Looking for fatigue damage on test sections submitted to the accelerated loading test

Bańkowski Wojciech, Gajewski Marcin & Sybilski Dariusz
Road and Bridge Research Institute, Warsaw, Poland

ABSTRACT: This paper presents results of field tests performed in Poland within SPENS project, task 4.2 (Tusar et al. 2008). The test sections were built in Poland (October 2007). All of construction works as well as research tests were conducted in cooperation with VTI (Sweden), STRABAG, TPA, Lafarge Kruszywa i Beton and ORLEN Asfalt (all Poland). The test section was divided into four parts of the same layer thickness, but with two different mixes in the base course: asphalt concrete (AC) and HMAC. This allowed direct evaluation of the influence of HMAC on pavement durability. Tests sections were subjected to accelerated loading test with use of the Heavy Vehicle Simulator (HVS). The HVS tests were accompanied by the field tests (FWD and GPR) and numerous of the laboratory tests (binder content, grading, air voids, resistance to rutting, stiffness and fatigue). This paper presents investigation of fatigue damage of asphalt layers.

KEY WORDS: accelerated loading test, fatigue, high modulus asphalt concrete

1 LOCATION AND GENERAL INFORMATION

In frame of this research project four test sections with a different structure of asphalt layers were constructed. Each section was 30 m long and 3 m wide. Sections were arranged to allow simultaneous testing of two structures (adequately A and B, or C and D) using HVS simulator. 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) and inductive coils for vertical strains (EMU) at the top layer of subgrade (figures 2-3).

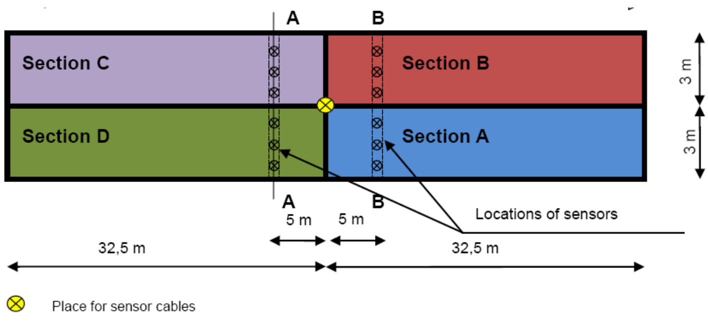

Figure 1: Sections location

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, while section B has conventional asphalt concrete AC 16 35/50 in the binder course (figure 2). Sections C has composite mix (porous asphalt with cement mortar) in the wearing course (figure 3). In case of other three sections A, B and D wearing course is made of SMA 8 mix with Orbiton 80C (PMB 45/80-65). The crucial feature of structure D is an application of anti-fatigue layer (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 tension 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 and requirements for heavy traffic category specified in polish national document WT NA 2008 (Sybilski et al. 2008). It should be also noted that HMAC mixture were made with use of limestone aggregate, which is usually considered by designers as less useful that stronger aggregate.

