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ANALYSIS OF FATIGUE DAMAGE ON TEST SECTIONS SUBMITTED TO HVS LOADING

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Abstract. This paper presents results of field tests performed in Poland within SPENS project. The test sections were built in Poland (October 2007). All of construction works as well as research tests were conducted in cooperation with the Swedish National Road and Transport Research Institute (VTI), STRABAG, TPA, Lafarge and ORLEN. The test section was divided into four parts of the same layer thickness, but with two different mixes in the base course: asphalt concrete and high modulus asphalt concrete. This allowed direct evaluation of the influence of high modulus asphalt concrete on pavement durability. Tests sections were subjected to accelerated loading test with use of the Heavy Vehicle Simulator. These tests were accompanied by field tests (Falling Weight Deflectometer and Ground-Penetrating Radar) and numerous of laboratory tests (binder content, grading, air voids, resistance to rutting, stiffness and fatigue). Investigation of fatigue damage development of asphalt layers is also presented. Four pavement structures with different binder courses made of: high modulus asphalt concrete with grains up to16mm and 20/30 binder, asphalt concrete with grains up to16 mm and binder 35/50 and fine graded anti-fatigue layer were compared using accelerated tests and also verification of applied design methods was made.

Keywords: fatigue damage, Heavy Vehicle Simulator (HVS), accelerated loading tests.

1. Introduction

Poland is a country where in recent years considerable resources have been allocated to infrastructure, particularly to the road construction taking into account the interaction of transport system elements (Sivilevičius 2011). Nevertheless, the assessment of the durability of roads built for several years is not always positive. Hence the conclusion that testing of typical for Poland road structures is quite important. Propositions of some solutions that would reduce the degree of degradation in a wide time perspective are also needed. These goals could be achieved only from models in real scale subjected to a load at an accelerated rate, e.g. by using Heavy Vehicle Simulator (HVS). The conclusions obtained from such analysis are objective and allow identify better design solutions and better materials. In literature, the Accelerated Pavement Tests (APTs) are applied in different contexts (Coleri, Harvey 2013; Ji *et al.* 2013). A systematic comparison of selected components of strain measurements obtained from the APTs with Finite Element Method (FEM) solutions in the frame of linear theory of visco-elasticity is presented (Park, Kim 2010). FEM solutions were obtained for 2D and 3D cases, taking into account the surface load distribution corresponding to that under the wheel of the vehicle or concentrated force. It was indicated that solution comparable with experiment could be obtained for 3D modeling and load distribution resulting from tire contact pressure distribution. In work by (Perez *et al.* 2006) the application of two small APT devices (for description of the device see Chabot *et al.* 2008) is presented and results were compared with solutions obtained with FEM package CESAR. The main objective of this work was, however, to identify regions where reflective cracking initiate, and then to track the development of crack in the function of the number of load cycles. Thus it needed to prepare a special test road construction and usage of special experimental setup, but eventually the constitutive model of the interface could be validated. At work (Suh *et al.* 2011) the APT were used to validate the empirical model for development of permanent deformation (rutting) in Korean conditions, see also (Khedr, Breakah 2011; Wang *et al.* 2009). In this work no attempt was made to reproduce the experimental results by solution of numerical task, but the accumulated results could be used for this purpose. The development of permanent deformation is also a key issue in the study presented in (Sirin *et al.* 2008) in the context of unmodified and modified asphalt used for mixtures

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designed using Superpave. The analysis confirmed the superiority of mixtures with modified asphalts. The difference was noticeable in the mechanism of the ruts formation. For pavements with unmodified binder, rutting was caused by the combination of compaction and shoving, but for the styrene-butadiene-styrene (SBS)-modified only by compaction. It is worth noticing that the phenomenon of rutting is an important factor influencing traffic safety (Vansauskas, Bogdevičius 2009; Solowczuk 2011). In turn, at work (Yeo *et al.* 2008) the APT was used to validate empirical fatigue models based on Miner's cumulative damage approach.

