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THE EFFECT OF COMPACTION DEGREE AND BINDER CONTENT ON PERFORMANCE PROPERTIES OF ASPHALT MIXTURES

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Abstract. The effect of compaction degree and binder content on performance properties of asphalt mixtures of an asphalt concrete type for wearing and binder courses are described in the paper. Measurements of stiffness modulus by two-point bending test on trapezoidal shaped specimens, fatigue characteristics, and resistance against frost cracking by thermal stress restrained specimen test have been performed on selected asphalt mixtures. The main aim of the experimental part was to determine to what extent the performance properties of the individual mixtures will be affected when decreasing the compaction degree by 3% in comparison to the optimal design, i.e. from 100% to 97% degree of compaction. This decrease simulates incomplete degree of compaction of courses during pavement construction, which is common and accepted during acceptance tests and it is in accordance with the Czech regulations. Then, the decreased dosage of binder content by 0.5% is simulated, which is the boundary parameter for lowering the binder content within the acceptance test. The results of performance testing have been affected by lower compaction degree and lower binder content have been used as course parameters and integrated into a mathematical model of a commonly used pavement construction, which is presented by a multi-layered linear elastic model based on the use of Burmister's equations. The outcome of the paper is a description of the effect of lower degree of compaction and lower binder dosage on the lifetime of a pavement construction.

Keywords: asphalt mixture, binder content, compaction degree, fatigue, multi-layer linear elastic model, performance properties, stiffness.

1. Introduction

The fundamental requirement of a pavement construction is safe, fast and comfortable traffic flow with minimal effects on the environment and with limited construction disruption (Pellinen *et al.* 2009; Petkevičius, Petkevičienė 2014). The pavement construction is especially affected by the traffic load and the effects of the surrounding environment (temperature and humidity) (Androjić, Dimter 2015; Vaitkus *et al.* 2014). The pavement bearing capacity is the ability of a pavement construction and course to bear traffic load, which is given as the number of repeated loadings during the course of the design period, which is expected to be 25 years in the Czech Republic. This bearing capacity is affected by the thickness of the individual pavement construction courses and also their properties.

The asphalt mixture is a three-phase system composed of optimally prepared aggregate mixture bound by an asphalt binder. After being coated and compacted, it forms a compact layer, where is a certain percentage of air voids (Di Benedetto *et al.* 2004, 2007; Harvey, Tsai 2007).

The compaction process of pavement layers is a key factor in the construction of asphalt pavements of a high quality (Pellinen 2003). Asphalt mixture layer compaction is purely a physical process, during which the granular material is compacted by rolling, kneading and/or by vibrations. During layer compaction the air void content decreases, inner friction and bulk density increases (Beuving, Luby 2016). Compatibility is especially affected by the type and origin of the filler and aggregate, particle size distribution, filler and binder content, binder viscosity, compaction temperature and compaction energy (Bahia *et al.* 2006). The degree of compaction of asphalt layers and binder content have a major effect over the course of the entire pavement construction lifetime and on the costs during its life cycle (Beckedahl 2008).

Due to the constantly increasing prices of input materials (especially asphalt binder, prices that are directly

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related to the price of crude oil), it is necessary that their functional potential is used as much as possible. Only optimally designed asphalt mixtures made exactly according to the initial type testing (ITT) and a construction with 100% degree of compaction can perform its maximum functional potential in pavement construction.

This paper describes the degree of decrease of selected performance parameters and their effects on shortening of the overall asphalt pavement construction lifetime, if the parameters, included in the standard, are on its lower limit of tolerance. In most of European countries, these parameters are for example:

– Tolerance in asphalt binder dosage during asphalt mixture production in asphalt mixing plant compared to ITT (typically –0.5% lowering is acceptable),

– Asphalt mixture degree of compaction in comparison to ITT (typically acceptable to use even a layer with 97% degree of compaction).

The deterministic pavement performance models vary from simplistic empirical relationships to complex mechanistic empirical computational algorithms. Numerical models for tensile strength and strain of pavements gradually developed from the Boussinesq's theory to dual-layer systems (Burmister 1945), Odemark (ElBadawy, Kamel 2011), then three-layer systems (Jones 1962), and finally multi-layer systems, which use computer technology. In the most commonly used multi-layer linear elastic mathematical model, each construction layer of asphalt pavement is composed of elastic homogenous and isotropic material and it is characterized by its stiffness modulus, Poisson number and thickness. Stiffness modulus, Poisson number and thickness characterize subgrade, which is considered as infinite (Pszczoła, Judycki 2012).

Heavy trucks, climate conditions, inadequate construction width, groundwater effect, unsuitable physical and mechanical properties of materials and inadequate or late performing of maintenance and repair negatively affect the pavement construction. One of the main criteria allowing describing vehicle impact on pavement is the number of equivalent standard axle loads (ESAL). The use of the ESAL index makes it possible efficiently predict durability of pavements and plan the repair and reconstruction works of roads.

ESAL evaluates the impact of vehicle axles on pavement performance. Maximal axle load is 100 kN and its impact is equal to one. The impact of axle, which varies from the normal axle, is called the equivalent of standard axles and it is calculated by Eq (1) (Čygas *et al.* 2008).

$$ESAL_{100A} = \sum_{i}^{n} N_i \left(\frac{A_i}{100} \right)^4, \quad (1)$$

where $ESAL_{100A}$ – number of equivalent standard 100 kN axle loads; n – potential number of the variations of vehicle axle loads; N_i – number of axles with the equal load; A_i – vehicle axle load, kN.

