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PERPETUAL PAVEMENT UTILIZING CRUMB RUBBER MODIFIED BITUMEN: A CASE STUDY OF THE TRIAL SECTION ON THE S-19 EXPRESSWAY

DŁUGOWIECZNA NAWIERZCHNIA Z WYKORZYSTANIEM ASFALTÓW MODYFIKOWANYCH GUMĄ Z RECYKLINGU NA PRZYKŁADZIE ODCINKA DOŚWIADCZALNEGO DROGI EKSPRESOWEJ S-19

STRESZCZENIE. W celu ograniczenia wpływu budowy dróg na środowisko naturalne i zmniejszenia śladu węglowego, konieczne jest projektowanie nawierzchni w oparciu o zrównoważony rozwój, uwzględniając cały jej okres eksploatacji. Na ciągu głównym drogi ekspresowej S19 Kraśnik – Janów Lubelski zaprojektowano i wybudowano 400-metrowy odcinek doświadczalny, który w pełni wpisuje się w tę strategię. Konstrukcja nawierzchni została zaprojektowana i wykonana zgodnie z amerykańską koncepcją nawierzchni długowiecznej, czyli z zastosowaniem sztywnej i odpornej na koleinowanie warstwy wiążącej oraz elastycznej i odpornej na zmęczenie warstwy podbudowy. Taki układ warstw umożliwił znaczące wydłużenie okresu eksploatacji nawierzchni bez konieczności zwiększania grubości konstrukcji. Ponadto do wszystkich warstw asfaltowych zastosowano asfalt modyfikowany miałem gumowym pochodzącym z recyklingu zużytych opon samochodowych. Zagospodarowanie odpadów jakimi są zużyte opony samochodowe oprócz walorów ekologicznych ma również korzystny wpływ na parametry materiałowe lepiszczy bitumicznych. Wykonana konstrukcja nawierzchni umożliwia ograniczenie zużycia naturalnych surowców, wydłużenie okresów między remontowych nawierzchni oraz wykorzystanie pełnowartościowego odpadu jakim są zużyte opony samochodowe. Ponadto tego typu konstrukcja jest w pełni recyklowalna co oznacza, że po założonym okresie eksploatacji będzie mogła być wykorzystana do budowy nowych dróg. W artykule opisano metodę projektowania konstrukcji nawierzchni długowiecznej. Przedstawiono wyniki badań asfaltu modyfikowanego gumą w porównaniu do standardowo stosowanych lepiszczy oraz wyniki badań zastosowanych mieszanek mineralno-asfaltowych. Przedstawiono również wyniki pomiarów ugięć po wykonaniu odcinka doświadczalnego.

SŁOWA KLUCZOWE: nawierzchnia długowieczna, asfalt modyfikowany gumą, FWD.

ABSTRACT. To minimize the environmental impact of road construction and reduce the carbon footprint, it is essential to design pavements with sustainability in mind, considering their entire life cycle. On the S19 expressway between Kraśnik and Janów Lubelski, a 400-meter-long trial section was designed and constructed in full alignment with this strategy. The pavement structure was developed following the American concept of perpetual pavement, incorporating a stiff and rut-resistant binder course along with a flexible and fatigue-resistant base course. This layer arrangement significantly extended the service life of the pavement without increasing the structure's thickness. Additionally, recycled crumb rubber-modified bitumen from used vehicle tires was used for all asphalt layers. Beyond its ecological value, recycling waste tires also positively impacts material parameters. The constructed pavement structure enables the reduction of natural resource consumption, elongation of the periods between maintenance, and the utilization of fully valuable waste, like used car tires. Moreover, this type of structure is entirely recyclable, allowing for its use in the construction of new roads after its designated service life. The paper describes a method for designing perpetual pavement structures, presents a comparison of properties between crumb rubber-modified binders and standard binders, and provides test results for asphalt mixtures. The deflection measurements obtained by the falling weight deflectometer are also discussed.

KEYWORDS: perpetual pavement, crumb rubber-modified bitumen, FWD.

