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Research paper

Asphalt pavement structure optimization with alternative materials

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Abstract: The paper briefly describes modern method assessment of the pavement structure based on the simplified viscoelastic continuum damage (S-VECD) model. The method was used to compare two types of pavement structures. There were analysed classical cstructures with asphalt concretes with neat bitumen and innovative one- or two layered structures with SMA 16 with highly polymer modified bitumen (HiMA). Pavement structures using SMA 16 are especially recommended for local roads, thus two traffic categories were analysed – light and medium. Furthermore, due to specific properties of layers with HiMA, for each variant two different types of improved sub-base were checked. The examples presented, despite reduced thickness of asphalt layers, structures with SMA 16 HiMA are much more resistant to fatigue than classic structures with asphalt concretes with neat bitumen. The results of the research confirm that it is possible to develop innovative structures with materials with above standard properties. New materials both with new arrangement of layers can bring a lot of advantages especially in the areas of sustainable development, costs reducing and improving properties of asphalt pavements.

Keywords: asphalt pavement structures, fatigue performance, S-VECD, HiMA, SMA 16

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1. Introduction

The increasing transport and communication needs of the global economy and society are putting pressure to expand, upgrade and maintain the world's road network to a high standard of travel. As a consequence of increasing transport needs, the durability of pavement structures is becoming increasingly important, which translates into network reliability. At the same time, increasing emphasis is being placed on environmental protection, as reflected in the introduction of The European Union's Green Deal policy [1]. As a consequence, a change of approach of pavement structures design. A more rational use of natural resources and the use of recycled materials is required. It is desirable for the design, construction and maintenance of road infrastructure to have the smallest possible carbon footprint and to be as cost-effective as possible. Projects should be assessed over their entire life cycle, i.e. from "cradle to grave" according to Life Cycle Cost Analysis (LCCA), on the basis of reliable parameters [2]. This approach will favour the most durable solutions, e.g. perpetual pavements.

Highly polimer modified asphalt binders, known as HiMA, are one of the latest materials for constructing asphalt pavements with improved durability. The first tests with this material took place in the USA in 2009 on a test section and then also on the NCAT Pavement Test Track [3,4]. The experiments with HiMA were described by [5–7]. In Poland, for the first time the asphalt pavement with HiMA binder was built in 2013 on the experimental section. Since then, many sections with this binder have been successfully constructed all over the world. The collected field data have showed that asphalt mixtures with HiMA are characterized by above-standard properties in relation to classic neat and PMB binders [8,9].

Despite very good properties of HiMA asphalt mixes confirmed in laboratory tests and in situ, the problem that needs to be addressed nowadays is how to simulate and predict the functional and structural parameters leading to a reliable determination of the durability of pavements with modern materials such as HiMA. Classical pavement structures design methods take into account parameters such as the stiffness modulus of the layers, Poisson's ratios, the volumetric parameters of the asphalt mixtures and the traffic loads and thickness of the asphalt layers conversion factors [10,11]. The classical approach based on the elastic parameters of the structure layers does not allow the potential of modern materials to be exploited, leading to unnecessary oversizing of structures with such materials [12,13].

One of the method that is able to capture outstanding fatigue properties of structures with HiMA is *similarity method* developed by Nagórski, Złotowska and Bł ażejowski on Warsaw Univeristy of Technology [14]. However a method that is increasingly being used to assess structures with materials with above-standard properties such as HiMA binders is now VECD (viscoelastic continuum damage). It is a method developed on the basis of Schapery's work [15–17], who applied the thermodynamics of irreversible processes to describe the occurrence of damage in viscoelastic materials. More detailed information of the method can be found in [18]. The method is still being improved mainly through work commissioned by the US Federal Highway Administration (FHWA) [19]. The method was upgraded and now performs as S-VECD (simplified viscoelastic continuum damage) [20]. FlexPAVE™tool has been developed at the University of North Carolina, USA, in which algorithms are implemented to estimate fatigue damage based on the S-VECD method [21]. The latest modification in the method is the use of S_{app} fatigue index parameter [22].

