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Research paper

The influence of highly modified asphalt binder on pavement fatigue life prediction – selected problems

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Abstract: The introduction of new road pavement materials causes the need to verify whether the existing pavement design methods enable correct incorporation of their properties. In the case of asphalt pavements, the origins of contemporary methods may be traced back to the mid-20th century, when solely unmodified binders were used. The introduction of highly SBS-modified binders in 2009 significantly changed the behaviour of the asphalt mixtures and the entire pavement structure. Asphalt courses are now characterised by very high flexibility, elasticity and fatigue resistance, with simultaneous high resistance to rutting. The aim of the article is to present the effect of the use of asphalt mixtures with HiMA (Highly Modified Asphalt) binders in different variants of flexible pavement structures – including one, two or three courses containing HiMA. Fatigue life calculations were performed using the "Similarity Method", which enables estimation of the fatigue life of the structure based on its relationship with the results of laboratory fatigue tests. The layer system with HiMA in the asphalt base course proved the most advantageous, combining excellent fatigue properties of the mixture containing HiMA with greater stiffness of the wearing and binder courses containing classic binders. The other aspect taken into account in the calculations was the effect of changing the mixture in the asphalt base course from AC 22 to AC 16. This change proved advantageous in all the analysed structures. The deflections and critical strains decreased, while pavement life, determined by fatigue and permanent deformation criteria, increased.

Keywords: road pavement, highly modified asphalt binder, HiMA, fatigue life prediction, durability analysis

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1. Introduction

Polymer-modified bituminous binders have been used in road technology for several decades. The concept encompasses the use of various organic polymers, among which SBS block copolymers (elastomers) have gained considerable popularity. There is an extensive literature on the subject of the influence of polymer modification on the performance of asphalt, including the effect of polymer content on the functional properties of the binder and asphalt mixtures. In recent years (since 2009) SBS-polymer-based solutions, known as Highly Modified Asphalt, have been tested worldwide, often referred to as HiMA, HPMB etc. [5, 6, 10–12, 24]. The new HiMA binders, with the so-called reversed bitumen-polymer phase – volumetric domination of the polymer network over the bituminous binder – have opened up new possibilities in the construction of highly durable pavement structures. The polymer network that dominates in the microstructure of HiMA binder consists of a block copolymer of polystyrene and polybutadiene (SBS), which makes the binder acquire the properties of an elastomer to a considerable degree – including high elasticity, flexibility and tensile strength. It results in the improvement of many functional characteristics of the asphalt pavement, including resistance to rutting, low-temperature cracking and fatigue. The effect has been confirmed by various asphalt mixture tests – four-point bending of prismatic specimens (4PB-PR) according to EN 12697-24 [31], thermal stress restrained specimen test (TSRST) according to EN 12697-46 [34], semi-circular bend test (SCB) according to EN 12697-44 [33], (see also [2, 4]) – and binder tests including the bending beam rheometer (BBR) test [3] and linear amplitude sweep (LAS) fatigue test [5, 26]. The specific properties that the asphalt mixtures acquire due to the influence of elastomer-dominated binders prove important in mechanical analyses of pavement structures. Elastomers are characterised by significantly greater elasticity, higher strain tolerance and lower thermal sensitivity than bitumen. Therefore, HiMA does not stiffen considerably at low temperatures and does not flow at high temperatures. Consequently, while the asphalt mixtures containing HiMA may be characterised by a lower stiffness modulus, they remain resistant to fatigue cracking despite greater strains. Low values of stiffness modulus at low temperatures also provide mitigation of low-temperature shrinkage cracking.

Bearing in mind that the primary aim of the analysis is to determine the optimal arrangement of layers and materials for pavement structure to increase fatigue life, it is necessary to take into account the specificity of HiMA binders and its impact on the performance of the entire structure. In the most straightforward variant, greater pavement life may be achieved by introducing HiMA in the base asphalt course, without changing the thickness of the asphalt layers or, in some cases, with a reduction in the total thickness of the asphalt layers [12]. In both cases the thickness of the asphalt courses is related to design with classic neat binders or modified binders with lower polymer content and typical phase proportions [14].

Despite the fact that the properties of HiMA asphalt mixtures are known [6], inclusion of their influence in pavement life calculations is by no means a trivial matter. The results of laboratory fatigue tests of asphalt mixtures with HiMA binders indicate durability that is many times greater than in the case of unmodified asphalt mixtures [1, 11]; however, the standard formulas used to calculate the fatigue life of the pavement, e.g. the Asphalt Institute equations, do not enable direct evaluation of the benefits of using binders with lower stiffness and greater fatigue resistance. In consequence, with a HiMA layer (or layers) of 20–30% lower stiffness introduced in the analysed system, greater critical strains of the structure are obtained, resulting in a decrease in the calculated fatigue life of the pavement. The fact that material laboratory tests of HiMA asphalt mixtures indicate increased life – greater by an order of magnitude – than that of mixtures with unmodified binder, raises questions about the validity of the classic analytical approach. The literature still lacks sufficiently accurate, reliable and relatively simple tools to quantify the fatigue life and, more broadly, the durability [21] of pavements containing asphalt mixtures with HiMA bitumen. Thus far, the greatest problems have been posed by evaluation of fatigue life of the entire layered system of the pavement after replacement of standard bitumen with HiMA binder in the asphalt base course, which is essentially the crucial layer in terms of bottom-up fatigue cracking.

In the work [28], the Similarity Method (SiM) was proposed, which uses the results of laboratory fatigue tests of mixtures containing HiMA (fatigue life equations) and subjects them to a realistic reduction based on the AASHTO 2004 formulas. The SiM method may be used for prediction of fatigue life of typical pavement layer systems with modified binders in the asphalt courses. In summary, the method is based on a hypothesis that the laboratory fatigue equation coefficients of an asphalt mixture with HiMA are related to fatigue equation coefficients of a set of layers of the structure with this mixture in the asphalt base course analogously to the manner in which the laboratory-determined fatigue equation coefficients of a mixture with unmodified binder are related to the fatigue equation coefficients of pavement structure with the unmodified mixture in the asphalt base course, e.g. according to the AASHTO 2004 formula. The key aspects of the method also include the fact that the fatigue equations are plotted as straight lines on a log-log chart – they express the relationship between the logarithm of fatigue life and the logarithm of critical strain at the bottom of asphalt layers.

