Asphalt Mixtures that Dissipates Energy—Comparison of Conventional and Newly Developed Mixtures

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Abstract. Efforts to design cost-effective and high-quality pavements leads to the need to innovate the design of road construction materials. Part of this process is an innovation of procedures that are used to analyze the mechanical and physical properties of these materials. The paper deals with the description of results of ongoing project titled as Asphalt Mixtures Dissipating Energy. Thus, laboratory measured results of conventionally produced asphalt mixtures and selected asphalt binders are reported in the paper. Dynamic shear rheometer and bending beam rheometer was utilized to access linear viscoelastic properties of asphalt binders at low, intermediate and high temperatures. The susceptibility of asphalt mixtures to permanent deformation was evaluated by Hamburg Wheel Tracking Test and Uniaxial Shear Test. Four Point Bending Beam test was utilized to analyze fatigue resistance of asphalt mixtures. The paper summarizes principles used to develop new types of asphalt mixtures that, when loaded by traffic, better dissipate energy. The main target of the research project is to develop new asphalt mixtures that in situ prevent occurrence of rutting on the pavement. Thus, core part of the paper focuses on the analysis of linear viscoelastic properties related to pavement permanent deformation and its change depending on the change of input materials.

1 Introduction

The development of asphalt mixtures requires a multidiscipline solution: It is necessary to study the conditions that the product is exposed to (climatic influences, traffic loads) and as well as the mechanical properties of the material. The properties to consider should include the appropriate use of asphalt mixtures for energy dissipation in structures, the interaction with other pavement layers and pavement interaction with the subsoil. The solution is primarily determined by the material composition: The component proportions, material structure and the chemical bonds between the different components. Equally important is the development of a material that meets defined requirements on a macro-scale, so that it can be efficiently produced and processed in the volumes needed for infrastructure construction.

At present, national and European efforts are being made to innovate in the design of flexible pavements. That is, trying to find the most efficient pavement in terms of

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service life, functionality and whole-life cost; throughout design, production, construction and maintenance of the road. The need for innovation around construction materials has come from the increase in transport volume, the anticipated increase in wheel loads effects due to the increase in axle loads and new designs for heavy truck tires, and the effort to design economical and quality pavements. Part of this innovation is to review material characterization, to focus on the physical-mechanical nature of the processes and components that influence the behavior and overall value of the pavement as an asset.

Empirical methods of asphalt mix design can produce sub-optimal solutions by not fully utilizing the potential of the materials, and often they do not reflect the true behavior of the material in the pavement. These empirical approaches are gradually being replaced by a mechanical approach, but at the moment to only a limited extent. ‘Dissipating asphalt’ mixtures are a new material in this respect, developed through a new approach to the design and assessment of asphalt mixtures. The development is based on both conventional and innovative laboratory analyzes of the properties of individual components, additives, analyzes of their interaction, empirical and physical-mechanical properties.

This article presents the analysis of conventionally produced (reference) bituminous mixtures material properties. These analyzes are used in the next stages of the project for qualitative comparison. The key objective is to design of new asphalt mixtures that dissipate energy based on these data. This article also lists results from the design of asphalt mixes for wearing course.

2 Materials, Methodology and Testing

Analyzes were performed on three conventional mixtures for the surface courses—ACO 11+ 50/70, ACO 11+ PmB 45/85-65, SMA 11S PmB 45/80-65 and three conventional (reference) base courses—ACL 16S 50/70, ACL 22S 50/70 and ACL 22S PmB 25/55-65 (ČSN EN 13108-1 2008, ČSN EN 13108-5 2008).

Grading of the individual mixtures consists of crushed aggregates (granodiorite). The grading curve of these mixtures is shown in Fig. 1. Asphalt binder (50/70) and polymer-modified asphalt binder (PmB 45/80-65, PmB 25/55-65) were used for asphalt mixture production.