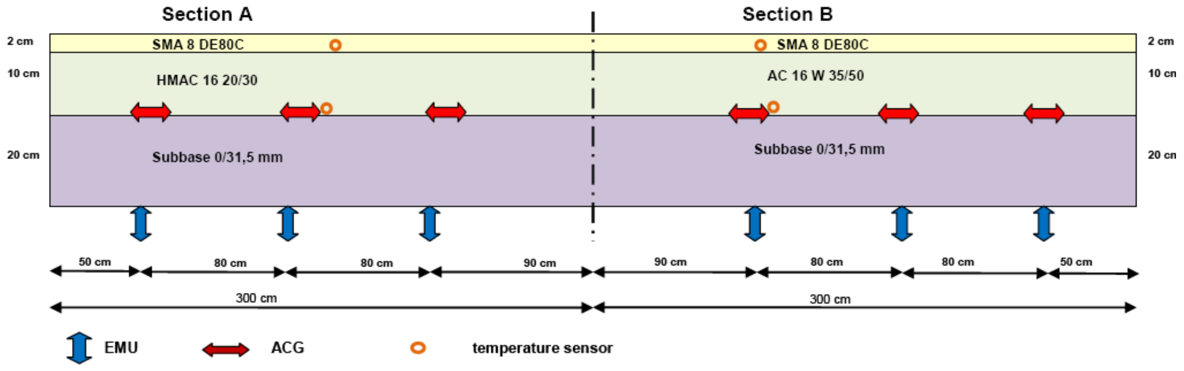

Figure 2: Sections A and B

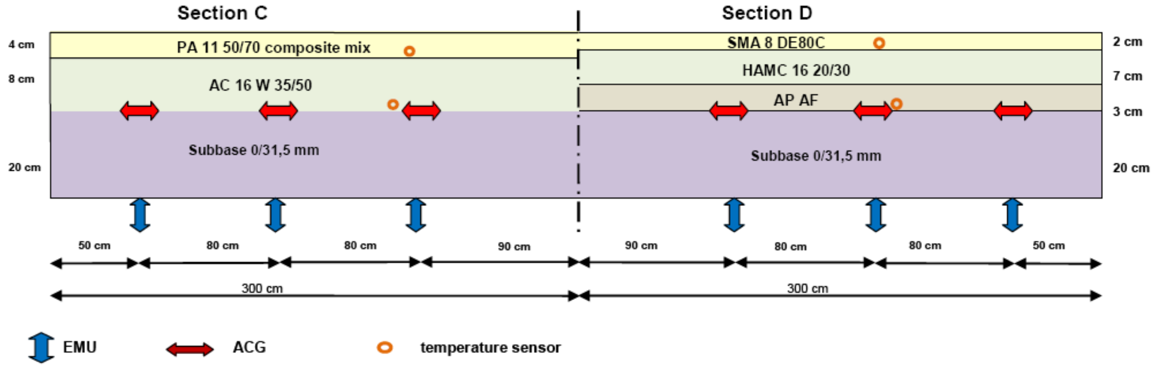

Figure 3: Sections C and D

Table 1: Properties of bituminous mixtures designed for test sections

Properties	SMA 8 DE80C	AC 16 35/50	ACWMS 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	-	19435	16312	-	10052
Fatigue (4PB, 10°C, 10Hz), $\mathcal{E}_6$, µm/m	-	116	180	-	279

3 HVS TESTING CONDITIONS AND PROGRAM

Heavy Vehicle Simulator (HVS) is a testing mobile device, used for accelerated loading simulation on road pavement in full scale (Erlingson and Wiman, 2008). With this device it is possible to simulate loads from heavy vehicles and analyze response from different pavement constructions and materials.

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, 40, 50 and 60 kN.

4 HVS TEST RESULTS

The following figures present results of measurement during HVS test: rut depth development (figure 3), development of transverse horizontal strain (ε_y^e), development of vertical strain (ε_z^e) at the top of subgrade (figure 4 and 5).