2. Objectives

The aim of the work is to attempt qualitative and quantitative evaluation of the influence of highly modified bitumen HiMA on pavement life predictions calculated using the SiM method. The following variants were chosen for analysis:

- use of HiMA binders in three combinations of asphalt courses (only in the asphalt base, in the asphalt base and the binder course, and in all three asphalt courses),
- use of two types of asphalt concrete in the asphalt base (AC 16 and AC 22).

All the variants were compared with a traditional (reference) system of asphalt layers. According to the information presented in Section 1, it was expected that fatigue life of the analysed layer system, determined according to the classic approach (e.g. the AI method), should decrease with an increase in the number of layers containing HiMA binder (layers with lower stiffness).

3. Numerical model

3.1. Assumptions

Pavement structure intended for a total service life of up to 22 million 100 kN equivalent standard axle loads according to the guidelines of the General Directorate for National Roads and Motorways 2014 was assumed as the reference structure with asphalt courses containing only standard binders. This layer system was gradually changed through introduction of HiMA binders in the asphalt mixtures, to obtain the variants described in Section 2. The arrangement and thickness of the layers was constant throughout the analysis.

The calculation model adopted in the analysis assumed that the “structural fatigue life” was dependent on the area of the bottom-up fatigue crack mesh on the road surface, with failure occurring at the assumed cracking index of 5% of the lane/roadway area. The method was presented in Złotowska at al. [28].

The following aspects were not investigated in the analysis: top-down cracking of asphalt layers [20, 22], resistance to permanent deformation of asphalt layers (functional/viscoelastic rutting) [23], life of geo-grid reinforced asphalt pavements [18] and the issues of ageing of asphalt layers [7, 13].

Based on the data obtained from laboratory tests of three mixtures with unmodified road asphalt and three analogous mixtures with highly modified asphalt HiMA, eight analysed layer systems (pavement structures) were created. Their maximum deflections and critical strains were calculated with VEROAD software [8], using the Huet–Sayegh material model [19] for the asphalt layers at the equivalent temperature of 10°C and the assumed typical speed of heavy vehicle traffic in non-built-up areas (loading frequency of 10 Hz). The pavements were loaded with a vertical force $P = 50$ kN representing a standard equivalent wheel load, distributed evenly with an intensity of 850 kPa on a circular surface (of radius 13.68), moving at a constant speed of 60 km/h, typical of a heavy vehicle. Their fatigue life values were determined using the SiM method, in the manner described in Section 4.

3.2. Pavement structures

A typical flexible pavement structure with arrangement and thickness of the layers shown in Fig. 1 (standard for the traffic load assumed in Section 3.1) was considered in the analysis.

The following pavement structures were assumed in the first part of the analysis (Table 1):

- Reference structure (RS) – flexible pavement structure; wearing course of SMA 8 *surf* mixture with modified bitumen PMB 45/80-55 including SBS polymer content of 3-4% m/m; binder course of z AC 16 *bin* and asphalt base of AC 22 *base*, both containing unmodified road bitumen 35/50.
- Structure H1 – structure with one layer containing HiMA binder; wearing course of SMA 8 *surf* mixture with classic modified bitumen PMB 45/80-55 including SBS polymer content of 3–4% m/m; binder course of z AC 16 *bin* with unmodified road bitumen 35/50, but with the asphalt base course of AC 22 *base* containing highly modified bitumen PMB 45/80-80 HiMA.

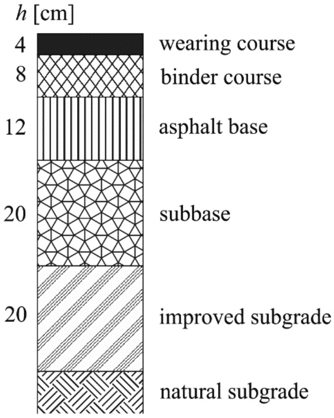

Fig. 1. Pavement structure for analysis

- Structure H2 – structure with two layers containing HiMA binder; wearing course of SMA 8 surf mixture with classic modified bitumen PMB 45/80-55 including SBS polymer content of 3–4% m/m; both the AC 16 *bin* binder course and the AC 22 *base* base course containing highly modified bitumen PMB 45/80-80 HiMA.
- Structure H3 – structure with three layers containing HiMA binders (so-called "full HiMA"); wearing course of SMA 8 *surf* containing PMB 65/105-80 HiMA; the binder course of AC 16 *bin* and the base course of AC 22 *base* both containing PMB 45/80-80 HiMA.

Layer systems considered in the first part of the analysis are shown in Table 1 with designations of the used types of asphalt mixtures and bituminous binders.

In the second part of the analysis, which focused on the effect of change in the grading of the asphalt base mix from AC 22 to AC 16, pavement structures shown in Table 2 were adopted. In contrast to the structures RS, H1, H2 and H3, the structures used in the second part (RSa, H1a, H2a and H3a) included asphalt base course of AC 16 *bin* mixture instead of AC 22 *base* mixture. The types of bituminous binders used in the asphalt base course remained the same as in corresponding structures from the first part of the analysis (as in the original AC 22 *base* mixture).

All the asphalt mixtures – SMA 8 surf, AC 16 *bin* and AC 22 *base* – were designed in accordance with the requirements for national roads provided in the Polish technical guidelines [41] issued by the General Directorate for National Roads and Motorways. Every mixture type (AC 22, AC 16 and SMA 8) was characterised by the same grading across all variants, regardless of the type of binder used (neat, modified, highly modified). Mixture designations were used in accordance with the EN 13108:2016 standards [35, 36]: wearing course – *surf*, binder course – *bin*, asphalt base course – *base*.