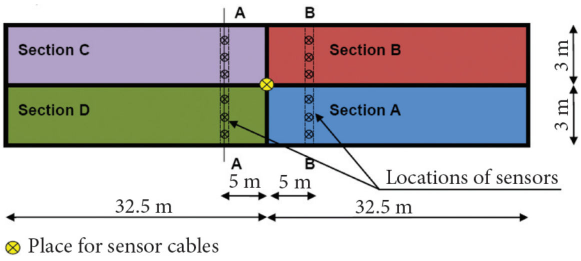

Fig. 1. Location of tested sections

In this paper the main objective was to verify the durability of various road structures and verification of design methods, which are used with application of standard FEM programs and selected empirical equations, for determining the fatigue life and the level of permanent deformation.

In frame of research project conducted in Poland, four test sections with a different structure of asphalt layers were constructed. Each section was 30 m long and 3 m wide. The sections were arranged to allow simultaneous testing of two structures (adequately A and B, or C and D) using HVS simulator (Fig. 1). It was assumed that all of the structures have the same thickness of asphalt layers, as it was very convenient for direct comparison of the structural and technological solutions. Tested pavements were instrumented with temperature sensors, strain gauges for horizontal strains in the bottom of asphalt layers (ASG – Active Strain Gauge) and inductive coils for vertical strains (EMU – acronym for strain measuring unit) at the top layer of subgrade (Figs 2 and 3), c.f. e.g. (Sirin *et al.* 2008).