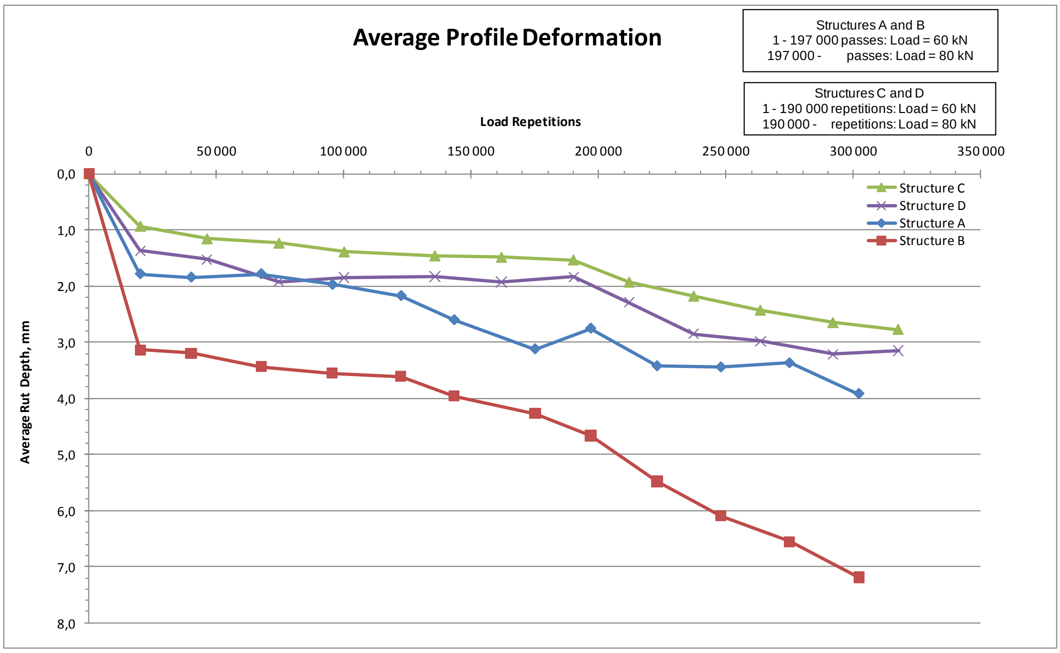

Figure 3: Development of average rut depth, mm

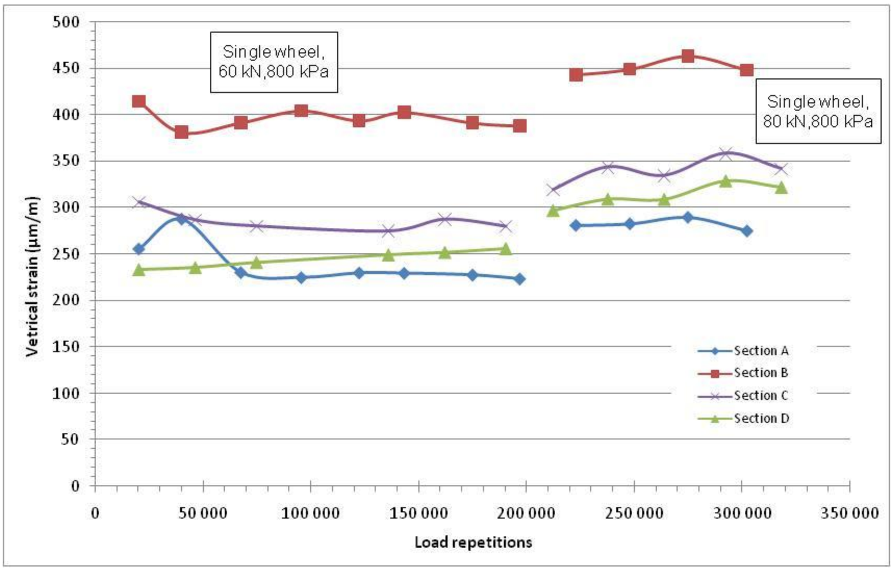

Figure 4: Development of vertical strain at the top of subgrade (ε_z^e)

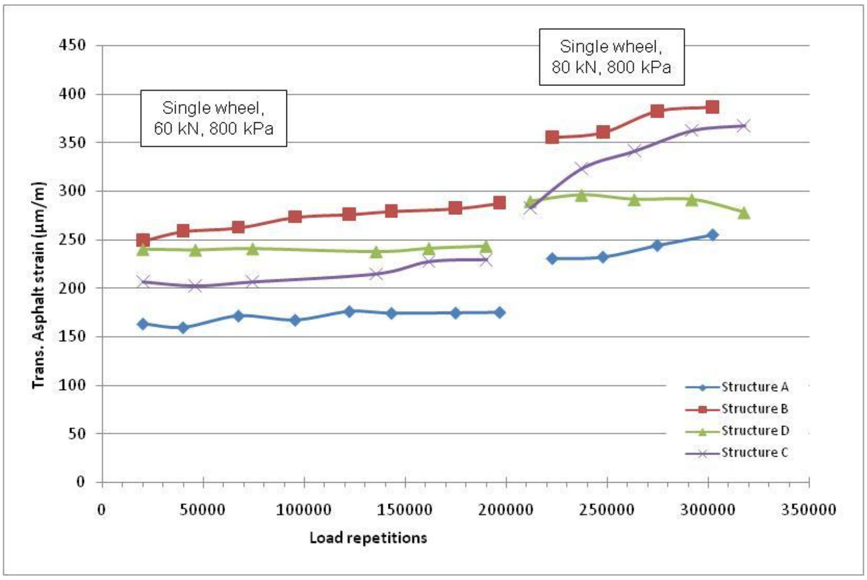

Figure 5 : Development of transverse horizontal strain in the bottom of asphalt layers (ε_y^e)

5 COMPLEMENTARY TESTS AND INVESTIGATIONS

5.1 Results of FWD tests

The 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 19,8ºC (section C and D) and 23,2˚C (section A and B) on a basis of FWD tests are presented in table 2. Values E1, E2 and E3 stand adequately for asphalt layers, subbase and soil base. In the figure 5 the average vertical displacements as a function of distance (from middle point of FWD plate) are presented.