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1. INTRODUCTION

Extending the fatigue life of a pavement structure can be achieved in two ways. The first is to thicken the layers of the pavement structure to a level where the strain values generated by vehicle loads are minimized so that they do not cause fatigue damage to the asphalt layers. Scientific studies report that pavement structures with asphalt layer thicknesses greater than 41cm, regardless of the materials used, will not suffer from fatigue failure [1]. The second approach consists of modifying the properties of the asphalt base course to increase its resistance to fatigue. The concept using the second approach was first described in 2000 by the Asphalt Pavement Alliance [2, 3]. It involves the use of a durable wearing course, a rut-resistant binder course with a high stiffness modulus and a flexible, fatigue-resistant anti-fatigue course, where the fatigue enhancement properties are mainly achieved by increasing the asphalt content. Such structures have come to be known as perpetual pavements. Since then, research projects and studies on the durability of this type of pavement have been carried out in North America, Europe and Asia [4, 5, 6, 7, 8, 9]. New experimental sections were built to verify the assumptions [9, 10, 11, 12]. Guidelines for the construction of perpetual pavements and new methods for designing such structures have been developed [7, 8, 10, 11, 13]. In recent years, in addition to the analysis of existing roads that have survived many years of exploitation and in addition to the construction of new test sections, the assumptions of perpetual pavement technology have been used in the construction of roads of strategic importance to the national economy and with particularly high truck traffic loads [4, 5, 6]. In Poland, this type of structure was first used in 2014 on a 12-kilometer section of one of the most heavily traffick loaded roads in Poland, the S8 expressway from the southern border of Warsaw towards Kraków and Wrocław on the Opacz – Paszków section [12, 14]. In the perpetual pavement concept used for this section, particular attention was paid not to the asphalt content of the base course, but to its quality and fatigue resistance. A specially modified asphalt binder was used in the asphalt base course, the use of which made it possible to achieve the highest fatigue resistance of the asphalt mixture, compared to all the analyzed bitumen [14]. Another application of perpetual pavement design was the execution of a 4.5-kilometer-long section of an expressway within the city of Kraków, the so-called ‘Trasa Nowohucka’, in 2017. In 2019, another road project using the long-life pavement concept was built on the approximately 24-kilometre-long section of the S6 Ustronie Morskie – Koszalin expressway. In 2020, as part of the renovation of the Poznań bypass along the A2 motorway, four transition sections with a total length of 0.6 kilometers were executed using perpetual pavement technology. The next step to achieve both durable roads that do not require frequent renovations, as well as roads that are fully ecological and part of sustainable development, was to build the roads with recycled crumb rubber-modified bitumen. The good performance of crumb rubber-modified bitumen, combined with the suitable and appropriate design of the mixture composition, makes it possible to design asphalt mixtures with the desired parameters for each layer. The first step towards this type of pavement construction was the execution of an experimental section in Pruszków, where a structure using crumb rubber-modified bitumen for both the wearing course and the base course acting as an anti-fatigue layer was constructed on an over a 200-meter section [15]. Since then, a number of projects have been carried out using bitumen modified with crumb rubber mainly for wearing courses. However, it was not until 2021 that a 400-metre-long trial section was designed and built on the main carriageway of the S19 Kraśnik – Janów Lubelski expressway, where a perpetual pavement construction was carried out using crumb rubber modified bitumen for all asphalt layers. Specially designed crumb rubber asphalt mixtures made it possible to achieve a weather-resistant wearing course, a stiff and rut-resistant binder course and a flexible and fatigue-resistant base course. The entire design and construction process involved the selection of materials for the individual layers, their characterisation and testing, the preparation of technical specifications and a detailed description of production and execution control.

2. CRUMB RUBBER-MODIFIED BITUMEN IN WET PROCESS

The application of crumb rubber modified bitumen for the wearing course, binder course and base course was intended to address both environmental aspects such as the utilisation of waste vehicle tires, as well as quality aspects. Numerous works around the world show the possibility of obtaining high functional parameters for mixtures with crumb rubber modified bitumen [16, 17]. In the USA, the development of technology for the production of bitumen modified with crumb rubber has been carried out since the early 1960s [18]. In Poland, intensive work on developing these technologies has already been going on for more than 20 years [19, 20]. This high performance can be achieved through the performance of the rubber from which the tires are constructed. The high requirements of today's car tires have resulted in the rubber from which they are produced now becoming a very advanced material consisting of various chemicals, including synthetic rubber, natural rubber, carbon black, sulphur, UV filters and high quality oils and plasticisers, which reduce the aging of the binder during the reaction between the bitumen and the rubber.