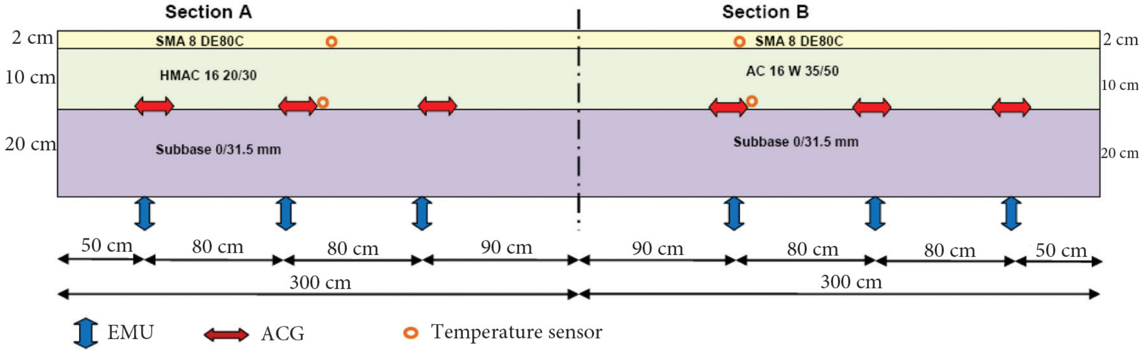

Fig. 2. Sections A and B

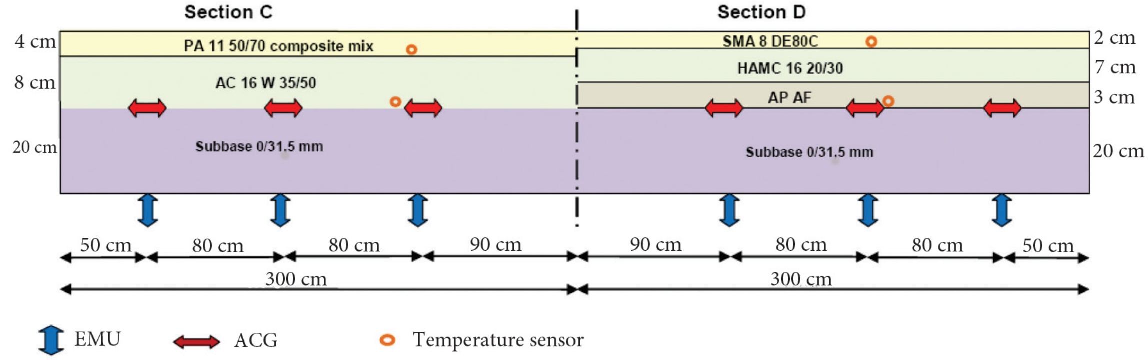

Fig. 3. Sections C and D

Table 1. Properties of bituminous mixtures designed for test sections

Properties	SMA 8 DE80C	AC 16 35/50	HAMAC 16 20/30	PA 11 50/70	AP AF
Binder content, % m/m	7.1	4.3	5.5	4.7	7.4
Air voids, % v/v	3.3	3.8	3.8	29.5	2.4
Rutting (large device, 60 °C, 10000/30000 cycles), %	9.2	2.1	3.6	–	–
Resistance to water, ITSR, %	92.6	90.2	91.8	–	–
Stiffness (4PB, 10 °C, 10Hz), MPa	–	19 435	16 312	–	10 052
Fatigue (4PB, 10 °C, 10Hz), ε_6, μm/m	–	116	180	–	279

2. Pavement structures

Structures A and B have the same asphalt layer thickness, the only difference is in binder course: section A has high modulus asphalt concrete (HMAC) 16 20/30 mix, while section B has conventional asphalt concrete (AC) 16 35/50 mix in the binder course (Fig. 2). Section C has composite mix (porous asphalt with cement mortar) in the wearing course (Fig. 3). In case of other three sections A, B and D wearing course is made of stone mastic asphalt (SMA) 8 mix with Orbiton 80C (polymer modified binder 45/80-65). The crucial feature of structure D is an application of fine graded anti-fatigue mix (marked as AP AF). The assessment of AP AF layer was also the subject of this research. The main idea of such a layer is an improvement of structure fatigue life. It is possible to obtain positive effects by placing such a layer (with a very good fatigue properties) in the bottom of asphalt layers, i.e. in the place where tensile strain have the highest value and where fatigue cracks are being initiated. Very good fatigue properties of applied AP AF mix were obtained by application of: very fine grained aggregate, modified binder (Orbiton 80C) and adding TOFIC polymer fibres. All mixtures were designed according to the standards *EN-13108-x Bituminous Mixtures – Materials Specifications* and requirements for heavy traffic category specified in the Polish national document WT NA 2008 (Technical Requirements – Asphalt Pavements on Public Roads, Sybilski *et al.* 2008). It should be also noted that HMAC mixture was made with use of limestone aggregate, which is usually considered by designers as less useful than stronger aggregate. The wearing course for section C was designed as porous asphalt (PA) with non-modified binder.

3. HVS testing conditions and program

HVS is a testing mobile device used for accelerated loading simulation on road pavement in full scale (Erlingson, Wiman 2008). This device simulates loads from heavy vehicles and allows analysis of response from different pavement constructions and materials (Tusar *et al.* 2008).

During HVS main test the following conditions were used: pavement temperature +10 °C, single wheel, wheel load of 60 kN (80 kN after 190 000 cycles), tire pressure of 800 kPa, normal lateral distribution and speed of 10–12 km/h. Testing program consisted of daily measurements of transverse profile, vertical strain in the top of the subgrade and transverse horizontal strain in the bottom of asphalt layers. Moreover on the second day and on the last day of HVS testing the same measurements were repeated in central line position for the set of different loading 30 kN, 40 kN, 50 kN and 60 kN.

4. Test results

Figs 4–6 present results of measurement during HVS test: rut depth development (Fig. 4), development of transverse horizontal strain (ε_y^e), development of vertical strain (ε_z^e) at the top of subgrade (Figs 5–6).