The assessment of the individual mixtures was carried out using two criteria: The first is the resistance to permanent deformation. This parameter has been determined by a Wheel Tracking Test on a small test device according to ČSN EN 12697-22 and a Uniaxial Shear Test according to (Zak et al. 2016). The second criterion was the fatigue parameters measured on the 4 PB-PR instrument according to ČSN EN 12697-24, but evaluated by the conventional method of 50% reduction of stiffness moduli according to ČSN EN 12697-24, Hopman and Pronk (Hopman 1989) and its modified method based on the relative reduction of the complex stiffness moduli—(Rowe) (Zak et al. 2013; Rowe 1996; Maggiore et al. 2014). These two methods are based on the same

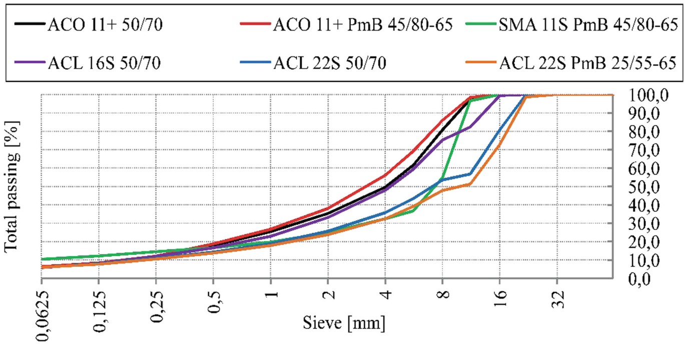

Fig. 1. Grading curves of reference asphalt mixtures

idea of the distribution of the fatigue test results in the controlled strain mode, in the form of the dissipated energy ratio into three phases and the definition of the cycle value (N1) at the phase II and III interfaces as resistance to fatigue (Zak et al. 2013).

The basic volumetric parameters, according to the relevant technical standards, were also determined for the produced mixtures:

• Maximum bulk density	according to ČSN EN 12697-5
• Compacted bulk density	according to ČSN EN 12697-6
• Air void contents	according to ČSN EN 12697-8
• Asphalt binder content	according to EN 12697-1
• Grading curve	according to ČSN EN 12697-2
• Voids in the mineral aggregate	according to ČSN 736160
• Voids filled with asphalt	according to ČSN 736160

Furthermore, the deformation parameters of asphalt mixtures were determined:

• Asphalt stiffness modulus IT-CY	according to ČSN EN 12697-26

All asphalt mixtures were produced at the asphalt plant.

3 Results and Discussion of Reference Mixtures

For the above-mentioned reference mixtures, the basic descriptive parameters (see Table 1) have been determined in accordance with the relevant standards. The stiffness modulus was determined by cyclic loading, using an indirect tensile loading test in controlled strain mode and at a defined loading pulse, on a Universal Testing Machine (UTM). For test mixtures, temperatures of 5, 15 and 30 °C were selected. This non-destructive test was performed on Marshall test specimens.

Table 1. Basic volumetric properties of conventionally produced (reference) mixtures

Asphalt mixture		ACO 11+	ACO 11 +	SMA 11S	ACL 16S	ACL 22S	ACL 22S
Asphalt binder		50/70	PmB 45/80-65	PmB 45/80-65	50/70	50/70	PmB 25/55-65
Air void	(%)	3.0	2.2	3.4	3.1	4.6	3.4
Asphalt binder content	(%)	5.6	5.9	6.6	5.3	4.3	4.2
Aggregate air void content	(%)	16.1	16.0	19.0	15.6	14.8	12.9
Asphalt binder content in the mixture	(% volume)	13.1	13.8	15.5	12.5	10.2	9.4
Voids filled with asphalt	(%)	81.1	86.2	81.9	80.0	68.8	73.2
Stiffness modulus—IT-CY (MPa)	5 °C	12,662	10,226	8373	18,208	23,722	16,012
	15 °C	6480	5514	4452	10,127	12,815	8862
	30 °C	1685	1808	1337	2721	3892	3028

Table 2. Parameters of resistance to permanent deformation

Asphalt mixture		ACO 11+	ACO 11+	SMA 11S	ACL 16S	ACL 22S	ACL 22S
Test temperature		60 °C	60 °C	60 °C	50 °C	50 °C	50 °C
Asphalt binder		50/70	PmB 45/80-65	PmB 45/80-65	50/70	50/70	PmB 25/55-65
Wheel Tracking Test	WTS_{AIR} (%)	0.135	0.034	0.013	0.017	0.014	0.020
	PRD_{AIR} (%)	5.85	3.10	1.90	1.00	1.50	1.30

Resistance to permanent deformation was tested on an air-conditioned Hamburg Wheel Tracking test—small test device. This teste method parameters examine the susceptibility of the asphalt mixture to a permanent deformation, demonstrated by the depth of the rut caused by the repeated travel of the load wheel at a defined temperature. Asphalt mixtures for the permanent deformation resistance test were compacted in the roller compactor according to (ČSN EN 12697-33+A1 2007). The degree of compaction of all samples was maintained in the range of 99.0–101.0%. The test was carried out at 60 °C for the surface layers and at 50 °C for the base layers. The results are shown in Table 2 and Fig. 2.