Table 2: Stiffness modulus evaluated from FWD tests

Section	Not loaded pavement			Pavement after HVS test		
	E1, MPa	E2, MPa	E3, MPa	E1, MPa	E2, MPa	E3, 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

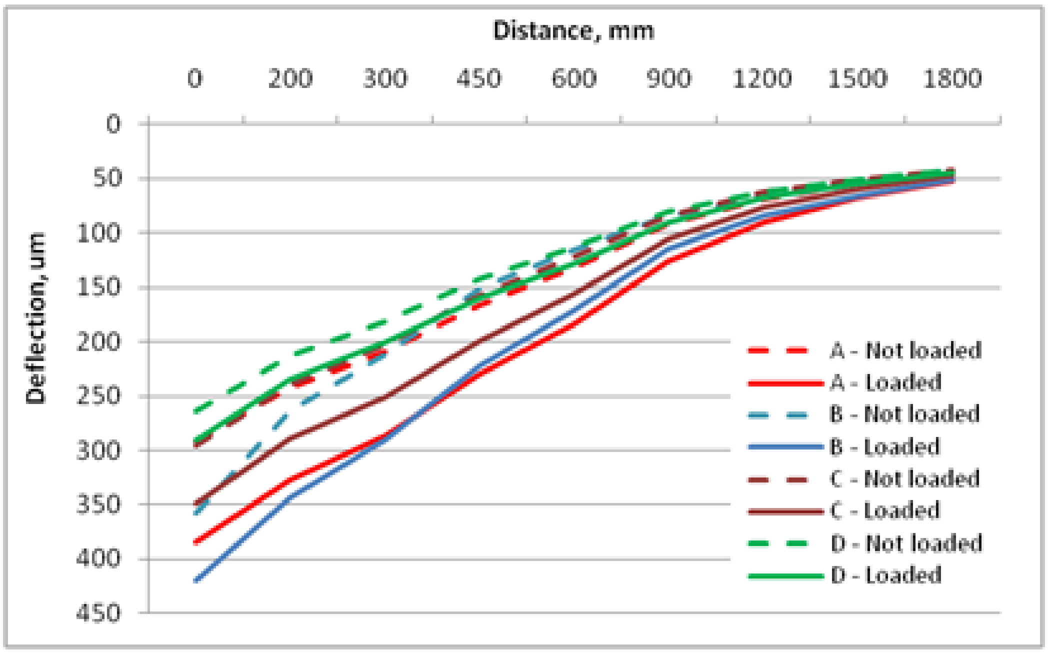

Figure 6: Deflection bowl – sections A-D

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 simplify comparative analysis for four sections tested with HVS is limited, comparative abilities in these cases are limited but not impossible.

5.3 Stiffness modulus and fatigue determined from 4PB tests

In the table 3 and 4 results of the stiffness and fatigue obtained in 4PB tests according to PN-EN 12697-24 and PN-EN 12697-26 (10˚C,10Hz) 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 allows to draw a conclusion that there was no fatigue damage in the pavement due to HVS loading.

Table 3: Stiffness modulus and phase angle for mix AC 16 W and HMAC 16

	Stiffness modulus, MPa					Phase angle, °				
	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 35/50									
	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 mix 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	4,4E+25	3,1E+23	1,6E+23	7,9E+20	9,7E+19	3,1E+18	3,8E+19	9,1E+19	3,8E+17	1,4E+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

6. PAVEMENT MODELING

Mechanistic method of pavement designing stands on 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 laying 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 60kN or 80kN, contact pressure: q = 800 kPa, equivalent temperature: 10ºC, real layer thicknesses, full bonding between asphalt layers. Evaluations of asphalt layers fatigue life (N) were conducted using Asphalt Institute method:

$$N = 18{,}4 \cdot C \cdot (6{,}167 \cdot 10^{-5} \cdot (\varepsilon_y^e)^{-3{,}291} \cdot |E|^{-0{,}854} \quad (1)$$

$$C = 10^{4{,}84 \cdot (\frac{V_B}{V_A + V_B} - 0{,}69)} \quad (2)$$

where: $\varepsilon_y{}^e$ – tensile strain, (μm/m), E – stiffness modulus, (MPa), V_B – bitumen volume content, (% v/v), V_A – aggregate 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:

$$\varepsilon_z^e = 0{,}0105 \cdot N^{-0{,}223} \qquad (3)$$

where $\varepsilon_z{}^e$ is 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).