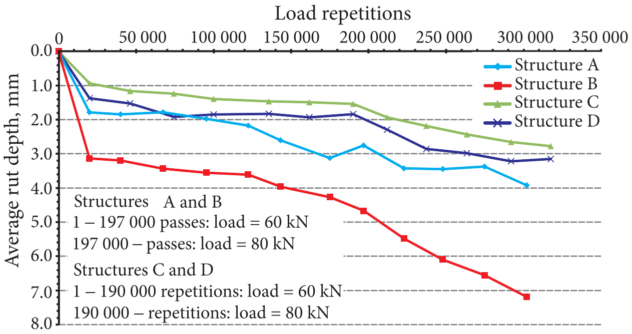

Fig. 4. Development of average rut depth, mm

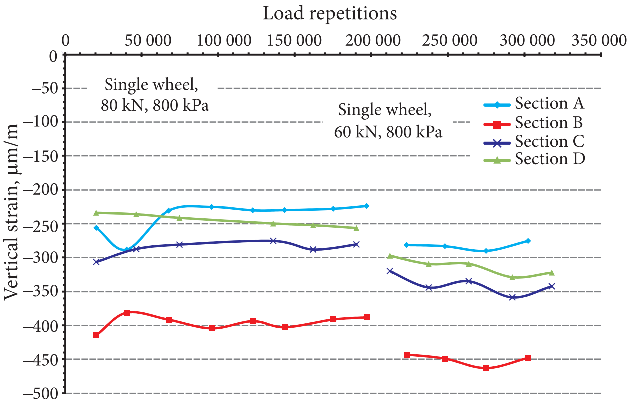

Fig. 5. Development of vertical strain at the top of subgrade (ε_z^e)

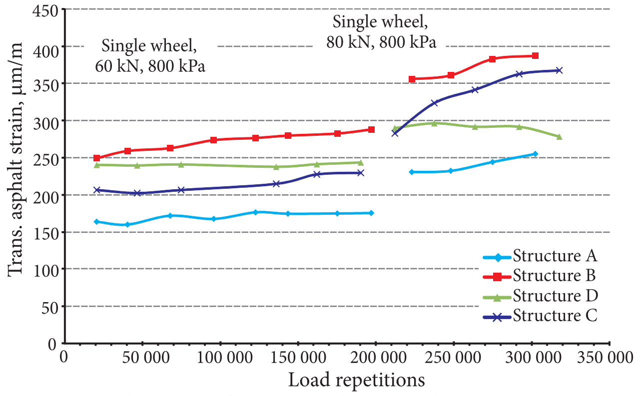

Fig. 6. Development of transverse horizontal strain in the bottom of asphalt layers (ε_y^e)

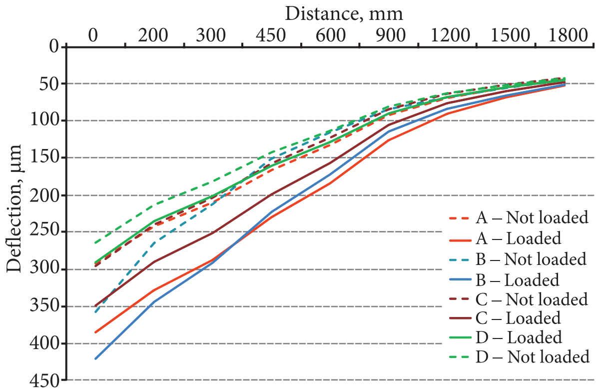

Fig. 7. Deflection bowl – sections A–D

5. Complementary tests and investigations

5.1. Results of Falling Weight Deflectometer tests

The Falling Weight Deflectometer (FWD) tests (load of 50 kN and contact pressure of 700 kPa) were carried out directly in line where wheel was passing and next to it. The evaluation results of average stiffness modulus of characteristic layers (asphalt layers, subbase and base) in temperature 19.8 °C (section C and D) and 23.2 °C (section A and B) on a basis of FWD tests are presented in Table 2. Values E_1, E_2 and E_3 stand adequately for asphalt layers, subbase and soil base. In the Fig. 7 the average vertical displacements as a function of distance (from middle point of FWD plate) are presented.

5.2. Determination of asphalt layers thickness

On the basis of cores measurement the following thicknesses of asphalt layers were found in the testing area (values in brackets represents layers from the bottom to the top): 15 cm on section A (12.6 cm + 2.4 cm), 11.8 cm on section B (10.0 cm + 1.8 cm), 13.4 cm on section C (8.6 cm + 4.8 cm) and 14.3 cm on section D (4.6 cm + 7.8 cm + 2.2 cm). Thicknesses of asphalt layers were different than planned. It means that comparative analysis for four sections tested with HVS is limited, but not impossible.