One of the most characteristic features of crumb rubber modified asphalt mixture is their high flexibility due to the high content of synthetic and natural rubber in the rubber additive. In addition, once the rubber particles are swollen during the reaction with the asphalt, their volume increases many times, resulting in rubber accounting for almost half the volume of the entire bitumen in the finished product. The numerous advantages and test results of rubber-modified binders are presented in [19, 21, 22]. For the purpose of the task, additional tests were carried out on PMB 45-80/55, PMB 25/55-60, 35/50 road bitumen and CRMB bitumen to determine their resistance to repetitive loading, hence determining their fatigue resistance. The study was performed in accordance with AASHTO TP 101 *Estimating Damage Tolerance of Asphalt Binders Using the Linear Amplitude Sweep (LAS)*. The test was performed for comparison purposes without simulating technological aging. The LAS test is performed in a dynamic shear rheometer, where in the first stage, to determine the rheological properties of the asphalt, the sample is subjected to constant oscillatory deformation at variable frequency. Then, in order to induce accelerated fatigue damage, the sample is tested by applying a constant-frequency oscillatory strain with a linear increase from 0% to 30%. Using Viscoelastic Continuum Damage (VECD) analysis, the fatigue resistance of the tested specimen is calculated for any

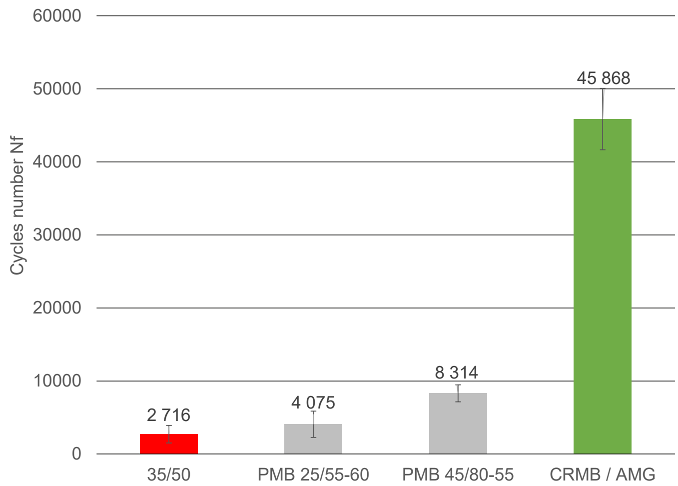


Fig. 1. Mean fatigue life results with a confidence interval of P=95%, at a strain of 2.5%, for bitumen 35/50, PMB 25/55-60, PMB 45/80-55, and AMG at 15ºC according to the LAS study

strain level at the tested temperature. The result of the LAS test is the value of the number of cycles leading to failure at 2.5% strain for asphalt layer thicknesses higher than 10 cm. Figure 1 presents the average test results obtained, together with the confidence interval range P=95%.

It can be seen that the average durability values of the CRMB at 15°C are characterised by more than 5 times the fatigue resistance of PMB 45/80-55 bitumen and more than 14 times the fatigue resistance of 35/50 bitumen.

3. PAVEMENT STRUCTURE DESIGN METHODOLOGY

The durability of the pavement structure was calculated using mechanistic-empirical methods, using stress-strain state analysis of the structure according to the multilayer elastic half-space theory. The computer program WinJULEA [23, 24] was used to calculate the stress-strain state. Assumptions for the calculations were made according to [25, 26].

The following fatigue criteria were used in the calculations:

- fatigue cracking criterion for asphalt layers with a rubber-modified asphalt mixture in the base course as an anti-fatigue layer (French method),
- fatigue cracking criterion for new asphalt layers due to " top-down" cracks (AASHTO 2004 method),

– the criterion of structural deformation of the pavement (subgrade).

Due to the use of a rubber modified asphalt mixture with improved fatigue resistance in the base course, the French method for calculating the fatigue life of asphalt layers was applied according to [27] and [28]. This allowed the functional parameters of the mixture to be taken into account, such as the stiffness modulus or fatigue parameters. The French fatigue criterion for asphalt layers which was used [27, 28, 26, 29, 30, 31] has the following form:

$$\varepsilon_{rdop} = \varepsilon_6 \cdot \left(\frac{N_{asf}}{10^6}\right)^b \cdot \left(\frac{E(10°\mathrm{C})}{E(\theta)}\right)^{0,5} \cdot k_c \cdot k_r \cdot k_s \ , \qquad (1)$$

where:

ε_{rdop} – the permissible horizontal tensile strain determined at the bottom of asphalt layers [μm/m],

ε_6 – horizontal strain under 1 000 000 loads (determined on a two-point bending trapezoidal beam) (2PB-TR) [μm/m],