2. Selecting an asphalt mixture

Mixtures have been chosen from a sieve curve range of asphalt concretes for wearing courses with a sieve size less than 11 mm (AC 11) and asphalt concrete for binder courses with sieve sizes less than 16 mm (AC 16). They are defined in the Czech national appendix of the European harmonized material standard *EN 13108-1 Bituminous Mixtures – Material Specifications – Part 1: Asphalt Concrete*. Aggregate sieve size distributions have been chosen in a way that they cover the entire range of particle sizes. The Fuller parabola was used for easier definition of the individual sieve size distributions. In general, three representative mixtures were designed for both cases.

Mixture naming:

„I"– mixture with a sieve size distribution exceeding the Fuller parabola and being on the upper limit of the sieve curve range, given by the standard,

„II" – commonly used mixture with sieve size distribution slightly below the Fuller parabola,

„III" – mixture with sieve size distribution running on the lower limit of the sieve curve range.

Sieve size distributions of AC 11 mixtures are depicted in Fig. 1 and sieve size distributions of mixtures AC 16 are shown in Fig. 2.

The design of the mixtures and finding the optimum binder content was based on previous experience from designing asphalt mixtures, where the decisive value for determining the optimum was searched for air void content ranging from:

– 3.5% to 4.0% interval in case of AC 11 mixtures,

– 4.0% to 5.0% interval in case of AC 16 mixtures.

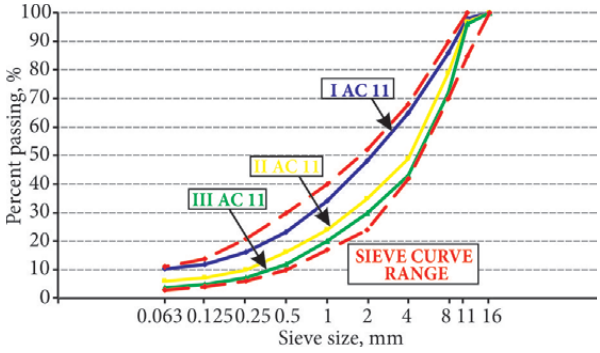


Fig. 1. Sieve size distributions of asphalt mixtures AC 11

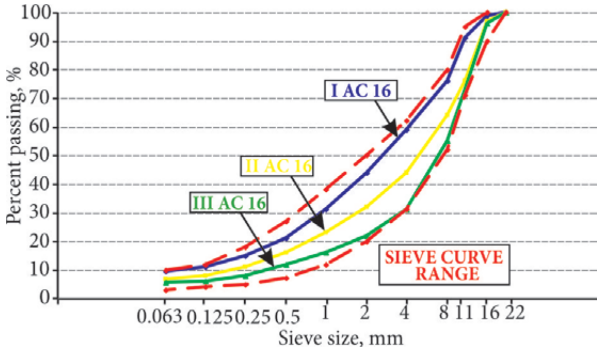


Fig. 2. Sieve size distributions of asphalt mixtures AC 16

Mixtures were designed using the Marshall design method (Luminari, Fidato 1998) and testing specimens were compacted by Marshall compactor in accordance with *EN 12697-30 Bituminous Mixtures – Test Methods for Hot Mix Asphalt – Part 30: Specimen Preparation by Impact Compactor*. The air void content parameter is one of the mandatory volumetric parameters, based on which the designed mixtures are evaluated. The effect of compaction degree was analysed on non-typical asphalt mixtures of asphalt concrete type and their composition covered the entire spectrum of sieve size distributions required by the standard. This was subsequently reflected in the dosage of bitumen in order to comply with the air void content criterion.

Taking into account the climate conditions in the Czech Republic and based on the fact that the mixtures are usually used on roads with a heavy traffic load, the paving bitumen of 50/70 gradation was used as the asphalt binder for both mixture types. Volumetric parameters of the individual AC 11 and AC 16 mixtures are given in Table 1 and Table 2 respectively.

3. Stiffness modulus

Stiffness modulus (Di Benedetto, De La Roche 1998) of the individual mixtures was determined based on the *EN 12697-26 Bituminous Mixtures – Test Methods for Hot Mix Asphalt – Part 26: Stiffness* using two-point bending test on trapezoidal shaped specimens performed at 15 °C and load frequency of 5 to 25 Hz. The appendix of the national standard *EN 12697-26* and *Technical Recommendation No. 170 Pavement Design* require determination of stiffness modulus at 10 Hz frequency. The mixtures, prepared in laboratory, were compacted according to *EN 12697-35 Bituminous Mixtures – Test Methods for Hot Mix Asphalt – Part 35: Laboratory Mixing* using a compactor with a roller running on vertical sliding steel plates. (Specified in *EN 12697-33 Bituminous Mixtures – Test Methods for Hot Mix Asphalt – Part 33: Specimen Prepared by Roller Compactor*). Mixtures have been compressed into slabs with dimensions of 260×320×50 mm. Trapezoidal shaped specimens were prepared using sliding table circular saw. For the purposes of the stiffness modulus test, 18 trapezoidal shaped specimens were produced from each mixture.

AC 16 mixture testing specimens are shown in Fig. 3. Stiffness modulus of AC 11 mixtures is described in Table 3 and stiffness modulus of mixtures AC 16 is given in Table 4. The influence of compaction degree and binder content decrease on stiffness is shown graphically in Figs 4 and 5, where ΔM is the difference between air void content of mixture with optimal binder content and air void content of mixture with binder content reduced by 0.5%.