Other recorded parameters describing the durability of asphalt mixtures against permanent deformations were obtained from the Uniaxial Shear Test (UST) (Zak et al. 2016). The recorded parameters were; the shear modulus, the coefficients of regression accumulated permanent deformation, the number of cycles to permanent shear strain, the constant shear strain values at 5000 and 10,000 cycles, and the increment of permanent strain (see Table 3; Fig. 3). The test was carried out at 60 °C for the surface

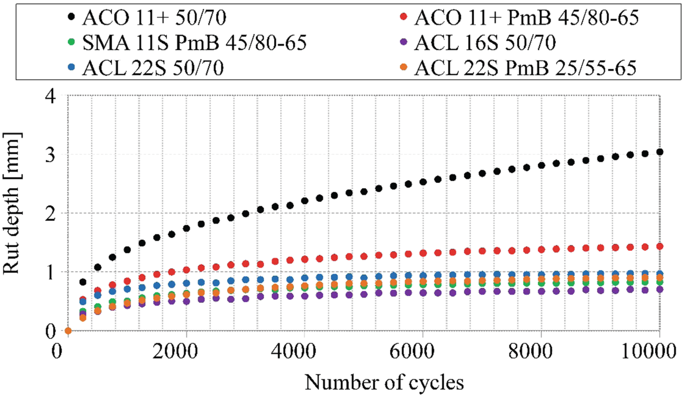

Fig. 2. Permanent deformation during Wheel Tracking Test

layers and at 50 °C for the base layers. The test specimens were manufactured on a gyrator according to ČSN EN 12697-31 in the compaction range of 99.0–101.0%.

The results of the Wheel Tracking Test indicate that ACL 16S, SMA 11S and ACL 22S show higher resistance to permanent deformations. This higher resistance is mainly due to the suitable aggregate composition and the use of a modified binder to fill the air voids to the optimum extent. However, it is difficult to derive the causal relationship between the effects on resistance to permanent deformation from the test parameters, mainly due to the low-resolution capability of the Wheel Tracking test. On the other hand, the ACO 11+ mixture tends to produce permanent deformations, however, the use of a modified binder reduces this deficiency. For ACO 11+ , the hard workability has to be noted.

The resistance to permanent deformation was further monitored using the UST. The UST results indicate a significant effect of the aggregate grain curve and the bituminous binder on the resulting resistance to permanent deformations. The UST allows a better differentiation of individual mixtures from several perspectives: shear modulus, increment of permanent deformation, ratio of elastic and plastic deformation. This makes it possible to identify the susceptibility of asphalt mixtures to permanent deformations.

In the UST test, the effect of the aggregate composition and the binder used is more evident. It can be seen from the evaluation of asphalt mixtures used in surface layers. These mixes exhibit a higher resistance to permanent deformation, especially the SMA 11S mixture and of the ACL 22S mixture with polymer-modified binder. Figure 4 shows test specimens of the ACL 16S mixture, which exhibits the lowest resistance to permanent deformation. The picture was taken after testing so that the accumulated permanent deformation is evident.

The resistance of asphalt mixtures to degradation processes is an important material property because it affects the life of the entire highway construction.

The effect of a parameter characterizing fatigue resistance is apparent from the established design methodologies of pavement structures: It is usually found as an exponent in the calculation and thus exponentially affects the value of the calculated