The characteristics of the highly modified PMB 45/80-80 HiMA and PMB 65/105-80 HiMA binders were in accordance with the Polish national appendix to EN 14023 [38] from 2014 [39]. The basic parameters of the binders are given in Table 3.

Table 1. Arrangement of layers and materials in the analysed pavement structures

Layer	Thickness h [cm]	Structure code			
		RS	H1	H2	H3
Wearing	4	SMA 8 45/80-55	SMA 8 45/80-55	SMA 8 45/80-55	SMA 8 65/105-80 HiMA
Binder	8	AC 16 35/50	AC 16 35/50	AC 16 45/80-80 HiMA	AC 16 45/80-80 HiMA
Base	12	AC 22 35/50	AC 22 45/80-80 HiMA	AC 22 45/80-80 HiMA	AC 22 45/80-80 HiMA
Subbase	20	E = 400 MPa			
Improved subgrade	20	E = 300 MPa			
Natural subgrade	–	E = 100 MPa			

Table 2. Arrangement of layers and materials in the structures considered in the second part of the analysis, after the change of the asphalt base course mix from AC 22 to AC 16

Layer	Thickness h [cm]	Structure code			
		RSa	H1a	H2a	H3a
Wearing	4	SMA 8 45/80-55	SMA 8 45/80-55	SMA 8 45/80–55	SMA 8 65/105-80 HiMA
Binder	8	AC 16 35/50	AC 16 35/50	AC 16 45/80–80 HiMA	AC 16 45/80-80 HiMA
Base	12	AC 16 35/50	AC 16 45/80-80 HiMA	AC 16 45/80–80 HiMA	AC 16 45/80-80 HiMA
Subbase	20	E = 400 MPa			
Improved subgrade	20	E = 300 MPa			
Natural subgrade	–	E = 100 MPa			

Table 3. Basic properties of the binders used in the asphalt mixtures

Binder	Specification	Penetration@25°C EN 1426 [0.1 mm]	Softening Point R&B EN 1427 [°C]	Elastic Recovery EN 13398 [36] [%]	PG AASHTO M320 [–]
Paving grade 35/50 (unmodified)	EN 12591 [30]	43	53,5	–	70–22
PMB 45/80-80 HiMA (highly modified)	EN 14023 [39] Polish National Spec. 2014	69	92	95	88–28
PMB 45/80-55 (conventionally modified)	EN 14023 [39] Polish National Spec. 2014	65	59	85	70–28
PMB 65/105-80 HiMA (highly modified)	EN 14023 [39] Polish National Spec. 2014	88	90	95	76–28

3.3. Mechanical model of the pavement structure and the used materials. Material parameters

For modelling of the analysed pavements, a linear layered half-space model was used (as a general initial mechanical model), consisting of horizontally unlimited homogeneous and isotropic layers of constant thickness representing structural layers and improved subgrade, and a homogeneous and isotropic half-space representing natural subgrade [15]. Full continuity of displacements on layer interfaces was assumed (for comparative analytical purposes), meaning full bonding of pavement layers.

The viscoelastic Huet–Sayegh model (hereinafter abbreviated to H-S) [15, 19] was used to describe the material properties of the asphalt pavement layers. For the remaining (non-asphaltic) layers, Hooke's elastic model (hereinafter abbreviated to H) [15] was used.

The constitutive equations of these materials in the "stress-strain" relation were presented in the work Złotowska et al. [28], using the same designations of quantities as in this article.

The values of material parameters of the H-S model of asphalt layers were assumed for an equivalent temperature of $T = 10°\mathrm{C}$ (for the entire year) and for frequency $f = 10$ Hz (corresponding to the typical speed of heavy vehicle traffic, estimated as 60–75 km/h under free-flow traffic conditions). These values, determined from the master curves based on measurements of complex stiffness moduli E^* (for a specific set of frequencies f) during the four-point bending of samples (according to the standard EN 12697-26:2018 [32]), were taken from the work of Błażejowski et al. [1].

In relation to the asphalt layers, the dynamic stiffness moduli $|E^*|$ (determined experimentally along with the material parameters of the H-S models) used for prediction of the fatigue life of the pavement were also given.

The values of Young's modulus of elasticity E (for the H models) of materials in non-asphaltic layers and the values of Poisson's coefficients ν of all materials were adopted in accordance with the Ordinance of the Minister of Transport and Maritime Economy (in Poland) [29].

The values of material parameters of pavement layers adopted in the H-S and H models are listed in Tables 4–6. Table 5 shows – beside the values of modulus $|E^*|$ and Poisson's coefficient ν – the values of V_a and V_v parameters of the mixtures used in the considered structures, obtained on the basis of measurements published by Błażejowski et al. [1], and used in prediction of fatigue life values.

Table 4. Material parameters of asphalt mixtures for the Huet–Sayegh model of asphalt layers at a temperature of $T = 10°\text{C}$

Asphalt mixture	Binder	η_a [MPa · s]	η_b [MPa · s]	E_a [MPa]	E_p [MPa]	k_a [–]	h_b [–]
SMA 8	PMB 45/80-55	1053	2790	28500	200	0.22	0.66
SMA 8	PMB 65/105-80 HiMA	259	700	29000	165	0.23	0.61
AC 16	35/50	19482	66240	27600	210	0.26	0.73
AC 16	PMB 45/80-80 HiMA	3019	9662	27500	230	0.26	0.58
AC 22	35/50	36717	110152	18800	450	0.26	0.80
AC 22	PMB 45/80-80 HiMA	4463	16065	18900	500	0.27	0.73

Table 5. Material parameters of asphalt mixtures (cont.)