Challenging the concept of constructing pavements with a reduced carbon footprint, but with retained durability parameters, this paper presents a comparison of pavement structures for two traffic categories: classic layers structure according to [23], and innovative structures made of SMA 16 mix with HiMA. A comparison of the durability of the pavement structure was conducted using the S-VECD method.

2. Materials

2.1. Pavement structures

Pavement structures for local roads with two traffic load levels were selected for the analysis. Structures for light traffic category KR2 and structures for medium traffic category KR4. Usually, according to [23] for such structures in Poland, asphalt concretes with neat bitumen are used. Pavement structures with SMA 16 with highly polymer modified asphalt were selected as an alternative to the classic pavement structures. Layer layouts and thicknesses are shown in Table 1.

Table 1. Variants of the pavement structures analysed

	Traffic category KR2				**Traffic category KR4**			
	***h*, cm**	**Reference structure**	***h*, cm**	**Test structure**	***h*, cm**	**Reference structure**	***h*, cm**	**Test structure**
Wearing course	4	AC 11 S 50/70	8	SMA 16 45/80-80	4	AC 11 S 50/70	7	SMA 16 45/80-80
Binder course	8	AC 16 35/50	–	–	6	AC 16 35/50	7	SMA 16 45/80-80
Asphalt base	–	–	–	–	10	AC 22 35/50	–	–
Mineral base	20	Crushed mineral aggregate	20	Crushed mineral aggregate	20	Crushed mineral aggregate	20	Crushed mineral aggregate
Hydr. bound agg.	15	C1.5/2 C3/4	15	C1.5/2 C3/4	18	C3/4 C5/6	18	C3/4 C5/6

The suggested alternative structures with layers of SMA 16 mix HiMA are an interesting alternative to the classic approach [24]. Such pavement structure concepts have a number of advantages. They make it possible to reduce the number of interlaminar joints – layers of SMA 16 mix can be paved with a thickness of up to 9–10 cm in a single pass of the paver, which reduces the cost of transporting and paving the material. Such mixes are characterized by a high heat capacity, so they can be properly compacted over a longer period of time, thus eliminating some of the compacting errors. The strong mineral matrix of SMA 16 mix gives adequate resistance to permanent deformation. In addition, the use of HiMA improves the fatigue resistance of such a solution compared to classic pavement structures – the reference structures.

Furthermore each variant was analysed using two types of sub-base – standard and reinforced strength. The reduced stiffness of asphalt layers with HiMA, compared to ma with neat bitumen [25], may determine the use of a reinforced sub-base of hydraulically bound aggregate for proper transfer of traffic loads to the soil.

2.2. Asphalt mixtures and binders properties

The analysed reference structures were made of asphalt concretes with neat bitumen according to [26] and the Polish technical guidelines [27]. Despite the differences in requirements for mixtures design according to [27] for traffic category KR2 and KR4, mixes were designed to meet the requirements for both traffic categories simultaneously. For the wearing course, asphalt concrete AC with a grain size of up to 11 mm was designed with neat bitumen 50/70. For the binder course, asphalt concrete AC with a grain size of up to 16mm with 35/50 neat bitumen was designed. For the asphalt base layer for traffic category KR4 reference structure, asphalt concrete AC with a grain size of up to 22 mm with 35/50 neat bitumen was selected. On the other hand, the test structures used SMA mixture up to 16 mm grain size with PMB 45/80-80 HiMA according to the [28] and technical guideline [24]. SMA 16 is gap graded asphalt mixture, with very strong mineral matrix, resistant to rutting. Due to its grain size it has high thermal capacity, enabling proper compaction over a long period of time.

Aggregate gradations of the investigated mixtures are shown on Fig. 1.