Table 3. Shear parameters

Shear parameters	ACO 11+ 50/70		ACO 11+ PmB 45/80-65		SMA 11S PmB 45/80-65	
	50 °C	60 °C	50 °C	60 °C	50 °C	60 °C
Shear modulus @ 1000c (MPa)	6.9E+01	5.5E+01	5.1E+01	4.5E+01	5.8E+01	6.0E+01
Regression of accumulated shear strain [–]						
parameter A	4.5E−03	7.1E−03	5.0E−03	7.4E−03	5.0E−03	1.6E−03
parameter B	1.6E−01	1.5E−01	1.3E−01	1.3E−01	1.8E−01	2.8E−01
Number of cycles to [–]						
1% γ	2.0E+08	9.2E+05	5.7E+08	3.8E+06	6.1E+05	7.1E+05
3% γ	2.0E+08	9.2E+05	5.7E+08	3.8E+06	6.1E+05	7.1E+05
5% γ	2.6E+10	3.3E+07	1.2E+11	2.8E+08	6.8E+06	1.3E+07
Permanent shear strain						
at 5000 cycles (mγ)	1.8E+01	2.2E+01	1.5E+01	2.1E+01	1.8E+01	1.7E+01
at 10,000 cycles (mγ)	2.0E+01	2.8E+01	1.6E+01	2.2E+01	1.9E+01	2.2E+01
Increment of permanent deformation (mγ/10^3)	4.4E−01	1.1E+00	2.1E−01	3.1E−01	2.6E−01	1.1E+00
Shear parameters	ACL 16S 50/70		ACL 22S 50/70		ACL 22S PmB 25/55-65	
	50 °C	60 °C	50 °C	60 °C	50 °C	60 °C
Shear modulus @ 1000c (MPa)	7.6E+01	5.1E+01	6.8E+01	4.9E+01	6.2E+01	5.6E+01
Regression of accumulated shear strain [–]						
parameter A	1.2E−02	4.1E−03	1.6E−02	5.2E−03	5.4E−03	7.8E−03
parameter B	1.7E−01	2.8E−01	9.3E−02	1.5E−01	1.5E−01	1.1E−01
Number of cycles to [–]						
1% γ	9.3E+04	3.1E+03	8.2E+02	1.5E+03	1.9E+05	6.6E+09
3% γ	9.3E+04	3.1E+03	8.2E+02	1.5E+03	1.9E+05	6.6E+09
5% γ	6.4E+05	2.1E+04	2.2E+05	3.3E+04	1.1E+07	4.3E+11
Permanent shear strain						
at 5000 cycles (mγ)	3.2E+01	3.7E+01	3.5E+01	4.2E+01	1.9E+01	1.9E+01
at 10,000 cycles (mγ)	3.5E+01	5.0E+01	3.6E+01	4.7E+01	2.1E+01	2.0E+01
Increment of permanent deformation (mγ/10^3)	6.3E−01	2.8E+00	2.9E−01	1.1E+00	3.3E−01	2.7E−01

pavement resistance (TP 170 2004; Epps et al. 2002; Monismith 2012; Balay, Caron, a Lerat, b.r.). The fatigue parameter value is therefore essential both for the design and for the life of the road construction.

Fatigue is defined as a consequence of a repeated load on the internal structure of the compacted asphalt mixture. It is manifested by the gradual decrease of the complex stiffness moduli in relation to the number of load cycles. The life of the asphalt mixture, which is defined as the number of load repetitions to sample failure, can therefore be measured. In a controlled strain test, the damage of the bond between the stressed