5.3. Stiffness modulus and fatigue determined from Four Point Bending beam tests

In the Tables 3 and 4 results of the stiffness and fatigue obtained in Four Point Bending (4PB) beam tests according to *PN-EN 12697-24 Bituminous Mixtures – Test Methods for Hot Mix Asphalt, Part 24: Fatigue Resistance* and *PN-EN 12697-26 Bituminous Mixtures – Test Methods for Hot Mix Asphalt, Part 26: Stiffness* (10 °C, 10 Hz) for mixes HMAC 16 20/30 and AC 16 W 35/50 on specimens taken from tested sections (taken from loading line A, B, C, D and next to it A’, B’, C’, D’) and specimens prepared in the laboratory conditions (Lab) during mix design are presented. Generally comparison of the stiffness and fatigue results of mix taken from loaded and not loaded pavement

Table 2. Stiffness modulus evaluated from FWD tests

Section	Not loaded pavement			Pavement after HVS test		
	E_1, MPa	E_2, MPa	E_3, MPa	E_1, MPa	E_2, MPa	E_3, MPa
A	6521	387	172	5624	347	83
B	4625	387	185	5498	332	109
C	6211	473	207	7270	407	159
D	5254	374	177	5348	357	119

Table 3. Stiffness modulus and phase angle for mixes AC 16 W and HMAC 16

	Stiffness modulus, MPa					Phase angle, ^{o}				
HMAC 16 20/30										
	Lab	A	A’	D	D’	Lab	A	A’	D	D’
Average	16312	11902	12008	12301	11880	7.1	10.7	10.6	10.1	10.8
St. dev.	531	670	494	521	770	0.3	0.5	0.4	0.7	0.5
AC 16 35/5										
	Lab	B	B’	C	C’	Lab	B	B’	C	C’
Average	19435	13274	13837	12795	12636	8.4	14.0	13.4	13.8	14.0
St. dev.	1044	708	549	666	716	0.5	0.6	0.4	0.4	0.7

Table 4. Results of the fatigue tests carried out on mixes HMAC 16 20/30 and AC 16 35/50

	HMAC 16 20/30					AC 16 35/50				
	Lab	A	A’	D	D’	Lab	B	B’	C	C’
A	4.4*E*+25	3.1*E*+23	1.6*E*+23	7.9*E*+20	9.7*E*+19	3.1*E*+18	3.8*E*+19	9.1*E*+19	3.8*E*+17	1.4*E*+17
b	–8.71	–7.79	–7.59	–6.60	–6.22	–6.05	–5.55	–6.56	–5.52	–5.32
R^2	0.92	0.85	0.89	0.91	0.84	0.91	0.91	0.89	0.88	0.91
ε_6	180	176	185	181	179	116	131	134	126	124
ε_{6max}	189	190	195	190	194	129	141	147	141	136
ε_{6min}	172	163	176	173	166	104	121	122	111	114

allows draw a conclusion that there was no fatigue damage in the pavement due to HVS loading.

6. Pavement modeling

Mechanistic method of pavement design was used for the evaluation of the pavement fatigue life on the basis of stress and strain field analysis. Pavement is treated as an elastic multilayer construction with defined thicknesses lying on an infinite half space. Each layer is described with: thickness, stiffness and Poisson ratio. Horizontal elastic tensile strain in the bottom of asphalt layers and vertical compressive elastic strain at the top layer of the soil base are calculated. Evaluations of the strain field in pavement structure were conducted with NOAH 2.0 software with the following assumptions: HVS wheel load equal to 60 kN or 80 kN, contact pressure: q = 800 kPa, equivalent temperature: 10 °C, real layer thicknesses, full bonding between asphalt layers. Evaluations of asphalt layers fatigue life (N) were conducted using Asphalt Institute Method:

$$N = 18.4C\left(6.167 \cdot 10^{-5}(\varepsilon_y^e)^{-3.291}\left|E\right|^{-0.854}\right), \tag{1}$$

$$C = 10^{4.84\left(\frac{V_A}{V_A+V_B}-0.69\right)}, \tag{2}$$

where ε_y^e – tensile strain, μm/m; E – stiffness modulus, MPa; V_A – aggregate volume content, % v/v (volume/volume); V_B – bitumen volume content, % v/v.