Table 5: Evaluation of pavement fatigue life

Method	Wheel load 60kN		Wheel load 80kN		Fatigue life according to IA (10^6)		Fatigue life according to laboratory tests (10^6)		Fatigue life concerning subgrade deformation (10^6)	
	$\varepsilon_y{}^e$ µm/m	$\varepsilon_z{}^e$, µm/m	$\varepsilon_y{}^e$ µm/m	$\varepsilon_z{}^e$, µm/m	60 kN	80 kN	60 kN	80 kN	60 kN	80 kN
	Section A									
I	170	-570	202	-740	1,9	1,1	1,3	0,4	0,3	0,1
II	173	-511	223	-664	1,8	0,8	1,2	0,2	0,5	0,2
III	164	-	-	-	2,1	-	2,5	-	-	-
	Section B									
I	205	-736	234	-948	0,3	0,2	5,6	2,7	0,1	0,03
II	268	-758	340	-973	0,1	0,06	1,3	0,3	0,09	0,03
III	249	-	-	-	0,15	-	0,02	-	-	-
	Section C**									
I	175	-550	206	-711	0,5	0,3	0,16	0,06	0,36	0,11
II	175	-605	204	-781	0,5	0,3	0,16	0,07	0,24	0,07
III	206	-	-	-	0,27	-	0,07	-	-	-
	Section D									
I	86*	-626	99	-809	17,5	11,0	135,0	53,3	0,2	0,06
	213		250		2,2	1,3	4,5	1,8		
II	197	-600	231	-777	2,9	1,7	6,9	2,9	0,24	0,08
III	240		-	-	1,5	-	2,3	-	-	-

* 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 modulus were obtained using indirect tension test

8 RESULTS ANALYSIS

8.1 Assessment of HVS test results

Generally the growth of reversible strain values in the bottom part of asphalt layers was more significant in sections B and C than in sections A and D (figure 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 closed to the results of modeling (figure 10).

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 to 80 kN, because of considerable strain development in structure C.

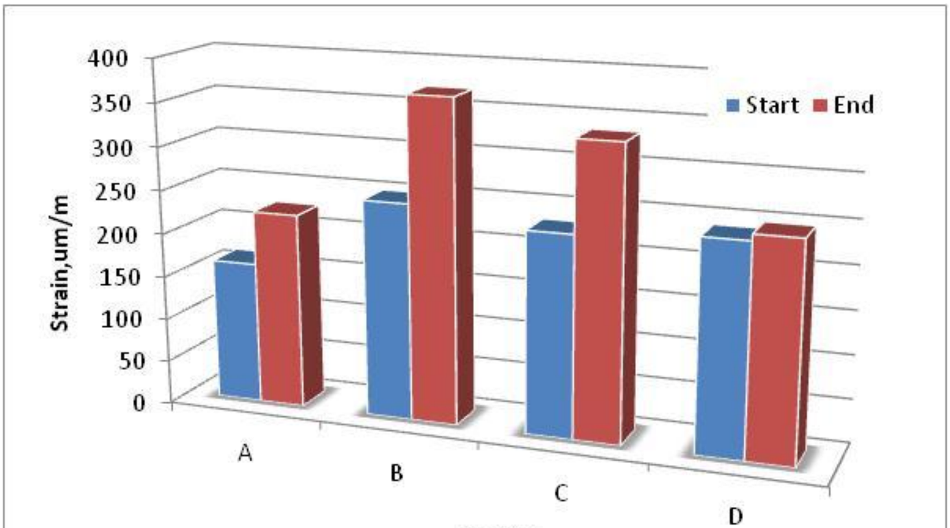

Figure 8: Comparison of strains in the bottom of asphalt layers (ε_y^e) for wheel load 60 kN obtained at the beginning and after the end of HVS test

8.2 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, what is equivalent to fatigue life from 90 000 to 510 000 100 kN axle loads. The test sections were subjected to the wheel load equal to 60 kN throughout first 200 thousands 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.

A 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 (figure 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.