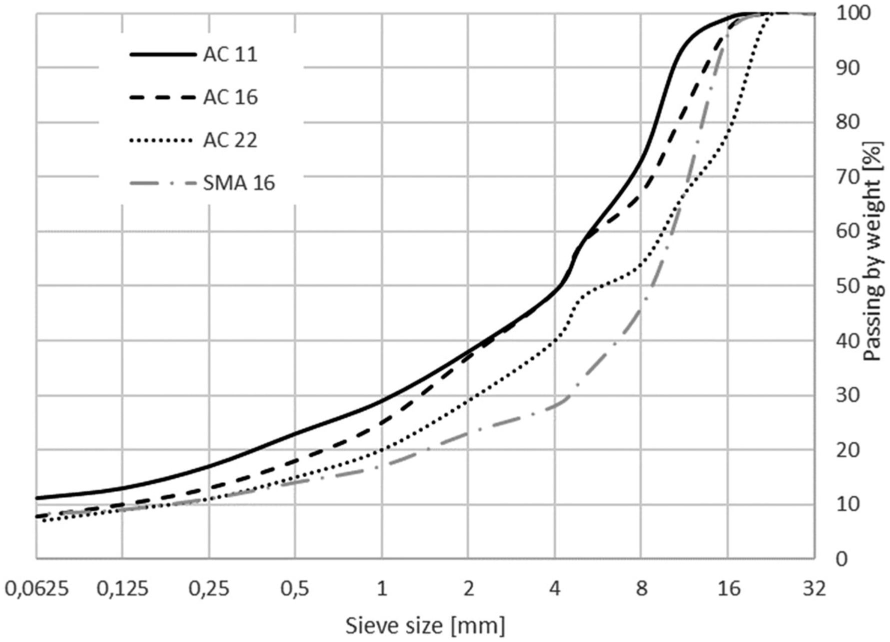

Fig. 1. Aggregate gradations of the investigated mixtures

Selected properties of asphalt mixes and binders used for particular layers are presented in Table 2 and Table 3.

Figure 2 shows the mastercurves of complex dynamic modulus for asphalt mixes used in the research. Complex dynamic modulus were determined according to [29] at temperatures of 4°C, 10°C, 20°C, 40°C, 50°C, 60°C, and at frequencies of 0.1–25 Hz. The functions for the a_T factors (not shown) were fitted using 2nd order polynomial.

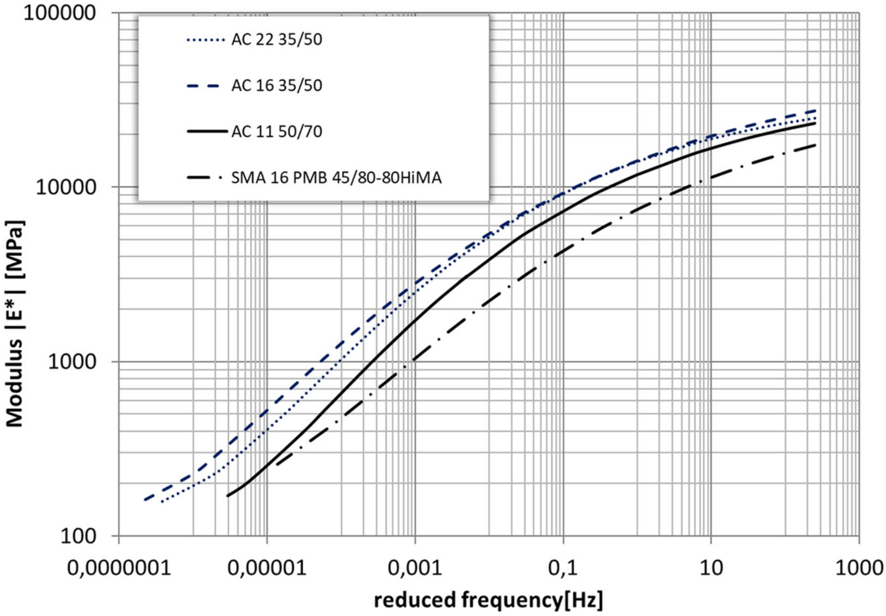

Fig. 2. Mastercurves of complex dynamic modulus (shift factors not shown, $T_{\text{ref}} = 10°\text{C}$)

Table 2. Selected properties of used asphalt mixes

		AC 11	**AC 16**	**AC 22**	**SMA 16**
Binder type		50/70	35/50	35/50	PMB 45/80-80
Binder content [%]		5.2	4.2	3.9	5.4
Va [%] acc. EN 12697-8		2.4	6.4	5.7	3.0
Additives	Adhesion promotor [%, m/m of the binder]	0.3	0.3	0.3	0.3
	Stabiliser [%, m/m of the mix]	–	–	–	0.4
Gmax [Mg/m^3]		2.686	2.733	2.758	2.671