Values of V_B and V_A parameters were assumed according to control tests. The value of the stiffness modulus of asphalt layers corresponds to results obtained in laboratory tests for frequency 0.3 Hz (frequency of the HVS test) or obtained from FWD tests and brought to temperature 10 °C. Additionally, the estimation of fatigue life was conducted using fatigue characteristics obtained in laboratory tests. Stiffness modulus of subbase and subgrade were assumed according to FWD tests.

Evaluations of fatigue life taking into account strain in the subgrade were carried out using Asphalt Institute equation:

$$\varepsilon_z^e = 0.0105N^{-0.223}, \tag{3}$$

where ε_z^e – the vertical strain in the top of the subgrade. Table 5 presents results of pavement structure fatigue life evaluation, assuming stiffness modulus from laboratory tests (Method I), stiffness obtained from FWD tests (Method II) and taking into calculation values of strains in the bottom of asphalt layers measured at the beginning of HVS test under 60 kN (Method III).

7. Results analysis

7.1. Assessment of HVS test results

Generally the growth of reversible strain values in the bottom part of asphalt layers was more significant in sections

Table 5. Evaluation of pavement fatigue life

Method	Wheel load 60 kN		Wheel load 80 kN		Fatigue life according to *Asphalt Institute* equation (10^6)		Fatigue life according to laboratory tests (10^6)		Fatigue life concerning subgrade deformation (10^6)	
	ε_y^e, μm/m	ε_z^e, μm/m	ε_y^e, μm/m	ε_z^e, μm/m	60 kN	80 kN	60 kN	80 kN	60 kN	80 kN
					Section A					
I	170	–570	202	–740	1.90	1.10	1.30	0.40	0.30	0.10
II	173	–511	223	–664	1.80	0.80	1.20	0.20	0.50	0.20
III	164	–	–	–	2.1	–	2.50	–	–	–
					Section B					
I	205	–736	234	–948	0.30	0.20	5.60	2.70	0.10	0.03
II	268	–758	340	–973	0.10	0.06	1.30	0.30	0.09	0.03
III	249	–	–	–	0.15	–	0.02	–	–	–
					Section C**					
I	175	–550	206	–711	0.50	0.30	0.16	0.06	0.36	0.11
II	175	–605	204	–781	0.50	0.30	0.16	0.07	0.24	0.07
III	206	–	–	–	0.27	–	0.07	–	–	–
					Section D					
I	86* 213	–626	99 250	–809	17.50 2.20	11.00 1.30	135.00 4.50	53.30 1.80	0.20	0.06
II	197	–600	231	–777	2.90	1.70	6.90	2.90	0.24	0.08
III	240		–	–	1.50	–	2.30	–	–	–

Note: * – strain values of asphalt layers in upper line respond to HMAC, however in lower line respond to AP AF; ** – in case of wearing course the stiffness moduli were obtained using indirect tension test.

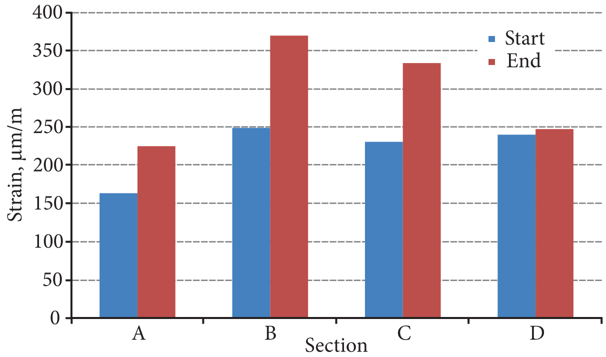

Fig. 8. Comparison of strains in the bottom of asphalt layers (ε_y^e) for wheel load 60 kN obtained in the beginning and at the end of HVS test