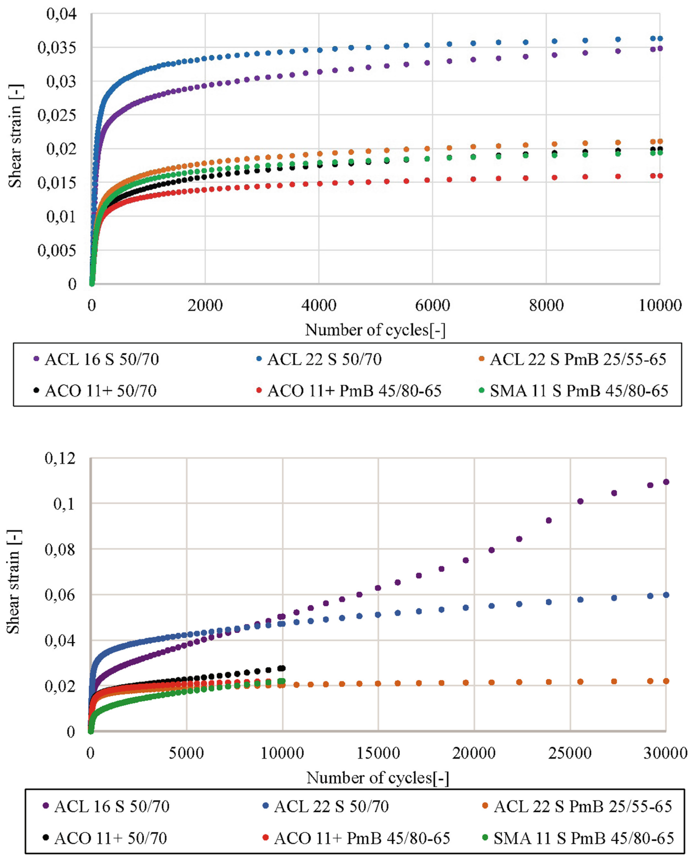

Fig. 3. Permanent deformation during Uniaxial Shear Test

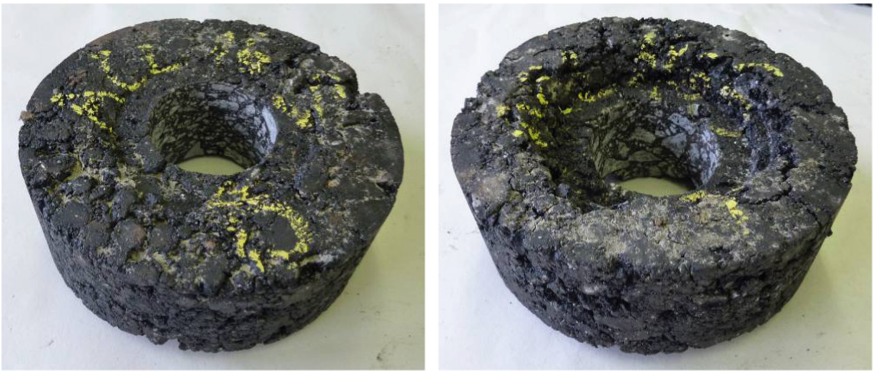

Fig. 4. Accumulated permanent deformation (ACL 16S 50/70)—Uniaxial Shear Test (UST)—50/60 °C

particles is recorded by a drop in force resistance, when the force resistance of the damaged bond is not transmitted to the other bonds (Zak et al. 2013; Zak et al. 2015).

Each fatigue test was performed on 18 test specimens in controlled strain mode with three strain levels, so that a 50% drop in the complex stiffness modulus occurred in the 10^4–2.10^6 load cycle interval. The temperature was kept constant at 20 ± 1 °C. The load frequency was 30 Hz according to ČSN EN 13108-20. The test samples were produced on a segment compaction equipment at a compaction range of 99.0–101.0%. The slabs were then cut to the defined dimensions required for the test samples. Test results are shown in Fig. 5.