Table 3. Selected properties of used binders

Binder	Standard	50/70	35/50	PMB 45/80-80
Penetration @ 25°C [0,1 mm]	EN 1426	60	43	59
R&B [°C]	EN 1427	49.4	51.4	94
T Fraass [°C]	EN 12593	–16	–16	–24
PG	AASHTO M 320	64–22	70–22	76–28
Real PG		67–26	70–23	79–21
PG MSCR	AASHTO M 332	50E-22, 60H-22, 70S-22	50E-22, 60E-22, 70V-22	50E-28, 60E-28, 70E-28

Mastercurves of comples dynamic modulus confirms that stiffness of mixes increses from wearing course mixes to base course mixes. Furthermore the results clearly shows that mixture with HiMA binder is characterised by the lowest stiffness within all analysed mixes.

3. Demonstration study

3.1. Input data

In order to analyse the fatigue performance using the S-VECD method of the described structures, in addition to the dynamic modulus tests shown in Fig. 2, cyclic fatigue tests acc. to [30] were conducted. Pavement structure analysis was carried out using the FlexPAVE™programme.

Table 4 shows input data for S-VECD method.

Base layers of pavement structures were assumed as:

- aggregate base layer $E = 400$ MPa, $\nu = 0.3$;
- hydraulically bound aggregate:
  - C1.5/2: $E = 200$ MPa, $\nu = 0.3$;
  - C3/4: $E = 400$ MPa, $\nu = 0.3$;
  - C5/6: $E = 500$ MPa, $\nu = 0.3$;
- natural subgrade $E = 50$ MPa, $\nu = 0.35$.

Fatigue life for different pavement variants were compared with the following assumptions:

- Load: $q = 850$ kPa, force 50 kN, single wheel;
- Speed: 17 m/s (app. 60 km/h);
- Constant temperature of layers: 13°C;
- Time of analysys: 30 years;
- Traffic category KR2: 50 standard axle load /day;
- Traffic category KR4: 1230 standard axle load /day.

Table 4. Input data for S-VECD method

		AC 11 50/70		**AC 16 35/50**		**AC 22 35/50**		**SMA 16 PMB 45/80-80 HiMA**	
α		3.86		3.65		3.45		3,88	
C(S)	C11	3.19E–03		3.60E–04		1.81E–03		1.81E–03	
	C12	4.57E–01		6.28E–01		5.15E–01		5.15E–01	
G^R Failure Criterion	γ	3.37E+06		4.99E+06		8.97E+08		1.48E+05	
	δ	–1.417		–1.169		–2.174		-0.630	
D^R Failure Criterion		0.32		0.47		0.41		0.46	
Linear Viscoelastic Properties	E_∞	9.17E+04		1.06E+05		8.91E+04		7.56E+04	
	T_{ref}	21.1		21.1		21.1		21.1	
	Shift Factor a_1	8.829E–04		1.331E–03		8.042E–04		9.716E–04	
	Shift Factor a_2	–1.661E–01		–2.005E–01		–1.636E–01		–1.637E–01	
	Shift Factor a_3	3.112E+00		3.638E+00		3.094E+00		3.022E+00	
Prony Series		Ti (s)	Ei (kPa)	Ti (s)	Ei (kPa)	Ti(s)	Ei (kPa)	Ti (s)	Ei (kPa)
		2.00E+08	5.29E+03	2.00E+08	7.29E+03	2.00E+08	4.53E+03	2.00E+08	6.08E+03
		2.00E+07	3.02E+03	2.00E+07	5.21E+03	2.00E+07	3.46E+03	2.00E+07	3.25E+03
		2.00E+06	7.44E+03	2.00E+06	1.31E+04	2.00E+06	8.71E+03	2.00E+06	8.07E+03
		2.00E+05	1.38E+04	2.00E+05	2.71E+04	2.00E+05	1.83E+04	2.00E+05	1.48E+04
		2.00E+04	2.77E+04	2.00E+04	6.13E+04	2.00E+04	4.19E+04	2.00E+04	2.97E+04
		2.00E+03	5.89E+04	2.00E+03	1.51E+05	2.00E+03	1.05E+05	2.00E+03	6.32E+04
		2.00E+02	1.35E+05	2.00E+02	4.10E+05	2.00E+02	2.95E+05	2.00E+02	1.46E+05
		2.00E+01	3.36E+05	2.00E+01	1.12E+06	2.00E+01	8.77E+05	2.00E+01	3.61E+05