Asphalt mixture	Binder	Dynamic modulus $\lvert E^*\rvert$ [MPa]	Poisson's ratio ν [–]	V_a [% vol]	V_v [% vol]
SMA 8	PMB 45/80-55	8087	0.3	16.36	2.2
SMA 8	PMB 65/105-80 HiMA	6972	0.3	16.38	2.6
AC 16	35/50	14818	0.3	10.49	5.4
AC 16	PMB 45/80-80 HiMA	11607	0.3	10.65	5.5
AC 22	35/50	11563	0.3	9.86	5.2
AC 22	PMB 45/80-80 HiMA	8668	0.3	9.93	5.8

Table 6. Material parameters of lower pavement layers for the H models

Layer	Material	Young's modulus of elasticity E [MPa]	Poisson's ratio ν [–]
Subbase	compacted crushed aggregate	400	0.30
Improved subgrade	soil stabilized with cement	300	0.30
Natural subgrade	natural soil	100	0.35

4. Calculated life of pavement structures

4.1. Pavement life based on aashto 2004

The AASHTO 2004 fatigue cracking criterion selected in this paper is one of the newer criteria used to determine the fatigue life of flexible pavement structures in the world and one of the main criteria adopted for the development of a new pavement structures catalog in Poland [9, 40]. Pavement life, determined by the AASHTO 2004 method – with fatigue cracks limited to an assumed percentage of the total lane area in the case of "bottom-up" cracks – and hereinafter referred to as "structural fatigue life" $N_{f(\text{struct})}$, is expressed by the formulas given in Złotowska et al. [28] and used in this work as well (using the same quantity designations). The key equation has the form

$$N_{f(\text{struct})} = C(\varepsilon_h)^{-\alpha}, \qquad \alpha = 3.9492 \tag{4.1}$$

where: $N_{f(textstruct)}$ – structural fatigue life [equivalent axle loads], ε_h – maximum tensile strain (horizontal) at the bottom of the asphalt layers in which the cracks are initiated, C – coefficient dependent on the arrangement of the layers and materials used.

The value of the *FC* cracking index for bottom-up cracks was assumed to be 5%, in order to obtain a reasonably "safe" prediction of pavement life.

Eq. (4.1) is basically calibrated for pavements with asphalt mixtures containing unmodified road bitumens, which differ significantly from the highly elastomer-modified binders (HiMA). The latter are characterised by greater resistance to fatigue failure. The use of such formulas in this work is justified by the assumption that a certain comparative evaluation of the resistance of HiMA-based mixtures vs the reference RS/RSa structure is possible.

4.2. Laboratory fatigue life

Laboratory fatigue equations were also determined for the tested asphalt mixtures. Such an equation has the form:

$$\log N_f = A_1 \log(\varepsilon_t) + A_0 \tag{4.2}$$

where: ε_t – amplitude of cyclic tensile strain of the specimen, applied with a frequency of $f = 10$ Hz in the four-point bending test (4PB-PR) at temperature $T = 10°\text{C}$, according to the standard (EN 12697-26), for which N_f represents the conventional fatigue life of the mixture, i.e. the number of strain cycles at which the initial value of the dynamic stiffness modulus $|E^*|$ of the mixture is reduced by 50%.

The laboratory-determined fatigue life of the mixture used in the bottom asphalt course is referred to as the "laboratory fatigue life" of the pavement ($N_{f(\text{lab})}$).

The values of the coefficients A_0 and A_1 for the mixtures considered in the work were determined on the basis of laboratory test results of these mixtures presented in Błażejowski et al. [1]. They are presented in Table 7.

Values of fatigue life $N_{f(\text{lab})}$ determined from laboratory fatigue curves (2) for strains of $\varepsilon_t = \varepsilon_h$ (strains calculated for real structures) are incomparable directly with the design

Table 7. Laboratory fatigue formula coefficients of the tested asphalt mixtures according to Eq. (4.2)

Asphalt mixture	Binder	A_1 [–]	A_0 [–]
AC 16	35/50	–4.7388	15.922
AC 16	PMB 45/80-80 HiMA	–7.0748	22.698
AC 22	35/50	–5.2853	17.007
AC 22	PMB 45/80-80 HiMA	–6.3487	20.598

life $N_{f(\text{struct})}$ determined on the basis of AASHTO formulas (Eq. (4.1)), which pertain to the behaviour of the entire pavement structure and a different failure criterion (a specific level of cracking on pavement surface), while $N_{f(\text{lab})}$ reflects a 50% decrease in the stiffness modulus of the mixture used in a particular asphalt layer (at the level of cyclic strain amplitude of this mixture equal to ε_h). However, the fatigue curves based on Eq. (4.2) appear to be useful for comparison between different asphalt mixtures that may be used in a given pavement course.

4.3. The similarity method for estimation of fatigue life of hima pavements

In Złotowska et al. [28], the authors of this article proposed a method for realistic estimation of the fatigue life of pavements with layers containing highly modified bitumen, based on their hypothesis regarding the relationships between the fatigue life values due to bottom-up cracking obtained for various mixtures. This method, called the Similarity Method (SiM), will be summarised and used in this article.

The key premise of the proposed method is the observation that, according to Wöhler's concept, each formula used for fatigue life calculation has the form:

$$N_f = C\left(\frac{1}{\varepsilon_{\text{cr}}}\right)^{\alpha}, \quad \text{therefore} \quad \log N_f = \log C - \alpha\log(\varepsilon_{\text{cr}}) = A - \alpha\log(\varepsilon_{\text{cr}}) \tag{4.3}$$

where ε_{cr} is the critical strain, on which the life N_f of the structure or layer mainly depends, and A and α are often products of coefficients dependent on specific factors and are subject to experimental calibration.

