11-R and SMA 11-P by TUG*

Figure 12. *Results of CPX measurements performed by SINTEF - 50 km/h*

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Figure 15. *Operation principle of the test trailer R^2 Mk.2*

Figure 16. *Trailer R^2 Mk.2 during measurements in Denmark*

Figure 17. *Interior of the Trailer R^2 Mk.2*

Figure 18. *Rolling resistance coefficients for SMA11-R and SMA11-P test sections*

Table 1. *Standard properties of bitumen according to PN-EN 14023 for modified bitumen (Król et al., 2012)*

Table 2. *Properties of SMA 11 with polymer-rubber modified bitumen 45/80-55 CR and conventional polymer modified bitumen 45/80-55 used on test sections*

Table 3. *Test tires used in the experiments*

Table 4. *Averaged Rolling Resistance Coefficients for tyres tested on test sections SMA 11-R and SMA 11-P*