Increasing the frequency leads to the increase in stiffness modulus of the mixture. The frequency sensitivity of asphalt mixtures was assessed by the ratio of stiffness modulus, determined at a frequency of 25 Hz and stiffness

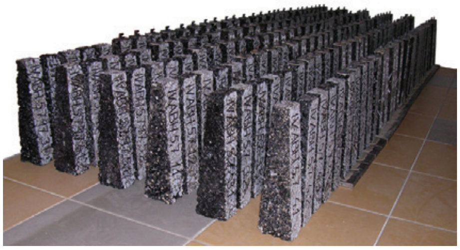


Fig. 3. AC 16 mixtures testing specimens for the determination of stiffness modulus and fatigue characteristics

Table 1. AC 11 mixture design evaluation

Mixture	Binder dosage	Binder content	Air void content	VMA	VFB	Sieve size distribution, %									
		%				16	11	8	4	2	1	0.5	0.25	0.125	0.063
I AC 11	optimum −0.5%	4.1	5.3	14.8	64	100	98	86	65	48	34	23	16	12	10.2
	optimum	4.6	3.8	14.6	74										
II AC 11	optimum −0.5%	5.1	4.4	16.2	73	100	97	79	49	35	24	16	10	7	6.0
	optimum	5.6	3.2	16.3	80										
III AC 11	optimum −0.5%	5.7	5.6	18.6	70	100	96	72	43	30	20	12	7	5	3.6
	optimum	6.2	3.9	18.1	79										

Note: VMA – Void in mineral aggregate; VFB – Void filled with binder.

Table 2. AC 16 mixture design evaluation

Mixture	Binder dosage	Binder content	Air void content	VMA	VFB	Sieve size distribution, %									
		%				16	11	8	4	2	1	0.5	0.25	0.125	0.063
I AC 16	optimum −0.5%	3.5	6.8	14.8	54	99	91	76	59	44	31	21	15	11	9.3
	optimum	4.0	4.5	13.9	67										
II AC 16	optimum −0.5%	3.9	6.2	15.2	59	97	76	64	44	32	23	16	11	8	6.8
	optimum	4.4	4.6	14.8	69										
III AC 16	optimum −0.5%	5.2	5.6	17.4	68	96	73	55	31	22	16	12	8	6	5.5
	optimum	5.7	4.2	17.2	75										

Note: VMA – Void in mineral aggregate; VFB – Void filled with binder.

Table 3. Stiffness modulus of AC 11 mixtures

Mixture	Compaction degree	Binder content		Stiffness modulus at 15 °C, MPa				
				5 Hz	10 Hz	15 Hz	20 Hz	25 Hz
I AC 11	100%	optimum –0.5%	4.1%	8518	9222	9503	9860	9970
		optimum	4.6%	7876	8644	8758	9156	9272
II AC 11		optimum –0.5%	5.1%	7536	8260	8586	8953	9136
		optimum	5.6%	6496	7353	7768	8229	8455
III AC 11		optimum –0.5%	5.7%	6631	7439	7758	8170	8326
		optimum	6.2%	5932	6641	6974	7326	7501
I AC 11	97%	optimum –0.5%	4.1%	7615	8370	8678	9020	9166
		optimum	4.6%	7075	7724	7866	8231	8363
II AC 11		optimum –0.5%	5.1%	6649	7278	7568	7930	8065
		optimum	5.6%	5511	6229	6569	6906	7083
III AC 11		optimum –0.5%	5.7%	5369	6016	6310	6646	6796
		optimum	6.2%	5025	5670	5989	6283	6433

Table 4. Stiffness modulus of AC 16 mixtures

Mixture	Compaction degree	Binder content		Stiffness modulus at 15 °C, MPa				
				5 Hz	10 Hz	15 Hz	20 Hz	25 Hz
I AC 16	100%	optimum –0.5%	3.5%	8559	9193	9222	9643	9734
		optimum	4.0%	8569	9342	9464	9900	10037
II AC 16		optimum –0.5%	3.9%	7957	8630	8679	9083	9226
		optimum	4.4%	7380	8046	8148	8540	8548
III AC 16		optimum –0.5%	5.2%	5699	6401	6572	6977	7105
		optimum	5.7%	5101	5867	6061	6464	6652
I AC 16	97%	optimum –0.5%	3.5%	6748	7316	7377	7710	7813
		optimum	4.0%	7096	7816	7942	8358	8499
II AC 16		optimum –0.5%	3.9%	5664	6296	6418	6642	6870
		optimum	4.4%	6141	6886	7049	7427	7585
III AC 16		optimum –0.5%	5.2%	4121	4735	4906	5243	5394
		optimum	5.7%	4078	4674	4856	5196	5347