In the SiM method, the A and α coefficients for the reference structure with typical (unmodified road asphalt) mixtures ($A^{\text{ref}}_{\text{struct}}$ and $\alpha^{\text{ref}}_{\text{struct}}$) are first determined using one of the known and recognised fatigue life calculation methods (in this work AASHTO 2004), and then scaled proportionally to the changes in A and α coefficients observed in the fatigue equations of the laboratory-tested asphalt base course mixtures with neat bitumen and with highly modified bitumen. Therefore, if the maximum strain at the bottom of the asphalt base ε_{cr} is known, pavement life due to fatigue cracking may be expressed as:

$$N_{f(\text{SiM})} = C_{\text{SiM}}\left(\frac{1}{\varepsilon_h}\right)^{\alpha_{\text{SiM}}} \tag{4.4}$$

where: $C_{\text{SiM}} = 10^{A_{\text{SiM}}}$, $A_{\text{SiM}} = A^{\text{ref}}_{\text{struct}}\dfrac{A^{\text{HiMA}}_{\text{lab}}}{A^{\text{ref}}_{\text{lab}}}$, $\alpha_{\text{SiM}} = \alpha^{\text{ref}}_{\text{struct}}\dfrac{\alpha^{\text{HiMA}}_{\text{lab}}}{\alpha^{\text{ref}}_{\text{lab}}}$.

4.4. Pavement design life due to permanent deformation

Pavement design life due to permanent deformation (caused by cyclic loading) calculated using the subgrade strain model may be expressed using the following formula [15]

$$N_d = \left(\frac{k}{\varepsilon_v}\right)^{1/m} \tag{4.5}$$

where: N_d – pavement life [equivalent axle loads], $k = 1.05 \times 10^{-6}$, $m = 0.223$, ε_v – maximum compressive strain (vertical) on top of the subgrade (equation uses the absolute value of ε_v).

As shown by Eq. (4.5), the estimations of pavement life based on permanent deformation criterion are calculated using the same formula across all variants, but for different values of ε_v. These values of pavement life are very sensitive to changes in the values of strain ε_v.

Pavement life determined by permanent deformation N_d plays a major role in the assessment of the effective life of pavements with highly modified binders, as shown below.

5. Results

5.1. Coefficients for the fatigue formulas of the analysed structures

Table 8 shows the values of A and α coefficients from the fatigue Eq. (4.3) of the analysed structures for the different life calculation methods described in Section 4 (the reference formula being the AASHTO 2004 equation at cracking index $FC = 5\%$).

Table 8. The values of A and α coefficients from Eq. (4.3) for the three methods of determining the lifespan of the structure

Method	Coefficient [–]	Pavement structure variant		
		Reference structure	H1, H2, H3	H1a, H2a, H3a
AASHTO 2004	α_{struct}	3.9492	3.9492	3.9492
	A_{struct}	14.386	14.433	14.407
Laboratory	α_{lab}	5.2853	6.3487	7.0748
	A_{lab}	17.007	20.598	22.698
SiM	α_{SIM}	3.9492	4.7438	5.8960
	A_{SIM}	14.386	17.424	20.349

It should be noted that the laboratory curves were determined based on tests conducted over a relatively narrow range of tensile strains (from 150 $\mu\varepsilon$ to 400 $\mu\varepsilon$), which may result in considerable inaccuracies for other strain ranges.

5.2. Comparison of structures with highly modified bitumen in different layer arrangements

5.2.1. Deflections and critical strains

Figs. 2, 3 present the results of calculations of the following critical values:
- the maximum deflection w of the entire structure,
- the maximum horizontal tensile strain ε_h at the bottom of the asphalt base course,
- the maximum vertical strain ε_v on top of the subgrade.

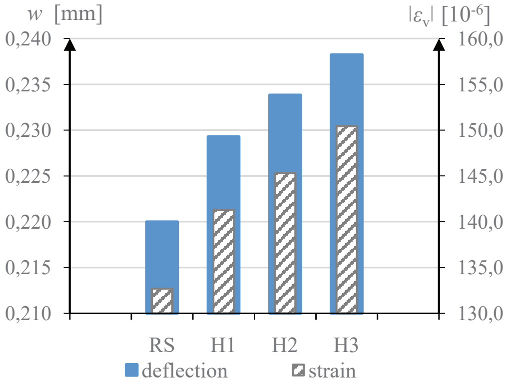

Fig. 2. Comparison of the maximum deflection w of the pavement and the maximum vertical strain on top of the subgrade ε_v depending on the number of layers containing HiMA binder

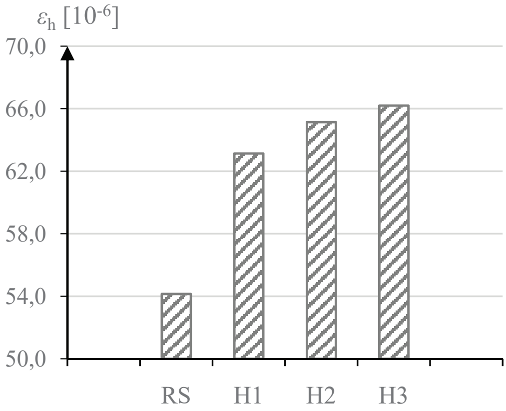

Fig. 3. Comparison of the maximum horizontal tensile strain ε_h at the bottom of the asphalt base course depending on the number of layers containing HiMA binder

Table 9 shows the ratios between the above values obtained for structures with HiMA and the corresponding values for the reference structure.

It is noteworthy that an increase in all critical values is observed every time another layer of HiMA-based asphalt mixture is introduced, and the greater the number of layers containing

Table 9. The ratios of maximum deflections and critical strains of the analysed pavement structures with HiMA binders to corresponding values of the reference structure with neat bitumen

Pavement structure variant	Deflection w	Strain ε_h	Strain ε_v
H1/RS	1.042	1.166	1.065
H2/RS	1.063	1.203	1.095
H3/RS	1.083	1.223	1.134

HiMA, the greater the increase in deflections and critical strains. In the extreme case, for the structure with three layers of HiMA-based mixtures, the critical strain ε_h increased by 22%, with an increase in ε_v by 13% and deflection w by 8%.