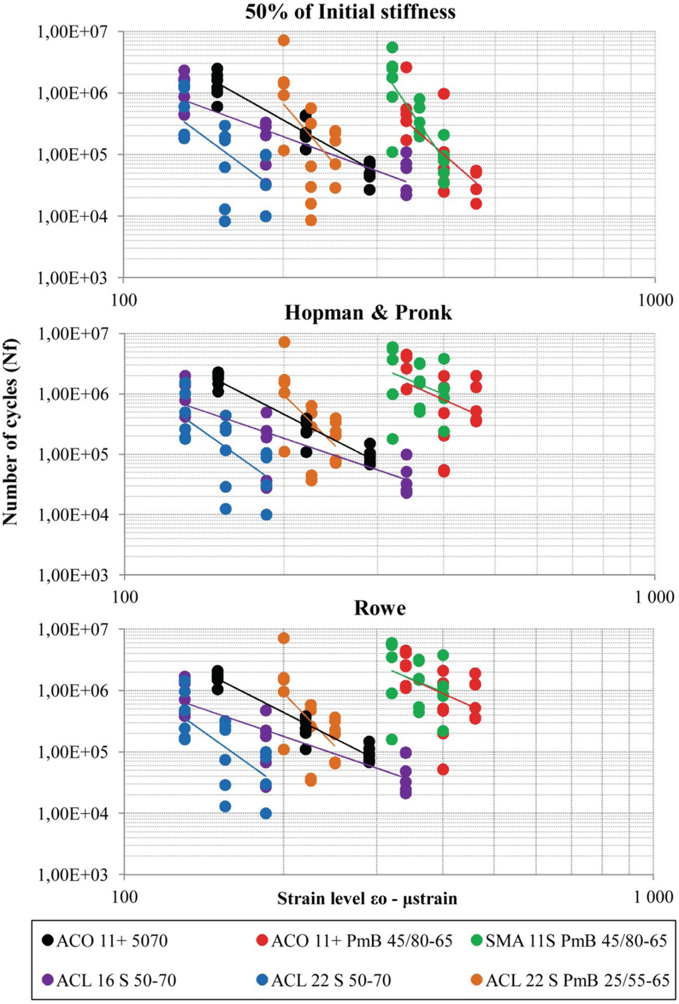

Fig. 5. Fatigue resistance

It follows from the results that the highest values of fatigue resistance are shown in SMA 11S for the surface layers and the ACL 22S mixture for base layers. Both of these mixtures contain a relatively high amount of a polymer modified binder. Figure 6 shows a comparison between the different mixtures, for the conventional 50% drop in stiffness modulus and energy dissipation methods (Rowe, Hopman and Pronk), by evaluating the fatigue parameter e_6 derived from the fatigue curve (Zak et al. 2014).

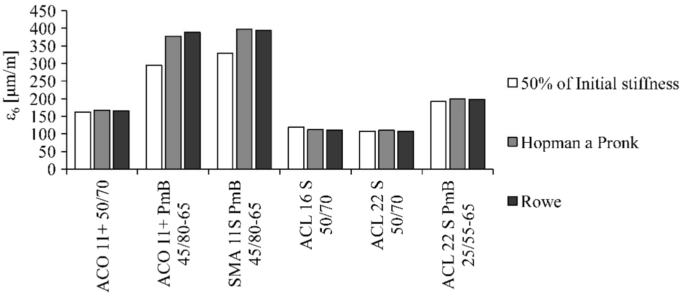

Fig. 6. Strain ε_6 derived from the Wöhler curve at 10^6 cycles

These test results prove that the resistance to fatigue of asphalt mixtures determined by the energy dissipation method, is higher than the 50% method of stiffness reduction. The results also show that this is more evident in asphalt mixtures with modified asphalt binders, which implies that the asphalt mixtures with polymer modified binders better dissipate energy in terms of fatigue resistance. The fatigue properties were determined based on the procedure described in (Zak et al. 2015; Zak et al. 2013).

4 Design and Evaluation of Asphalt Mixtures that Dissipates Energy—SMA 16

The basic principle of this design, methods and principles is to develop an asphalt mixture that, to the greatest extent, resists the accumulation of permanent deformations and at the same time exhibits the longest fatigue life.

For the development of the dissipating asphalt mixtures, five asphalt binders available on the market were selected and evaluated. Selected binders were evaluated primarily with respect to their mechanical properties. Individual binders were evaluated using both empirical and mechanical tests, with emphasis on changes caused during the aging of the asphalt binder. Short-term aging has been simulated to describe the changes that occur during the production, laying and compacting of the asphalt mixture, and long-term aging. From this research according to the tested parameters a modified binder PmB 45/80-85 was selected.

The choice of asphalt mixtures results from the evaluation of the reference mixtures or from the above mentioned assessment of the functional parameters of the reference mixtures. The study of the reference mixtures implies that tested variants with higher maximum grain size better resists to permanent deformations. Based on this, a mixture of SMA with a maximum grain size D = 16 mm was chosen. Thus the proposed new mixture that dissipates energy is SMA 16. Five variants of the gradation curves (see Fig. 7) were created to match the grading curves according to ČSN EN 13108-5. The aggregate used for new asphalt mixtures comes from the same source as the aggregate used in reference mixtures.