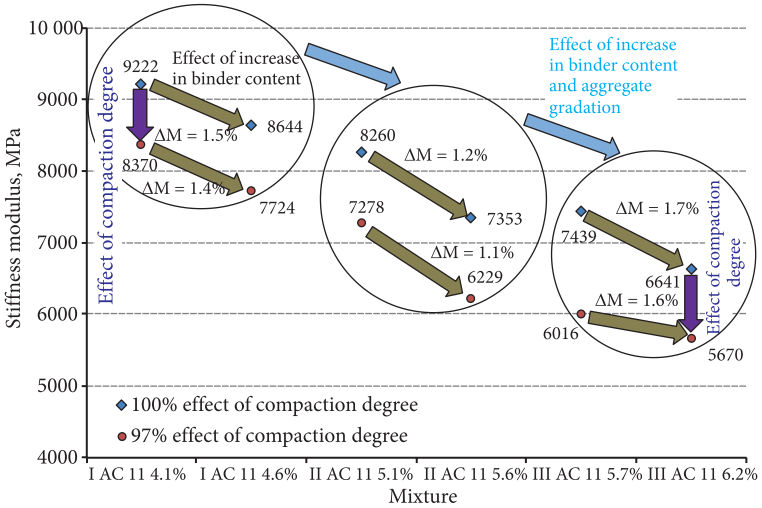


Fig. 4. Comparison of stiffness modulus of AC 11 mixtures depending on the degree of compaction (ΔM is the difference between air void content of mixture with optimal binder content and air void content of mixture with binder content reduced by 0.5%)

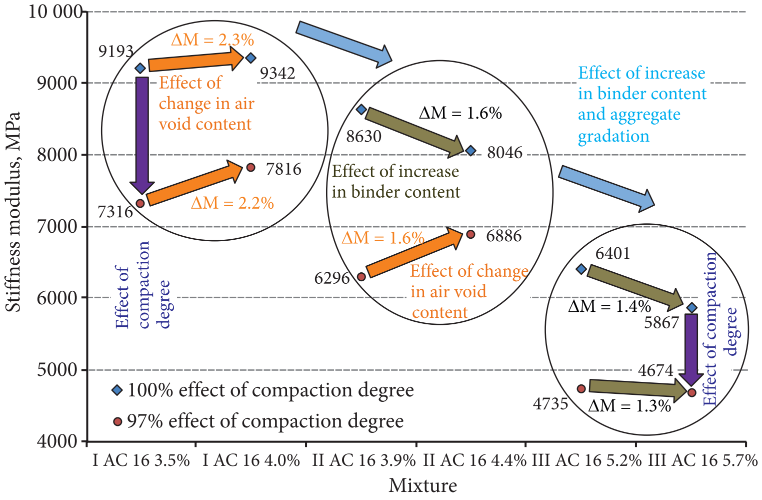


Fig. 5. Comparison of stiffness modulus of AC 16 mixtures depending on the degree of compaction (ΔM is the difference between air void content of mixture with optimal binder content and air void content of mixture with binder content reduced by 0.5%)

modulus determined at a frequency of 5 Hz. On average for all the compared asphalt mixtures, the stiffness modulus determined at a frequency of 25 Hz is 23% higher than stiffness modulus determined at 5 Hz frequency.

Lowering the degree of compaction by 3% did not have an effect on the ratio of stiffness modulus, determined at a frequency of 25 Hz and 5 Hz. When lowering the binder content of the individual mixtures by 0.5%, usually a slight increase was observed in the ratio of stiffness modulus determined at 25 Hz and 5 Hz (on average 3% for both AC 11 and AC 16 mixtures). The factor with largest effect on frequency sensitivity turned out to be the actual composition of the asphalt mixture, i.e. the aggregate gradation and the corresponding binder content: ratio of stiffness modulus determined at 25 Hz frequency and stiffness modulus determined at a frequency of 5 Hz of I AC 11 type mixture was 1.18 (1.17 for mixture I AC 16), in case of mixture II AC 11 the ratio was 1.25 (1.19 for mixture II AC 16) and for mixture III AC 11 the ratio was 1.27 (1.29 for mixture III AC 16). This can be explained by the difference in binder content of the individual mixtures.

The measured values of stiffness modulus depending on the sieve size distribution, binder content and degree of compaction ranges between 5670 MPa and 9222 MPa in case of the AC 11 type mixtures and 4674 MPa and 9342 MPa in case of the mixtures of the AC 16 type at frequency 10 Hz. For the asphalt mixtures of AC 11 type with a compaction degree decreased to 97%, there was a decrease in the value of stiffness modulus ranging from 9% to 19%. For the asphalt mixtures of AC 16 type with a compaction degree decreased to 97% there was a decrease in the value of stiffness modulus ranging from 14% to 27%. This shows that lowering the compaction degree has a more profound effect on the stiffness of mixtures of the AC 16 type.

In case of the AC 11 type asphalt mixtures with binder dosage decreased by 0.5%, there was always an increase in the value of the stiffness modulus (ranging from 6.1% to 16.8%), because AC 11 type mixtures are not affected too much by a change in air void content associated with decreased binder content. However, it should be noted that increase in stiffness modulus upon lowering the binder content does not lead to better properties of the mixture, even though the stiffness modulus increases. This is because lowering the amount of binder content also means worse fatigue characteristics as they will be described later.

The measured values of stiffness modulus of the AC 16 type mixtures upon lowering the binder content by 0.5% are affected by the air void content of the mixture. If the air void content of a mixture with lowered binder content increases more than 1.6% compared to air void content of the mixture with optimum binder content, the stiffness modulus of a mixture with lower binder content decreases. This is probably due to the fact that the properties of the mixture are affected more by an increase in air void content than by a decrease in binder content.