5.2.2. Calculated fatigue life values

Table 10 presents a comparison of critical strains and respective values of fatigue life determined according to the methods described in Section 4, using AASHTO 2004 at the cracking index $FC = 5\%$ as the reference method. Permanent deformation is also included. As shown by the results, fatigue life due to permanent deformation (subgrade strain model) becomes the limiting criterion in the case of structures with mixtures including HiMA binders.

Table 10. Critical strains and fatigue life values determined using the methods described in Section 4

Critical strains and predicted life [millions of 100 kN axles]	Reference structure	H1 structure	H2 structure	H3 structure
ε_h $[10^{-6}]$	54.1	63.1	65.1	66.2
$N_{f\,\text{(struct)}}$	35	21	19	17
$N_{f\,\text{(lab)}}$	70	1 474	1208	1 092
$N_{f\,\text{(SiM)}}$	35	765	659	611
ε_v $[10^{-6}]$	–132.7	–141.3	–145.3	–150.4
N_d	326	246	217	186

5.3. Comparison of structures with ac 16 mixture in the asphalt base course

The second part of the analysis focused on the influence of the change in the asphalt base mixture grading from AC 22 *base* to AC 16 *bin* (structures RSa, H1a, H2a, H3a).

Across all variants, the change of the type of the base course mixture from AC 22 *base* to AC 16 *bin* (structures RSa, H1a, H2a and H3a) resulted in a decrease in deflections and critical strains in relation to the values presented in Table 10. The greatest change was observed for the

Table 11. The ratios of maximum deflections and critical strains of the analysed pavement structures with HiMA binders to corresponding values of the reference structure with unmodified bitumen – all structures with AC 16 mixture in the asphalt base course

Pavement structure variant	Deflection w	Strain ε_h	Strain ε_v
H1a/RSa	1.039	1.165	1.061
H2a/RSa	1.061	1.201	1.095
H3a/RSa	1.081	1.220	1.134

tensile strain at the bottom of the asphalt layers (a decrease by approx. 9% for each structural variant). Interestingly, the relative decrease is similar for all variants, regardless of the number of HiMA layers.

Table 12. Critical strains and fatigue life values determined using the methods described in Section 4

Critical strains and predicted life [millions of 100 kN axles]	Reference structure RSa	H1a structure	H2a structure	H3a structure
ε_h $[10^{-6}]$	49.2	57.3	59.0	60.0
$N_{f(SiM)}$	39	**9 661**	**8 061**	**7 361**
ε_v $[10^{-6}]$	–128.3	–136.1	–140.4	–145.5
N_d	379	290	253	216

Table 13 shows a comparison of the relative effect of the change of the asphalt base mixture from AC 22 to AC 16 for every variant (the reference structure RS and the structures with various numbers of layers with HiMA-based mixtures).

Table 13. Relative change in deflection, critical strain and pavement life (both due to fatigue and permanent deformation) for RSa, H1a, H2a and H3a structures vs RS, H1, H2 and H3, respectively

Deflection, critical strains, pavement life	$\frac{\text{RSa} - \text{RS}}{\text{RS}}$ [%]	$\frac{\text{H1a} - \text{H1}}{\text{H1}}$ [%]	$\frac{\text{H2a} - \text{H2}}{\text{H2}}$ [%]	$\frac{\text{H3a} - \text{H3}}{\text{H3}}$ [%]
w	–2.0	–2.3	–2.2	–2.2
ε_h	–9.2	–9.3	–9.4	–9.4
ε_v	–3.3	–3.6	–3.4	–3.3
$N_{f(\text{SiM})}$	$11^{*)}$	1163	1123	1105
N_d	16	18	17	16

The considerable increase in $N_{f(\text{SiM})}$ is caused by its high sensitivity to changes in ε_h (ε_h is raised to the power of $\alpha = 5.8960$, as shown in Table 8).

In practical terms, the given values of $N_{f(\text{SiM})}$ should not be interpreted as a determined number of axle loads leading to fatigue failure, but rather as a number which guarantees that the area of bottom-up cracks will not exceed 5% of the total area of the roadway in the assumed service life. Moreover, the $N_{f(\mathrm{SiM})}$ values are very sensitive to potential errors in calculations or measurements of ε_h critical strain. It is noteworthy that the observed increase in fatigue life values is similar for all the cases of replacement of AC 22 in the asphalt base course with AC 16, regardless of the structural variant.

5.4. Discussion

As expected, the lowest deflections and critical strains were observed for the RS and RSa structures with courses of only road asphalt mixtures (without polymer modification), which were characterised by the greatest stiffness. The layers with highly modified binders are characterised by lower values of stiffness modulus (by approx. 30%) than layers with unmodified road asphalt, which results in greater values of deflection and critical strains. Deflections of variants with HiMA are greater than deflections of the RS reference structure by 4.2% (one layer with HiMA) to 8.3% (all asphalt layers containing HiMA).

The changes in horizontal tensile strain εh in relation to the RS reference structure are more pronounced and equal 16.6% for H1, 20.3% for H2 and 22.3% for H3 (full HiMA). A significant rise of ε_h between RS and H1 may be seen in Fig. 3. Moreover, the differences between strain values for variants H1-H3 are relatively low and do not exceed 3 microstrains. Therefore, it may be stated that the application of HiMA binder in the pavement will certainly lead to both greater critical tensile strain and a considerable increase in the predicted life based on the fatigue cracking criterion.

It should be noted that the heightened fatigue resistance of the HiMA-based mixtures The critical compressive strain on top of the subgrade also changes as a result of the application of layers with HiMA binder. As a consequence of the reduced stiffness of the system of asphalt layers, an increase in ε_v is observed in relation to the reference structure RS, ranging from 6.5% (H1) to 13.4% (H3). In contrast to ε_h, the range of ε_v values between H1 and H3 is greater (around 9%), and the rise between the results obtained for RS and H1 is not as pronounced, which may be explained by the fact that this strain is calculated at a point located relatively deep below the asphalt layers. It may be assumed that the introduction of each successive layer containing HiMA significantly affects the increase in ε_v.