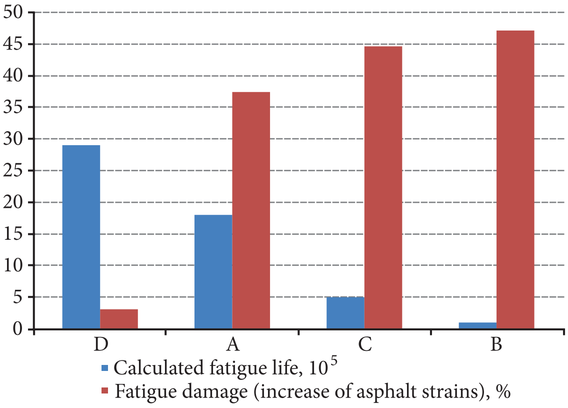

Fig. 9. Comparison of fatigue life for each individual section according to Asphalt Institute method and fatigue life estimated on the basis of strain analysis (under the load of 60 kN – in the beginning and at the end of the HVS test)

B and C than in sections A and D (Fig. 8). Measurements of tensile strain in the bottom of asphalt layers during the HVS test together with measurements at the beginning and end of the test carried out for different loads, allows to formulate statement that the strain systematically increased, same as it was expected. Only measurements on section D show small changes during HVS test. Comparison of the strain results under the load 60 kN obtained at the beginning and after HVS test also indicates the growth adequately 37%, 47%, 45% and 3% (A, B, C and D). The possible reason of such growth could be developing fatigue damage of asphalt layers. Concerning section D it should be noted that during the second stage only one (from three) sensor worked properly, so whole further analysis rely on this one reading. At that point it should be underlined that this finding is in good agreement with FWD measurement, where the lowest increase of deflection was observed on section D and also readings from the sensor were very close to the results of modeling.

Vertical strains of the soil top layer indicated small growth in case of sections B and C (2–8%) and bigger growth on section D (28%). In opposite measurements on section A show significant drop of vertical strains in the subgrade (14%). For sections A and D the thickness of asphalt layers were similar. For section A tensile strains were about 30% lower than for section D. The reason of such behavior is location of flexible anti-fatigue layer in the bottom part of asphalt layers in structure D. Unquestionable advantage of such solution is very low growth of tensile strains (ten times lower) in the bottom of asphalt layers measured at the beginning and after HVS test under wheel load 60 kN. Assuming that growth of strain values in asphalt layer is an indication of fatigue process development, then this result can be treated as a proof of achieving intended anti-fatigue effect.

The increase of tensile strain in the bottom of asphalt layers for section B and C is quite comparable in spite of 2 cm difference in layers thicknesses. The strains for structure C are lower than for structure B, but this difference is becoming lower after changing the wheel load from 60 kN to 80 kN, because of considerable strain development in structure C.

7.2. Estimation of structure fatigue life

Test sections for this research program were designed and built up as a typical structure for traffic category KR2 according to polish catalogue (Catalogue of typical flexible pavement structures), what is equivalent to fatigue life 90 000–510 000 100 kN axle loads. The test sections were subjected to the wheel load equal to 60 kN throughout first 200 000 cycles and then wheel load was increased for next 100 000 cycles to 80 kN. After conversion to the load of 100 kN per axis (50 kN per wheel) it is possible to make a statement that during whole test structures were subjected to 700 000 of 100 kN axle loads. This means traffic category KR3 simulated in 2 weeks instead of 20 years. Structures fulfilled with great reserve all requirements needed for category KR2.

The fatigue damage and structural deformation symptoms exceeding assumed criteria weren't observed. It is worth noticing here that for structures designed for lower traffic categories the decisive criteria is permanent strain of subgrade (structural deformation). The calculation results of asphalt layers fatigue life indicated that structures should not yield severe fatigue damage during HVS test. This conclusion was proved by results of HVS test as well as by calculations using mechanistic method. In both cases the best results (the lowest fatigue damage and the highest fatigue life) were reserved for structure D. On the opposite side of the scale was pavement of section B (Fig. 9).