Table 4 continued on the next page

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	AC 11 50/70		**AC 16 35/50**		**AC 22 35/50**		**SMA 16 PMB 45/80-80 HiMA**	
	Ti (s)	Ei (kPa)	Ti (s)	Ei (kPa)	Ti(s)	Ei (kPa)	Ti (s)	Ei (kPa)
Prony Series	2.00E+08	5.29E+03	2.00E+08	7.29E+03	2.00E+08	4.53E+03	2.00E+08	6.08E+03
	2.00E+07	3.02E+03	2.00E+07	5.21E+03	2.00E+07	3.46E+03	2.00E+07	3.25E+03
	2.00E+06	7.44E+03	2.00E+06	1.31E+04	2.00E+06	8.71E+03	2.00E+06	8.07E+03
	2.00E+05	1.38E+04	2.00E+05	2.71E+04	2.00E+05	1.83E+04	2.00E+05	1.48E+04
	2.00E+04	2.77E+04	2.00E+04	6.13E+04	2.00E+04	4.19E+04	2.00E+04	2.97E+04
	2.00E+03	5.89E+04	2.00E+03	1.51E+05	2.00E+03	1.05E+05	2.00E+03	6.32E+04
	2.00E+02	1.35E+05	2.00E+02	4.10E+05	2.00E+02	2.95E+05	2.00E+02	1.46E+05
	2.00E+01	3.36E+05	2.00E+01	1.12E+06	2.00E+01	8.77E+05	2.00E+01	3.61E+05
	2.00E+00	8.44E+05	2.00E+00	2.58E+06	2.00E+00	2.29E+06	2.00E+00	8.90E+05
	2.00E–01	1.89E+06	2.00E–01	4.18E+06	2.00E–01	4.20E+06	2.00E–01	1.92E+06
	2.00E–02	3.29E+06	2.00E–02	4.57E+06	2.00E–02	4.96E+06	2.00E–02	3.23E+06
	2.00E–03	4.14E+06	2.00E–03	3.62E+06	2.00E–03	4.05E+06	2.00E–03	4.00E+06
	2.00E–04	3.89E+06	2.00E–04	2.35E+06	2.00E–04	2.62E+06	2.00E–04	3.78E+06
	2.00E–05	2.95E+06	2.00E–05	1.37E+06	2.00E–05	1.49E+06	2.00E–05	2.92E+06
	2.00E–06	1.95E+06	2.00E–06	7.48E+05	2.00E–06	7.99E+05	2.00E–06	1.98E+06
	2.00E–07	1.19E+06	2.00E–07	3.97E+05	2.00E–07	4.13E+05	2.00E–07	1.24E+06
	2.00E–08	7.15E+05	2.00E–08	2.13E+05	2.00E–08	2.15E+05	2.00E–08	7.68E+05

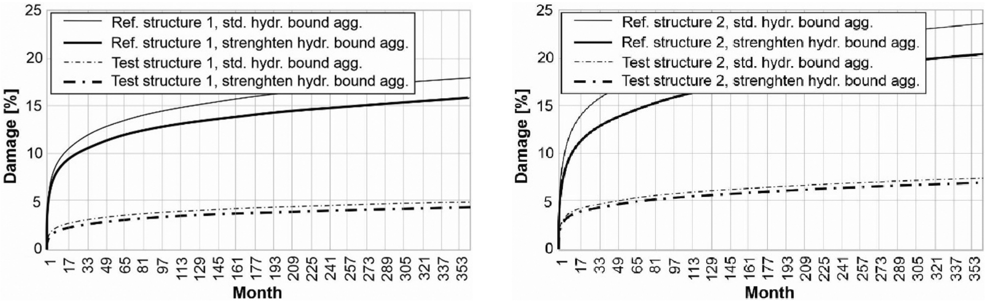
3.2. Results

Table 5 shows results of fatigue performance of analysed pavement structures.