The observed substantial increase in critical tensile strain ε_h should be reflected in the fatigue life values, at least in the cases where comparable materials are used in the asphalt base course. The results of such an analysis according to the AASHTO method are presented in Table 10 as $N_{\mathrm{f(struct)}}$ – they indicate that the calculated fatigue life of the H3 variant (full HiMA) is two times lower than the fatigue life of the RS variant with unmodified bitumen. However, bearing in mind the marked difference in fatigue resistance of the AC 22 mixtures with different binders (Table 7) – decidedly in favour of the highly modified bitumen – it should be noted that the order of results is reversed when fatigue equations based on the laboratory material tests are used: $N_{f(\mathrm{lab})}$ in Table 7. Fatigue life obtained from the AASHTO 2004 method should not be directly compared (in terms of values) with fatigue life obtained from "laboratory fatigue equations" of the base course material, since their defining criteria are incommensurable, as shown, among others, by the fatigue life values determined for the base course mixtures with unmodified binder.

For the pavements with HiMA binders, the SiM method generated fatigue life results $N_{f(\mathrm{SiM})}$ that were qualitatively consistent with the expected order – variants H1 to H3 are characterised by higher fatigue life than the reference variant RS.

It should be noted that the highest fatigue life according to the SiM method was obtained for the H1 structure with highly modified binder in the asphalt base. The decrease in fatigue life value observed for the variant with three HiMA asphalt layers (H3) by approx. 20% in relation to the H1 variant with HiMA in the asphalt base only may be explained by the increase in critical strains by approx. 3%. Therefore, it may be stated that pavement life due to fatigue cracking calculated according to the SiM method is highly sensitive to changes in the ε_h strain (the N_f formula includes low value of ε_h in the denominator of the fraction raised to the power of α, with α being greater than 5), but still significantly less sensitive than the results of the laboratory method.

Placement of HiMA-based asphalt mixtures in the system of asphalt layers leads to an increase in the values of critical strains ε_v on top of the subgrade by 6.5–13.6%, which reduces (objectively, regardless of the estimation of fatigue life of the asphalt layers) the predicted life due to permanent deformation by values ranging between 24% (H1) and 43% (H3).

Upon comparison of the predicted values of pavement life due to fatigue cracking $N_{f(\mathrm{SiM})}$ with the predicted life due to permanent deformation N_d, it can be seen that when HiMA-based asphalt mixtures (layers of lower stiffness) are used, the effective pavement life may be determined by the subgrade strain model (Table 10). However, even the least stiff HiMA structure, i.e. the system of three HiMA layers with the AC 22 mix type in the base, has an effective life 2.5 times greater than the RS reference structure. It should also be noted that all the structures with highly modified bitumen may be classified as long-life pavements (they meet the condition of minimum 87 million 100 kN standard axle loads in the period of 50 years [16, 17]).

Therefore, a significant change was noted in the behaviour of pavements with highly modified binders compared to those with neat road asphalt. Despite the reduction in N_d observed for pavement with HiMA (even with HiMA in all asphalt layers), the $N_{f(\mathrm{SiM})}$ value exceeds N_d so clearly that it is the permanent deformation criterion that will prove decisive in determining pavement structure thickness.

While the greatest calculated fatigue life values were obtained for the H1 variant (only one layer with HiMA), this result should be judged with skepticism. Pavement life in a broader sense is related to many factors beside the fatigue cracking criterion or the permanent deformation criterion, including low-temperature cracking, resistance to rutting of the asphalt courses and top-down fatigue cracking. From this perspective, structures H2 and H3 offer much better economic parameters within the pavement life cycle than structure H1.

The introduced change of asphalt base course mix from AC 22 to AC 16 proved advantageous across all the analysed structure variants, both reference RS-RSa and the remaining Hn-Hna. The greatest improvement is visible in reduction in tensile strain at the bottom of the asphalt base ε_h (decrease by approx. 9% in relation to corresponding structure with AC 22). This resulted in an increase in pavement life due to fatigue cracking by 11% for the RSa structure and by a factor greater than 10 for the structures H1a, H2a and H3a. One of the reasons for such a considerable change is the high sensitivity of calculated pavement life values to changes in tensile strain ε_h. In the case of pavement life determined by permanent deformation criterion the relative increase was similar across all variants at 16% to 18%.