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

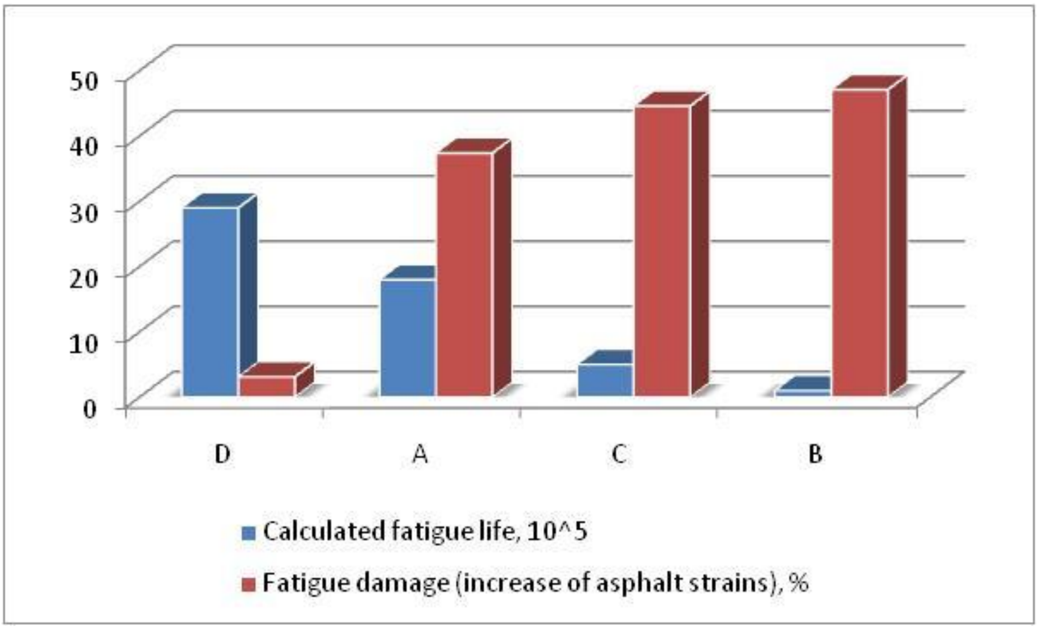

Figure 9: Comparison of fatigue life for each individual section according to Asphalt Institute method and fatigue life estimated on the basis of strain analysis (under the load of 60 kN – at the beginning and end of the HVS test)

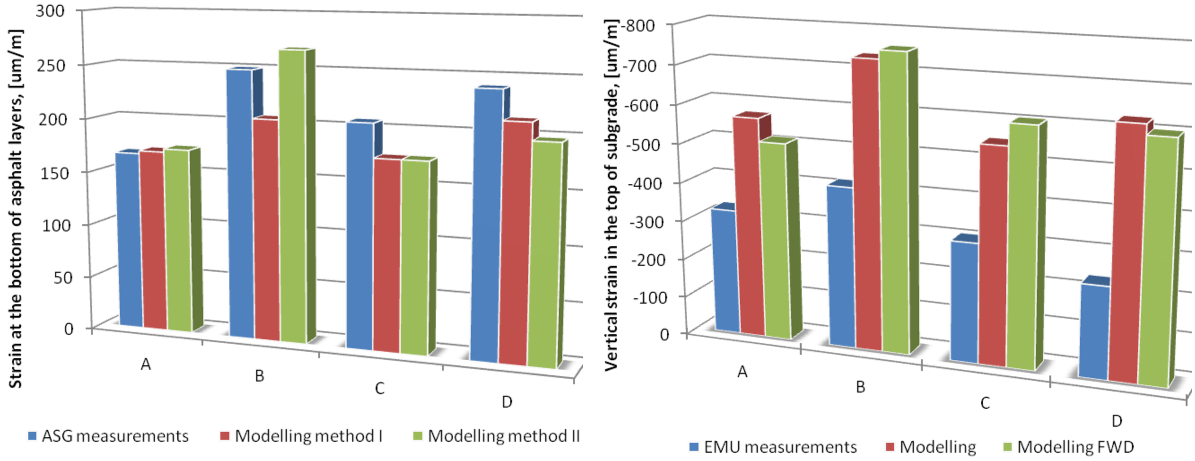

Figure 10: Comparison of measured and calculated strains at the bottom of asphalt layers (ε_y^e) at the top of subgrade (ε_z^e) and vertical strains at the top of subgrade (ε_z^e)

9 SUMMARY

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.

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.

REFERENCES

Erlingson, S., Wiman, L.G., 2008. *Accelerated Pavement Testing by HVS – a Trans-national Testing Equipment*,. Proceedings of Transport Research Arena Europe 2008, Ljubljana, Slovenia

Sybilski D. and GREN group, 2008. *Wymagania Techniczne – Nawierzchnie asfaltowe na drogach publicznych*, IBDiM 2008, Warsaw, Poland

Tusar, M., Bańkowski, W., Kalman, B., Wiman, L.G., 2008. *Evaluation of materials for road upgrading*,. Proceedings of Transport Research Arena Europe 2008, Ljubljana, Slovenia.

.