Table 5. Fatigue performance of reference structures (AC neat bitumen) and test structures (SMA 16 HiMA)

		KR2		KR4	
		Reference structure 1	**Test structure 1**	**Reference structure 2**	**Test structure 2**
Damage @end [%]	Standard hydr. bound agg.	17.9	7.1	26	7.5
	Strenghten hydr. bound agg.	15.7	6.0	20.5	7.0

Figure 3a shows the damage rate over time for structures loaded with traffic category KR2, and Fig. 3b for structures loaded with traffic category KR4.



(a) (b)

Fig. 3. Damage rate during time (a) structures for traffic category KR2, (b) structures for traffic category KR4

In both cases, a significant reduction in fatigue damage over the 30-year period is apparent for the SMA 16 HiMA structures. In the case of KR2 structures, the fatigue damage is about 2.5 times lower and in the case of KR4 structures about 3 times lower. The effect of using a reinforced layer of hydraulically bound aggregate for both traffic categories is also apparent. This solution reduces the fatigue damage by approximately 10–20%.

In addition, in order to compare the resistance to damage of the different mixtures, a synthetic index, called apparent damage capacity Sapp (Eq. (3.1)), was calculated for each of them (Fig. 4). This index was recently developed by Wang [22] to account for the effects of the material stiffness, damage properties and toughness on the fatigue resistance (AASHTO TP

133, 2021). S_{app} refers to a temperature that is based on the climatic PG of the location where the pavement is constructed. PGs based on [31] for the city of Warsaw, depending on traffic category and structure course are shown in the Table 6.

$$S_{\mathrm{app}} = 1000^{\left(\frac{\alpha}{2}-1\right)} \cdot \frac{a_T^{\frac{1}{\alpha+1}} \cdot \left(\frac{D_R}{C_{11}}\right)^{\frac{1}{C_{12}}}}{|E^*|_{\mathrm{LVE}}^{\frac{\alpha}{4}}} \tag{3.1}$$

where: α – damage growth rate; α_T – the time-temperature shift factor between the S_{app} temperature and the reference temperature considered for the dynamic modulus mastercurve; and $|E^*|_{\mathrm{LVE}}$ – the reference modulus calculated at the S_{app} reference temperature and at 10 Hz in GPa.

Table 6. PG climatic zones for the city of Warsaw depending on structure course and traffic category acc. to [31]

	Traffic category KR2 (50% probability level)	**Traffic category KR4 (80% probability level)**
wearing course	46–22	52–22
binder course	46–16	46–22
base course	–	46–16

Since it is a measure of the tolerable amount of damage under cyclic loading, threshold values of allowable traffic in terms of 80 kN equivalent single-axle loads (ESALs) are recommended based on Sapp values [22], as reported in Table 7. However it should be noted that traffic in Poland is reffering to 100 kN single axle load, so in second column of the Table 7 are calculed traffic values of 100 kN load. Values of S_{app} of tested mixes are shown on Fig. 4.

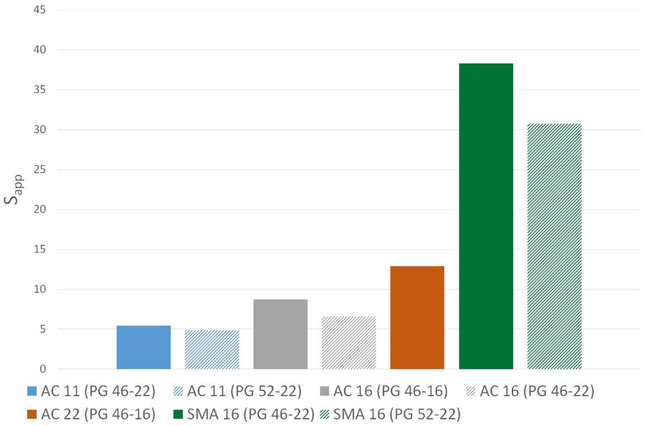


Fig. 4. S_{app} parameter for mixes used, depending on climate zone

Table 7. Recommended threshold values of S_{app} parameter at different traffic [22]