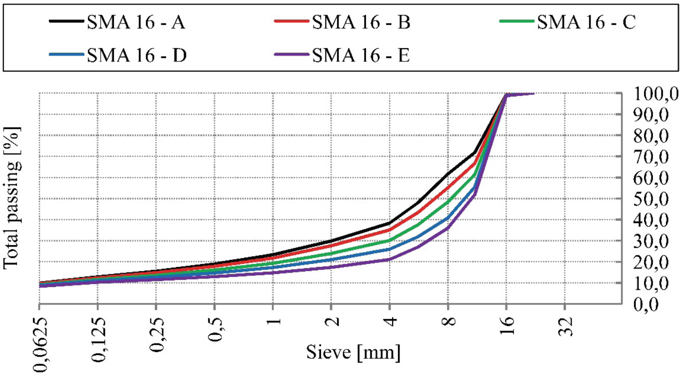

Fig. 7. Asphalt mixture grading curves—SMA 16

Table 4. Volumetric properties—SMA 16—new asphalt mixtures

SMA 16					
Variant	Binder content (%)	Air voids (%)	Voids in mineral aggregate (%)	Asphalt binder content (% volume)	Voids filled with asphalt (%)
A	5.3	3.1	15.6	12.5	80.1
	5.7	2.6	16.0	13.4	83.7
	6.2	1.4	16.1	14.6	91.0
B	5.3	3.1	15.5	12.4	80.1
	5.7	2.5	15.9	13.4	84.5
	6.2	1.9	16.5	14.6	88.2
C	5.3	3.5	15.9	12.4	78.0
	5.7	3.3	16.6	13.3	80.0
	6.2	3.1	17.6	14.5	82.3
D	5.3	4.4	16.7	12.3	73.7
	5.7	3.7	16.9	13.2	78.3
	6.3	2.9	17.5	14.7	83.6
E	5.3	7.8	19.7	11.9	60.3
	5.7	7.3	20.1	12.8	63.6
	6.3	6.3	20.2	13.9	68.9

For individual variants (A-E) of the grading curves an optimization was performed based on the graduated quantity (5.3–5.7–6.2 wt%) of the added asphalt binder. For these sub-variants, the basic volumetric parameters are presented in Table 4.

Individual variants (A-D) were subsequently optimized to meet the requirements of ČSN EN 13108-5. The variant E did not fulfill the standard requirements so it was excluded from further testing. The next step was to determine the resistance to permanent deformation in Hamburg Wheel Tracking Test and the IT-CY stiffness modules as first indicators of mixtures suitability for further testing. The results are shown in Table 5.

Table 5. Optimized variants—SMA 16

SMA 16					
Variant		A	B	**C**	**D**
Binder content (% weight)		5.4	5.5	**5.7**	**5.8**
Air voids (%)		2.8	2.9	**3.3**	**3.4**
Voids in mineral aggregate (%)		16.7	15.8	**16.5**	**16.9**
Asphalt binder content (% volume)		14.0	12.9	13.2	13.5
Voids filled with asphalt (%)		83.0	81.6	79.9	79.8
Wheel Tracking Test	WTS_{AIR} (%)	0.039	0.025	0.021	0.016
	PRD_{AIR} (%)	2.2	2.2	**1.5**	**1.1**
Stiffness modulus—IT-CY (MPa)	5 °C	13,935	15,146	**14,331**	**14,927**
	15 °C	5939	7023	**6905**	**7457**
	30 °C	1244	1507	**1571**	**1736**

Table 6. Shear parameters of SMA 16 C, D

Shear parameters	SMA 16-C		SMA 16-D	
	50 °C	60 °C	50 °C	60 °C
Shear modulus @ 1000c (MPa)	6.34E+01	6.40E+01	6.65E+04	5.15E+04
Regression of accumulated shear strain [–]				
parameter A	1.09E−02	9.78E−03	4.93E−03	9.29E−03
parameter B	9.81E−02	9.54E−02	2.39E−01	5.84E−02
Number of cycles to [–]				
1% γ	3.79E+04	2.29E+04	1.37E+02	4.91E+01
3% γ	3.79E+04	2.33E+07	2.77E+03	1.35E+07
5% γ	3.50E+06	5.89E+08	1.85E+04	1.30E+10
Permanent shear strain				
at 5000 cycles (mγ)	1.75E+01	1.40E+01	9.24E+00	7.86E+00
at 10,000 cycles (mγ)	1.82E+01	1.49E+01	9.65E+00	8.23E+00
at 30,000 cycles (mγ)	–	2.08E+01	–	1.77E+01
Increment of permanent deformation (mγ/10^3)	1.38E−01	1.69E−01	8.15E−02	7.33E−02