4. Fatigue characteristics

Fatigue characteristics (ε_6 and B) were chosen in accordance with the *EN 12697-24 Bituminous Mixtures – Test Methods for Hot Mix Asphalt – Part 24: Resistance to Fatigue* and determined using two-point bending test performed at 10 °C and load frequency of 25 Hz by the strain control method. The ε_6 parameter is the average size of strain derived from the fatigue line at 10^6 load cycles, and the B parameter describes the slope of a fatigue line in a Wöhler diagram (Bahia 1999; Bodin *et al.* 2004). AC 11 type mixtures did not undergo these tests because they are used as wearing courses and do not crack according to the classical fatigue theory (if the topdown fatigue is neglected). The results of the measurements of fatigue characteristics of AC 16 mixtures are given in Table 5 including the theoretical bitumen film thickness on the surface of the aggregate *t* in mm. Fig. 6 shows a graphical representation of the evaluation of fatigue characteristics using Wöhler diagrams. Wöhler diagram for each asphalt mixture was constructed using 18 test specimens.

Table 5. Fatigue characteristics of AC 16 type mixtures

Mixture	Binder content		100% compaction degree		97% compaction degree		Bitumen film thickness
			$\varepsilon_6 \cdot 10^{-6}$	B	$\varepsilon_6 \cdot 10^{-6}$	B	$\cdot 10^{-3}$ mm
I AC 16	optimum –0.5%	3.5%	95.1	4.70	87.6	4.61	2.37
	optimum	4.0%	99.0	5.59	90.0	4.53	2.72
II AC 16	optimum –0.5%	3.9%	113.9	5.03	87.9	4.55	3.60
	optimum	4.4%	118.4	4.31	109.0	4.72	4.08
III AC 16	optimum –0.5%	5.2%	125.9	3.09	110.3	3.62	6.12
	optimum	5.7%	130.2	4.55	117.0	3.81	6.74

When calculating the bitumen film thickness, it is, first, necessary to determine the mixture specific aggregate surface area ε (in m^2/kg) using Eq (2) according to Czech standard *CSN 736160 Testing of Bituminous Mixtures for Roads*:

$$\beta = 0.01(1.174G + 0.40g + 2.30S + 15.33s + 140f), \quad (2)$$

where β – specific aggregate surface area, m^2/kg; G – aggregate ratio retained on 8 mm sieve, % mass; g – aggregate ratio that passes through 8 mm sieve and is retained on 4 mm sieve, % mass; S – aggregate ratio that passes through 4 mm sieve and is retained on 0.25 mm sieve, % mass; s – aggregate ratio that passes through 0.25 mm sieve and is retained on 0.063 mm sieve, % mass; f – aggregate ratio that passes through a 0.063 mm sieve, % mass.

Then the binder content p (kg/100 kg of aggregate) is determined by Eq (3) and binder content p^* (%) is determined by Eq (4):

$$p = n\sqrt[5]{\beta}, \quad (3)$$

where p – binder content, kg/100 kg of aggregate; n – saturation factor (3.4 for wearing courses; 3.1 for binder courses).

$$p^* = \frac{p}{100 + p}100, \quad (4)$$

where p^* – binder content, %.

Then, the volume of bitumen in the asphalt mixture V_b is determined by Eq (5) and the bitumen film thickness t is determined by Eq (6):

$$V_b = \frac{p^*}{\rho_b}, \quad (5)$$

where V_b – volume of bitumen in the asphalt mixture, m^3; ρ_b – density of the bitumen (1020 kg/m^3 used), kg/m^3.

$$t = 1000\frac{V_b}{\varepsilon}, \quad (6)$$

where t – bitumen film thickness on the aggregate surface, mm.

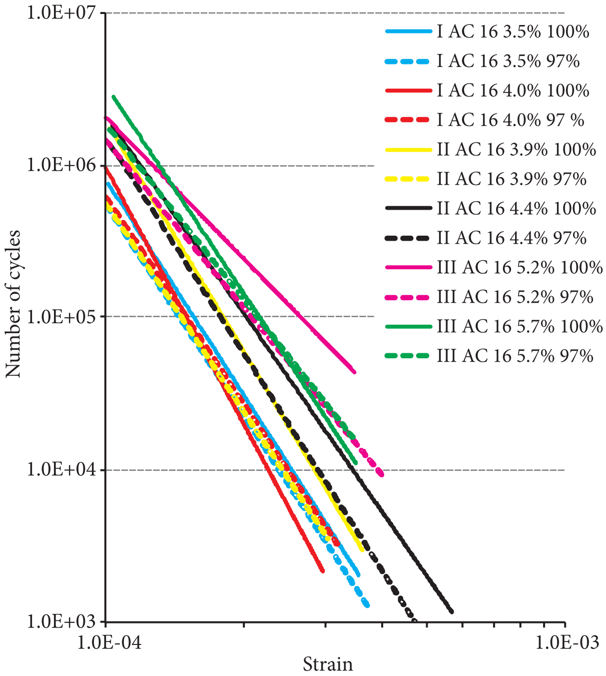


Fig. 6. Wöhler diagrams comparison of the individual AC 16 mixtures

The relationship between fatigue characteristic parameter ε_6 on the binder film thickness on the surface of the aggregate for the individual mixtures is shown in Fig. 7. It can be seen that there is a strong relationship between the ε_6 and the bitumen film thickness.

The measured fatigue parameter ε_6 for the AC 16 type mixtures ranged from 87.6·10^{-6} to 130.2·10^{-6} and the values for the B parameter from 3.09 to 5.59. The Czech requirement for AC type mixtures with unmodified binder used as a binder course is at least 115·10^{-6} for ε_6 and at least 5.0 for B according to national annex of *EN 13108-1* standard and *Technical Recommendation No. 170*.