Traffic (million ESALs – 80 kN)	**Traffic (million standard axle load – 100 kN)[1]**	**S_{app} Limits**	**Tier**	**Designation**
< 10	< 4	> 8	Standard	S
10–30	4–12	> 24	Heavy	H
> 30	> 12	> 30	Very Heavy	V
> 30 and slow traffic	> 12 and slow traffic	> 36	Extremely Heavy	E

[1] – calculed based on Fourth Power Law given by equation (3.2)

$$F_{j100} = \left(\frac{Q_j}{100}\right)^4 \tag{3.2}$$

where: F_{j100} – axle equivalence coefficient; Q_j – axle load.

The values of the S_{app} parameter are at a similar level for asphalt concretes with neat bitumen. However, this parameter shows significantly higher values for the SMA 16 HiMA mix. Among the asphalt concretes, only AC16 binder course and AC 22 base course for climate zone PG46-16 meet the requirements for standard traffic according to Tab. 7, both corresponding to traffic category. KR4 acc. to [23]. SMA 16 HiMA can be unambiguously assigned for Heavy or Extremely Heavy traffic, corresponding traffic category KR5 acc. to [23]. This confirms the validity of the choice of this mix for the innovative pavement structure.

4. Conclusions

According to the demonstration example it is possible to capture the field performance of HiMA with the S-VECD method. Structures with one- or two layered SMA 16 HIMA could be real alternative for classic structures, based on asphalt concretes with neat bitumen, due to all economical, functional and environmental advantages. SMA 16 HiMA meets requirements of Sapp for traffic category KR5.

In both analysed cases, a significant reduction in fatigue damage over the 30-year period is apparent for the SMA 16 HiMA structuresas. What is more, the effect of using a reinforced layer of hydraulically bound aggregate for both traffic categories is also apparent.

It can be concluded that S-VECD methodology is promising to reliably determine the fatigue life even for pavement structures constructed with innovative materials with above-standard properties.

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Optymalizacja konstrukcji nawierzchni asfaltowych z wykorzystaniem alternatywnych materiałów

Słowa kluczowe: asfalt wysokomodyfikowany HiMA, konstrukcja nawierzchni asfaltowych, metoda S-VECD, trwałość zmęczeniowa, SMA 16 JENA

Streszczenie:

W artykule krótko opisano nowoczesną metodę oceny konstrukcji nawierzchni opartą na uproszczonym modelu niszczenia w ośrodku lepkosprężystym (S-VECD). Metoda ta została wykorzystana do porównania dwóch typów konstrukcji nawierzchni. Analizowano klasyczne konstrukcje z betonami asfaltowymi z asfaltemami drogowymi oraz innowacyjne konstrukcje jedno- lub dwuwarstwowe z SMA 16 z asfaltem wysokomodyfikowanym polimerami (HiMA). Konstrukcje nawierzchni z zastosowaniem SMA 16 są szczególnie polecane na drogi lokalne, dlatego też przeanalizowano dwie kategorie obciążenia ruchem – lekką KR2 i średnią KR4. Ponadto, ze względu na specyficzne właściwości warstw z HiMA, dla każdego wariantu sprawdzono dwa różne rodzaje ulepszonego podłoża. Na przedstawionych przykładach, pomimo zmniejszonej grubości warstw bitumicznych, konstrukcje z SMA 16 HiMA są znacznie bardziej odporne na zmęczenie niż klasyczne konstrukcje z betonami asfaltowymi z asfaltami drogowymi. Wyniki badań potwierdzają, że możliwe jest opracowanie innowacyjnych konstrukcji z materiałów o ponadstandardowych właściwościach. Nowe materiały zarówno zastosowane w nowym układem warstw mogą przynieść wiele korzyści zwłaszcza w zakresie zrównoważonego rozwoju, obniżenia kosztów oraz poprawy właściwości nawierzchni asfaltowych.

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