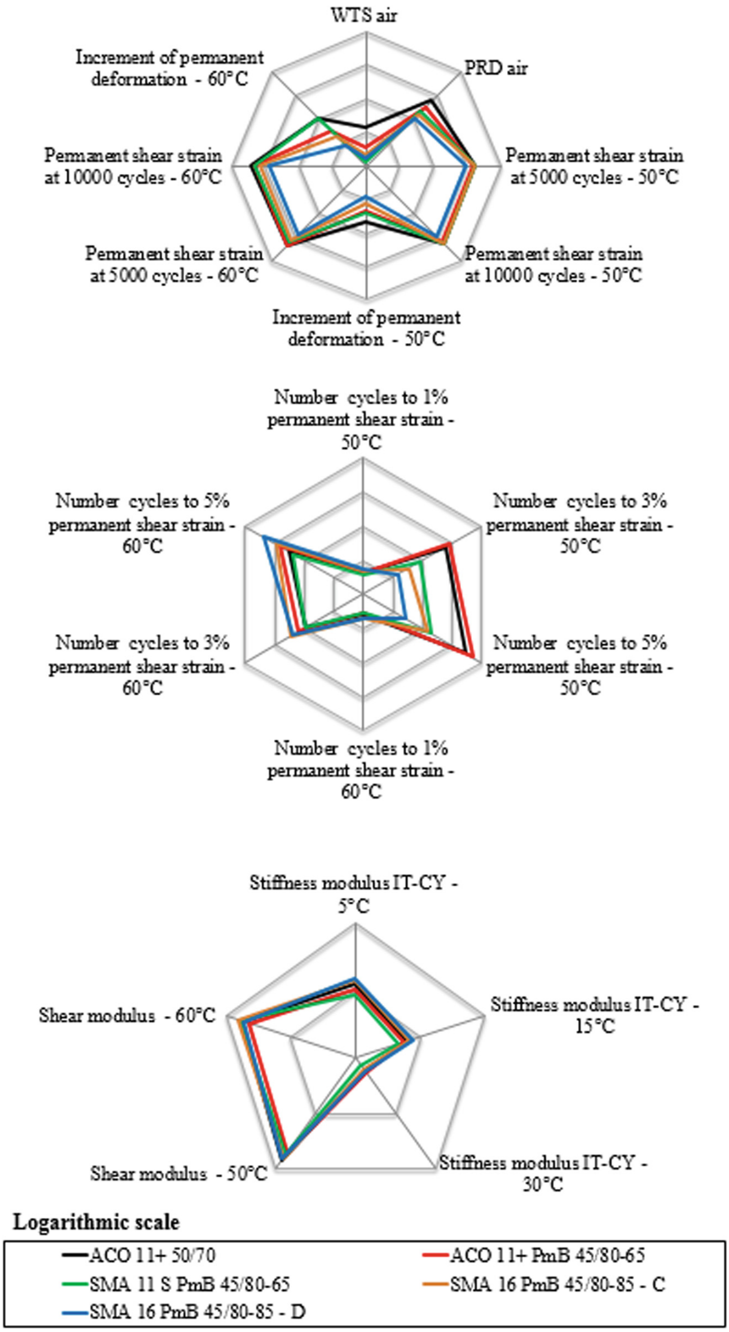

Fig. 8. Schematic comparison of the test mixtures

The results show a clear influence of the aggregate composition (grading curves), respectively with the increase in the content of coarser grains in the mixture the resistance to the permanent deformation increases. The influence of binder content is also significant. From the results obtained in Table 5, variants C and D were further evaluated and analyzed in Uniaxial Shear Test. Results are shown in Table 6.

The SMA 16-C and SMA 16-D variants are compared to the reference mixtures and results are presented in Fig. 8. Here it is quite clear that the SMA 16-D mixture qualitatively shows a very good resistance to permanent deformations compared to the other reference mixtures under consideration. This method of designing the mixture using empirical and functional tests made it possible to design a qualitatively more efficient asphalt mixture in terms of selected parameters. In addition the Uniaxial Shear Test is capable to better distinct than Hamburg Wheel Tracking between asphalt mixtures resistance to permanent deformation.

5 Conclusions

The objective of the research project is not to compare conventionally produced asphalt mixtures between each other, but to examine the influence of the individual components of the mixtures on the resulting mechanical and physical properties. Then, on the basis of this knowledge, the objective was to propose new mixtures that dissipate energy more effectively. From all studied new variants of asphalt mixtures the variant D has a better performance and asphalt mixture properties are reported in this paper.

It is not assumed that a newly designed asphalt mixture will be cheaper than conventional materials, but will be a better value material with better functional properties, thus reducing the cost of repairs, maintenance and reconstruction over the service life of the infrastructure. The economic benefits from the use of these materials will be predominantly felt by administrators and owners of transport infrastructure.

This article recommends the possibility of maximizing the useful properties of bituminous mixtures by using more accurate evaluation procedures and by using more accurate test procedures with higher resolution capabilities such as a Uniaxial Shear Tester.

The presented test results imply that the asphalt mixtures with polymer modified binders better dissipate energy in terms of both permanent deformation and fatigue resistance.

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