6. Summary and conclusions

1. Comparative analysis of pavement life of the RS, H1, H2 and H3 structures in terms of bottom-up fatigue cracking and permanent deformation shows unquestionable influence of stiffness of the asphalt layers on deflection and, consequently, on critical strains. Excluding other functional properties of asphalt mixtures, such as resistance to rutting of asphalt layers, frost/water action and crack propagation, structural life according to the AASHTO 2004 equations remained primarily dependent on stiffness.
2. The classic (AASHTO 2004, Asphalt Institute) equations indicate that the reference structure with unmodified binders (RS) is the system with the greatest lifespan. The more layers containing HiMA-based mixtures are introduced, the lesser the pavement life – both in terms of fatigue and permanent deformation. Such results were obtained due to the substantial decrease in stiffness of the HiMA-based courses (by about 30%), which resulted in greater deflections and critical strains, leading to lower $N_{f(\mathrm{struct})}$ and N_d. The considerably better fatigue properties that characterise the HiMA asphalt mixes are not incorporated in the AASHTO 2004 equations.
3. It may be concluded that the AASHTO formulas used for fatigue life calculations (N_f) are not adequate for pavements containing highly modified bitumen. In contrast, the calculations of pavement life based on permanent deformation using the subgrade strain model (N_d) remain valid, since their results depend on the stiffness of the entire layered system above the subgrade.
4. The following trend is visible in the results of the analysis: the greater the number of HiMA-based asphalt courses in the structure (with lower stiffness and, possibly, lower thickness), the greater the importance of the permanent deformation (subgrade strain model) criterion and the lower the importance of the fatigue criterion.
5. Among the structures in which highly modified HiMA binders were used, the greatest structural advantages were observed for the H1 variant, i.e. when HiMA was used only in the asphalt base course (as a kind of anti-fatigue course). The explanation for this is the greater general stiffness of the asphalt layers in H1 than in variants H2 and H3. Such a trend is obvious when the AASHTO 2004 method is used, but it should be noted that the same trend also exists for the results of direct calculations using the mixture fatigue equations and for the SiM method. However, the outcome mentioned in the first conclusion should be stressed again – life values based on structural criteria do not take into account the greater functional lifespan of the wearing and binder courses constructed using asphalt mixtures with HiMA binder.
6. The use of the SiM method enabled incorporation of the advantageous fatigue properties of HiMA-based mixtures in the analysis. The substantial increase in pavement fatigue life after introduction of HiMA in the structures, largely exceeding the level of pavement life due to permanent deformation (even at the assumed low value of the FC cracking index) means that permanent deformation became the dominant criterion for the design of lifespan and thickness of the analysed structure (Fig. 1).

7. Change of asphalt base course mixture from AC 22 to AC 16 proved advantageous across all the analysed structures. Deflections and critical strains decreased, while the pavement life values calculated based on fatigue cracking and permanent deformation criteria increased.

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Wpływ asfaltu wysokomodyfikowanego na prognozę trwałości zmęczeniowej nawierzchni drogowej – wybrane zagadnienia

Słowa kluczowe: nawierzchnia drogowa, wysokomodyfikowane lepiszcze asfaltowe, prognoza trwałości zmęczeniowej

Streszczenie:

Wprowadzenie do stosowania nowych materiałów do budowy nawierzchni drogowych pociąga za sobą konieczność weryfikacji, czy istniejące metody projektowania konstrukcji nawierzchni w prawidłowy sposób adaptują ich właściwości i czy w konsekwencji uzyskany wynik można uznać za prawidłowy.

W przypadku nawierzchni asfaltowych, współcześnie stosowane metody projektowania sięgają swoimi korzeniami połowy XX wieku, a więc czasów, gdy stosowano wyłącznie lepiszcza asfaltowe bez dodatku modyfikatorów. Wprowadzenie w latach 80 XX wieku bitumów modyfikowanych polimerami zmieniło w pewnym zakresie zachowanie nawierzchni, głównie jednak pod względem ulepszeń funkcjonalnych. Pojawienie się w 2009 r. lepiszczy wysokomodyfikowanych SBS, o odwróconej fazie polimer-bitum, gdzie lepiszcze w przejęło dużą część cech polimeru zmieniło bardzo wiele w zachowaniu mieszanek asfaltowych i w konsekwencji całej struktury. Warstwy asfaltowe stały się niezwykle podatne, sprężyste, wytrzymałe zmęczeniowo, z jednoczesną dużą odpornością na koleinowanie. Niesie to za sobą wiele konsekwencji dla pracy układu warstw, w tym na sposób powstawania odkształceń krytycznych. Celem artykułu jest przedstawienie efektów zastosowania mieszanek asfaltowych z asfaltami wysokomodyfikowanymi typu HiMA (Highly Modified Asphalt) w różnych wariantach nawierzchni podatnych – z jedną, dwiema i trzema warstwami HiMA (full-HiMA). Do obliczeń trwałości zmęczeniowej wykorzystano autorską "metodę podobieństw", która pozwala oszacować trwałości na podstawie relacji z wynikami zmęczenia uzyskanymi w laboratorium. Trwałość ze względu na deformacje strukturalnie obliczono klasycznie, wg równania Instytutu Asfaltowego. Wyniki wskazują, że wszystkie warianty z warstwami z HiMA prezentują z punktu widzenia trwałości zmęczeniowej lepsze wyniki niż wariant referencyjny z lepiszczami klasycznymi. Najkorzystniejszy okazał się układ z warstwą HiMA w ostatniej dolnej warstwie asfaltowej, łączący świetne właściwości zmęczeniowe mieszanki asfaltowej z HiMA, z wykorzystaniem większej sztywności warstwy wiążącej i ścieralnej z klasycznymi lepiszczami. Im więcej warstw z asfaltami wysokomodyfikowanymi HiMA, tym mniejsza trwałość, zarówno pod względem zmęczeniowym, jak i deformacji strukturalnych. Przyczyną takiego wyniku jest znacząco mniejsza sztywność warstw asfaltowych z HiMA (o około 30%) co przekłada się na wzrost ugięcia nawierzchni i odkształceń krytycznych. Dodatkowo, wyraźnie kształtuje się zależność, że im większa liczba warstw asfaltowych z HiMA – o mniejszej sztywności, tym większe znaczenie będzie miała trwałość ze względu na deformacje strukturalne a mniejsze trwałość zmęczeniowa. Niemniej jednak, stosowanie mieszanek asfaltowych z HiMA w więcej niż jednej warstwie ma swoje uzasadnienie w cechach funkcjonalnych, takich jak odporność na spękania niskotemperaturowe, odbite, koleinowanie itd., dzięki czemu nawierzchnia charakteryzuje się nie tylko dużą trwałością strukturalną, ale i użytkową. Ostatnim aspektem obliczeń było sprawdzenie efektu zamiany rodzaju mieszanki asfaltowej w podbudowie, z AC 22 na AC 16. Zamiana ta okazała się korzystna dla wszystkich analizowanych konstrukcji. Zmniejszyły się ugięcia oraz odkształcenia krytyczne, a zwiększyły się trwałości obliczeniowe zarówno ze względu na spękania zmęczeniowe, jak i na deformacje strukturalne.

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