For asphalt mixtures with compaction degree lowered by 3%, there was a decrease in the ε_6 characteristic by approximately 8% to 23% and the B characteristic decreased by 2% to 23%. Only in case of the mixture with sieve size distribution "II" and with 4.4% binder and 97% degree of compaction, the B characteristic increased slightly. This could be caused by measurement errors of the testing device. For all the tested asphalt mixtures with binder content lowered by 0.5%, there was always a decrease in the ε_6 value in the range of 3% to 19%. No effect upon lowering the binder content has been observed for the B fatigue characteristic.

When comparing the Wöhler diagrams of mixtures with particle sizes "I", "II" and "III", as the binder content increases, there is an obvious shift of the regression lines in the graph upwards and the ε_6 value increases.

5. Low temperature properties

The behavior of an asphalt mixture at low temperatures especially depends on the properties of the used asphalt binder, binder content and on the composition of the asphalt mixture (Arand 1990; Dave, Hoplin 2015; Pszczoła, Judycki 2012). The aim of a uniaxial tension test – Thermal Stress Restrained Specimen Test (TSRST) is to determine the critical temperature and the size of tensile stress in the tested specimen from asphalt mixture. When a crack forms by its cooling at a constant rate of 10 °C/h from the initial temperature, the given specimen is restricted from contracting – i.e. with no longitudinal strain. The low temperature properties were determined according to *EN 12697-46 Bituminous mixtures – Test Methods for Hot Mix Asphalt – Part 46: Low Temperature Cracking and Properties by Uniaxial Tension Tests*. The final values of critical temperature and maximum tensile stress of AC 11 mixtures are given in Table 6 and for AC 16 mixtures in Table 7. Each measured value given in Tables 6 and 7 is an average of the results from five measurements (5 test specimens).

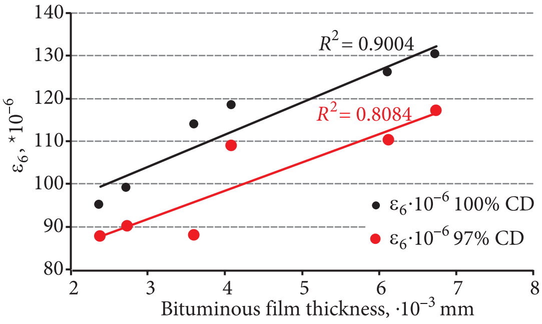


Fig. 7. Relationship between the fatigue characteristic ε_6 and the bitumen film thickness on the surface of the AC 16 mixture aggregate (CD – compaction degree)

Even though the particle size distribution of the individual AC 11 and AC 16 mixtures is quite different, the critical temperature at which frost crack forms lies in a relatively narrow interval and this holds for both 97% and 100% compaction degree. The critical temperature at disruption of the AC 11 mixture lied in the interval between −15.3 °C and −19.9 °C and for the AC 16 mixtures in the interval of −17.4 °C and −20.3 °C. The average critical temperature of the AC 11 mixture (degree of compaction both 100% and 97%) is −18.0 °C and average critical temperature of the AC 16 mixture (degree of compaction both 100% and 97%) is −18.8 °C. In case of the mixtures with 100% compaction degree and optimal binder content, there is an increase (worsening) of the critical temperature, when using aggregates with larger particle sizes (mixtures I → III). This trend, however, was not observed in asphalt mixtures with a lower degree of compaction (97%) and lower binder dosage (−0.5%). This could be due to different composition of the aggregate skeleton in the asphalt mixtures, which can be seen in Fig. 8. When lowering the degree of compaction to 97%, an increase (worsening) of the critical temperature

Table 6. Low temperature properties of AC 11 type mixtures

Mixture	Binder content		Maximum tensile stress, MPa		Critical temperature, °C	
			100% compaction	97% compaction	100% compaction	97% compaction
I AC 11	optimum −0.5%	4.1%	4.96	3.86	−18.4	−17.9
	optimum	4.6%	5.36	4.26	−19.4	−18.4
II AC 11	optimum −0.5%	5.1%	3.95	3.34	−16.9	−18.2
	optimum	5.6%	3.95	2.98	−18.8	−19.9
III AC 11	optimum −0.5 %	5.7%	2.90	2.45	−16.9	−19.4
	optimum	6.2%	2.92	2.40	−15.3	−16.0

Table 7. Low temperature properties of AC 16 type mixtures

Mixture	Binder content		Maximum tensile stress, MPa		Critical temperature, °C	
			100% compaction	97% compaction	100% compaction	97% compaction
I AC 16	optimum −0.5%	3.5%	3.72	2.75	−18.7	−17.6
	optimum	4.0%	4.95	3.77	−19.6	−19.8
II AC 16	optimum −0.5%	3.9%	3.72	1.98	−20.3	−19.2
	optimum	4.4%	3.39	3.08	−18.8	−18.8
III AC 16	optimum −0.5%	5.2%	2.53	1.58	−17.4	−18.1
	optimum	5.7%	3.22	2.04	−18.6	−19.0

(on average by 0.9 °C) was observed in 4 mixtures. For 7 mixtures there was a decrease (improvement) of the critical temperature (on average by 1.0 °C) and in case of one mixture no change was observed. This leads to a conclusion that lowering the degree of compaction by 3% does not have a significant effect on the change of the critical temperature.