The possibility of fatigue damage development in asphalt layers was not seen in results of stiffness and fatigue tests. It can be guessed that fatigue damage after the HVS test was quite significant, but then the pavement surface was exposed to hot weather (summer time, quite heavy sun operation, high temperature) and self-healing process started. It should be also noted that specimens were cut from the pavement in 6 weeks after the end of HVS tests. Some micro-cracks in pavement have closed and material recovered its previous stiffness.

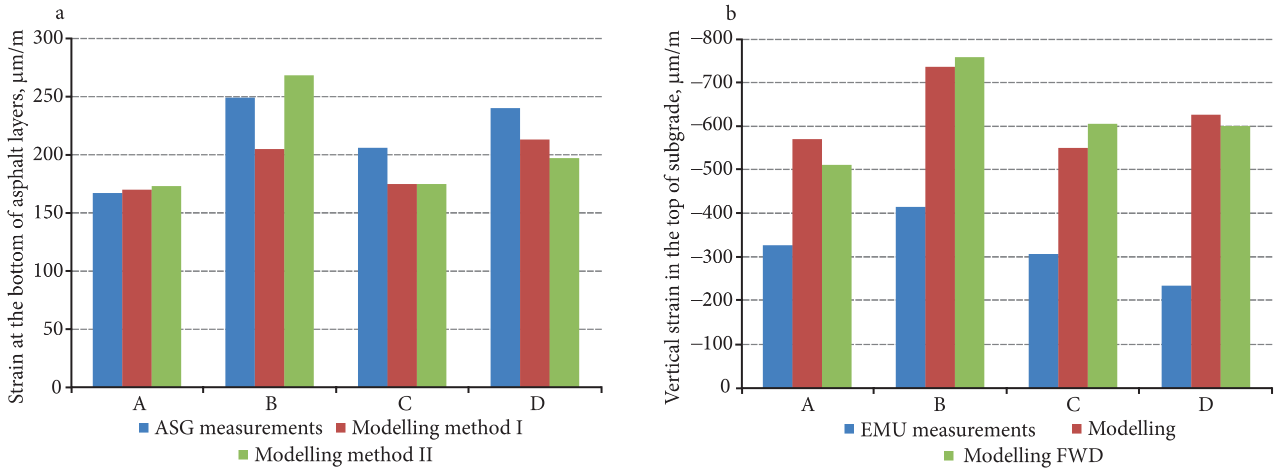

Fig. 10. Comparison of measured and calculated strains: a – horizontal strains at the bottom of asphalt layers (ε_y^e); b – vertical strains at the top of subgrade (ε_z^e)

Calculated strains in the bottom of asphalt layers were very close to the strains measured during HVS test. More differences were found for vertical strains at the top of subgrade (Fig. 10).

8. Conclusions

1. The main subject of this research was to compare four pavement structures with different binder courses made of: HMAC 16 20/30 mix, AC 16 35/50 mix and anti-fatigue layer AP AF placed in section D. Designed mixes fulfilled all technical requirements needed for heavy traffic category given in WT NA – 2008. Despite of problems with layer thicknesses and differences in mixes compositions the structures were not destroyed during the test even though the whole constructions were relatively thin and the load exceptionally high (about 700 000 of 100 kN axle loads in two weeks). There was no sign of fatigue cracking in the pavement. The structures accumulated slight permanent deformation, which was rather caused by soil deformation or compaction. This research proved that it is possible to use local aggregate like lime or dolomite (with lower strength limits) instead of stronger and expensive aggregates.

2. It was observed that structure D (with anti-fatigue layer and HMAC 16 20/30) had the best results. Structure with anti-fatigue layer is an innovation and was never used before in Poland, also experimental results are very promising. The structure in section A in comparison to section D thickness (about 0.5 cm thicker), shown a little worse results. Results for sections D were better than for other sections, but differences in thicknesses don't allow simple comparison. Similar situation is for sections B and C.

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