Larger differences between the individual asphalt mixtures in comparison to the assessment of critical temperatures were found when comparing the maximum tensile stress. Maximum tensile stress at disruption of testing specimens with 100% compaction degree is, however, on average 24% higher compared to maximum tensile stress of testing specimens with degree of compaction of 97%.

There exists optimum binder content (thickness of bitumen film) in asphalt mixtures, at which maximum tensile strength at low temperatures is achieved (Blab 2013; Hribar, Tušar 2012; Tušar *et al.* 2014). Asphalt mixtures with particle size distribution closer to the upper limit of size distribution range (mixtures "I") have lower bitumen film thickness (between $2.5 \cdot 10^{-3}$ mm and $3.1 \cdot 10^{-3}$ mm) and asphalt mixtures with particle size distribution closer to the lower limit of size distribution range (mixtures "III") have higher bitumen film thickness (between $6.5 \cdot 10^{-3}$ mm and $10.5 \cdot 10^{-3}$ mm). Mixtures "I" have the highest tensile strength compared to other mixtures. When increasing the binder content (mixtures "II" and "III"), there is a decrease in maximum tensile strength. This leads to a conclusion that "I" mixtures have a more suitable thickness of bitumen film relative to their tensile strength when compared to other mixtures. It can be explained by high strength of "bound" bitumen on grains at optimum thickness of bitumen film. For thicker bitumen film the strength decreases, for so called "free-unbound" bitumen which is located in further distance from a grain (mixture "III"). It can be seen in Fig. 9: optimum bitumen film of mixture I AC 11 (left) is so strong that mineral grains are broken. The surface of breaking of mixture III AC 11 goes within bitumen film, which is thicker and softer. It can be assumed that further decrease in bitumen film thickness below that of mixtures "I" would initiate decrease in maximum tensile strength.

Taking into account the relatively narrow interval of the temperature values at crack formation, in case of all the mixtures, it seems reasonable to evaluate the low temperature characteristics of asphalt mixtures using the maximum stress measured, when a frost crack appears in the test specimen.

6. Using mathematical modeling for data analysis

A schematic representation of a multi-layer linear elastic model and load on asphalt pavement is given in Fig. 10. To calculate the lifetime of the pavement construction, the considered parameters are radial stress (tensile bending) at the lower side of the asphalt layers and vertical stress at the level of the pavement subgrade.

The effects of lowering the compaction degree by 3% and the effects of lowering the asphalt content by 0.5% on the load distribution of the pavement were analyzed using a multi-layer linear elastic mathematical model. A standard pavement construction was chosen, which is described in Table 8. The design period (period, during which the pavement should not be be repaired or reconstructed) was considered as 25 years and during this time, the expected load was 20 million $ESAL_{100A}$. The calculation is derived from a superposition of relative damages, which shows that the given size of each load damages the material relative to the limiting number of these loads.

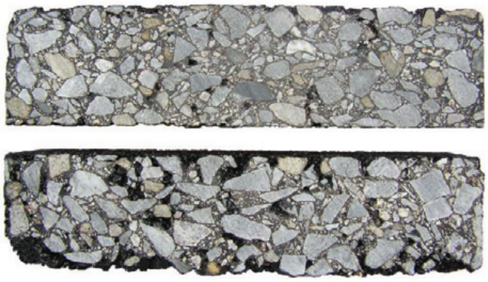


Fig. 8. AC 16 asphalt mixture with 100% degree of compaction (top) and AC 16 asphalt mixture with 97% degree of compaction (bottom)

Fig. 9. Fracture surface – binder film thickness difference between mixture I AC 11 (left) and III AC 11 (right)

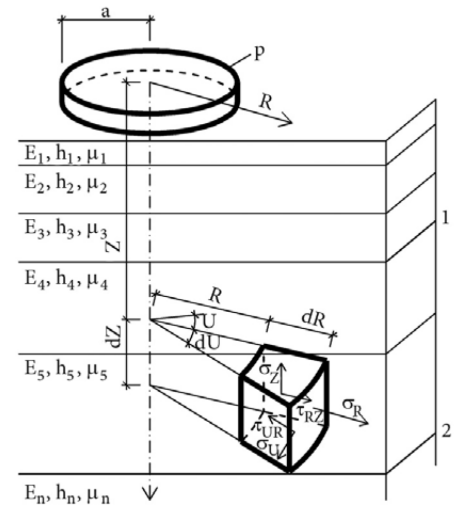
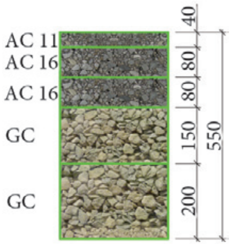


Fig. 10. Scheme of multi-layer linear elastic mathematical model

Subgrade modulus of elasticity was considered to be 80 MPa and Poisson number 0.35. Modulus of elasticity of the base courses, made from graded course, was considered as 400 MPa. Stiffness modulus E of the asphalt wearing course plugged into the mathematical model was obtained from the measurements of the stiffness modulus of the asphalt mixture AC 11 using the two-point bending

Table 8. Pavement construction and layer parameters

Layer property	Compaction degree: 100% Binder content: optimum				Compaction degree: 97% Binder content: optimum				Compaction degree: 97% Binder content: opt. –0.5%			
	E_s, MPa	ε_6 10^{-6}, m/m	B	μ	E_s, MPa	ε_6 10^{-6}, m/m	B	μ	E_s, MPa	ε_6 10^{-6}, m/m	B	μ
	7353	135	5.00	0.33	6229	135	5.00	0.33	7278	135	5.00	0.33
	8046	118	4.31	0.33	6886	109	4.72	0.33	6296	88	4.55	0.33
	8046	118	4.31	0.33	6886	109	4.72	0.33	6296	88	4.55	0.33
	400	0	0	0.30	400	0	0	0.30	400	0	0	0.30
	400	0	0	0.30	400	0	0	0.30	400	0	0	0.30
Lifetime, years	25.0				17.4				5.1			
$ESAL_{100A}$	20 000 000				13 600 000				4 000 000			
Relative lifetime, %	100.0				69.6				20.4			

Note: E_s – Elastic modulus; ε_6 – Strain size; B – Fatigue characteristic; μ – Poisson number; GC – grading course.

test performed at 15 °C and loading frequency 10 Hz. Fatigue characteristics of the wearing course were individually replaced by design fatigue parameters ($\varepsilon_6 = 135{\cdot}10^{-6}$ and B = 5.0) and the properties of the asphalt binder course and asphalt base course were obtained from the measurements of performance characteristics of the AC 16 asphalt mixture (stiffness modulus E and fatigue characteristics ε_6 and B determined at 10 °C and loading frequency 25 Hz). Poisson number of asphalt layers was considered as 0.33 and Poisson number of layers made from graded course as 0.30.

Table 8 shows that lowering the compaction degree of asphalt layers to 97% and fulfilling the prescribed dosage of asphalt binder leads to shortening of the lifetime from 25 to 17.4 years. This lifetime reduction can also be represented by reducing the number of ESAL from 20.0 million to 13.6 million.

When the 3% reduction of compaction degree is combined with a 0.5% decrease from the optimum in asphalt binder content, the lifetime is reduced substantially, from 25 to 5.1 years, which is equivalent to a lifetime reduction of ESAL to 4.0 million. The same degree of reduction would be observed in case the overall thickness of the asphalt layer was reduced by 50 mm (from 200 mm to 150 mm).

7. Conclusion

The paper uses performance tests of asphalt mixtures to model the effects of lowering selected performance parameters on shortening of asphalt pavement construction lifetime if the parameters monitored in the standards are at their lower acceptable limit. 216 trapezoidal-shaped specimens for stiffness modulus and fatigue test and 60 beams for Thermal Stress Restrained Specimen Test were used.

Asphalt mixtures of asphalt concrete type with aggregate gradation up to 11 mm and 16 mm were used to assess the performance characteristics. Aggregate sieve size distributions of asphalt mixtures were chosen in order to cover the entire range of particle sizes defined in the Czech national appendix of *EN 13108-1* standard.

1. The results of the stiffness tests show that increasing the frequency also leads to increase in stiffness modulus of the mixtures. Lowering the degree of compaction of asphalt mixtures by 3% did not have an effect on the ratio of stiffness modulus determined at frequencies of 25 Hz and 5 Hz (frequency sensitivity). Lowering the binder content by 0.5% in the individual mixtures, usually led to a slight increase in the ratio of stiffness modulus determined at frequencies of 25 Hz and 5 Hz. The factor with largest effect on frequency sensitivity turned out to be the actual composition of the asphalt mixture, i.e. the aggregate gradation and the corresponding binder content.

2. For the asphalt mixtures of asphalt concrete type with aggregate gradation up to 11 mm with a compaction degree decreased to 97%, there was a decrease in the value of stiffness modulus ranging from 9% to 19%. For the asphalt mixtures of asphalt concrete type with aggregate gradation up to 16 mm with a compaction degree decreased to 97%, there was a decrease in the value of stiffness modulus ranging from 14% to 27%. Lowering the binder content by 0.5% usually led to increase in stiffness modulus of the asphalt mixture.

3. For asphalt mixtures of asphalt concrete type with aggregate gradation up to 16 mm with compaction degree lowered by 3% there was a decrease in the average size of strain derived from the fatigue line at 10^6 load cycles by approximately 8% to 23%. For asphalt mixtures of asphalt concrete type with aggregate gradation up to 16 mm with binder content lowered by 0.5% there was always a decrease in the average size of strain derived from the fatigue line at 10^6 load cycles value in the range of 3% to 19%. There is a strong relationship between this fatigue characteristic and the bitumen film thickness.

4. The critical temperature at disruption of the asphalt concretes with aggregate gradation up to 11 mm at

Thermal Stress Restrained Specimen Test lied in the interval between –15.3 °C and –19.9 °C and for the asphalt concretes with aggregate gradation up to 16 mm in the interval of –17.4 °C and –20.3 °C. In case of the mixtures with 100% degree of compaction and optimal binder content, there is an increase (worsening) of the critical temperature when using aggregates with larger particle size. Lowering the degree of compaction did not have a significant effect on the change in critical temperature. Maximum tensile stress at disruption of testing specimens with 100% compaction degree is on average 24% higher compared to maximum tensile stress of testing specimens with degree of compaction of 97%.

5. The effects of lowering the compaction degree by 3% and the effects of lowering the asphalt content by 0.5% on the load distribution of the pavement were analyzed using a multi-layer linear elastic mathematical model. When the measured performance parameters of asphalt mixtures (stiffness modulus and fatigue parameters) were plugged into a mathematical model and evaluation of commonly used standard pavement performed, substantially worse results were obtained. When using the lower tolerated limit for compaction degree and binder content of asphalt layers, there is a rapid decrease in the expected lifetime by up to 80%, which is equivalent to reducing the pavement thickness by one layer, which corresponds to 50 mm.

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