N_{asf} – number of equivalent single axle loads [-],

b – slope of the fatigue law for the material (bilogarithmic law) [-],

$E(10°C)$ – stiffness modulus of the asphalt mixture at 10°C [MPa],

$E(\theta)$ – stiffness modulus of the asphalt mixture at a given seasonal temperature [MPa],

k_c – calibration coefficient for the purpose of adjusting the results of the design model to the performance observed on pavements of the same type [-],

k_s – reducing coefficient that takes into account the effect of local heterogeneousness in the bearing capacity of subbase layers with low rigidity [-],

k_r – coefficient which adjusts the working strain value to the calculated risk [-], calculated according to the formula:

$$k_r = 10^{(-\mathrm{u}b\delta)}, \qquad (2)$$

where:

u – random variation of a normal distribution associated with risk r [-],

δ – standard deviation of the distribution of logN at failure, calculated according to the formula:

$$\delta = \left[SN^2 + \left(\frac{c^2}{b^2}\right) \cdot Sh^2\right]^{0,5}, \qquad (3)$$

where:

c – coefficient linking the change in strains and thickness,

SN – standard deviation of fatigue tests,

Sh – standard deviation of thickness.

The possible variability in the thickness of layers and fatigue material parameters associated with their natural heterogeneity can result in differences in the durability of the pavement. The fatigue criterion for asphalt layers, according to the French method, assumes probabilistic design of the fatigue durability of pavement structures. This means that in its procedure, by applying the coefficient k_r, the method takes into account the probability of the occurrence of material heterogeneity or construction process, such as changes in layer thickness or properties of embedded materials. Fatigue durability calculated according to the French method depends on the acceptable level of the risk of premature pavement damage adopted at the initial stage. For roads with low traffic intensity and low strategic importance, such as local roads, a 50% risk of premature pavement structure loss is assumed. In the case of highways, an acceptable risk is assumed not greater than 2%. When designing a long-lasting pavement, the highest assumed level of safety is 2% of acceptable risk.

Calculations for top-down cracking were performed based on the AASHTO 2004 model, which is a modified version of the Asphalt Institute model. This model is described in the Manual of Mechanistic-Empirical Design of Road Pavements under Polish conditions, developed by IBDIM at the request of GDDKIA [19]:

$$N_{FC} = D_{FC} \cdot 0.007566 \cdot C \cdot k_1' \cdot \left(\frac{1}{\varepsilon_t}\right)^{3.9492} \cdot \left(\frac{1}{E}\right)^{1.281}, \qquad (4)$$

where:

N_{FC} – number of repetitive load cycles to induce top-down cracking, at a length specified by the FC parameter expressed in feet per mile,

D_{FC} – fatigue damage expressed as a decimal fraction, corresponding to the assumed number of cracks that initiated from the top of the asphalt mixture layer, calculated using the formula:

$$D_{FC} = 0.01 \cdot 10^{\frac{7-\ln\left(\frac{10560}{FC}\right)-1}{3.5}}, \qquad (5)$$

C – coefficient dependent on the volumetric properties of the asphalt mixture, determined by the following formulas:

$$C = 10^M, \qquad (6)$$

$$M = 4.84 \cdot \left(\frac{V_b}{V_m + V_b} - 0.69 \right), \qquad (7)$$

V_b – effective content of bitumen, % (v/v),
V_m – air void content, % (v/v),
k_1' – calibration coefficient dependent on the thickness of asphalt layers, for 'top-down' cracking, calculated by the formula:

$$k_1' = \frac{1}{0,001 + \frac{12.00}{1+e^{15.676-2.8186 \cdot h_{ac}}}}, \qquad (8)$$

where:

h_{ac} – asphalt layer thickness [inches],
ε_t – tensile strain at the critical point,
E – stiffness modulus of the asphalt mixture [psi].

Durability due to deformation of the subgrade, according to the Asphalt Institute method, was calculated using the following criterion [26, 32]:

$$\varepsilon_p = k \cdot \left(\frac{1}{N_{def}} \right)^m, \qquad (9)$$

where:

ε_p – vertical compressive strain induced on the upper surface of the subgrade,
N_f – the number of allowable equivalent single axle loads,
k, m – empirical coefficients.

4. PAVMENT STRUCTURE DESIGN

The construction of the experimental section's pavement has been designed for a service life of 50 years, assuming that no reinforcing interventions will be required during this period. When calculating the durability of the structure, the values of parameters for the improved subgrade, lower construction layers, and the base course from an unbound mixture were adopted based on the Polish Catalog of Typical Flexible and Semi-Rigid Pavement [2]. The design parameters for the layers of asphalt mixtures were adopted based on Type Tests intended for use in the trial section. Grain size, binder content, particle size distribution, and

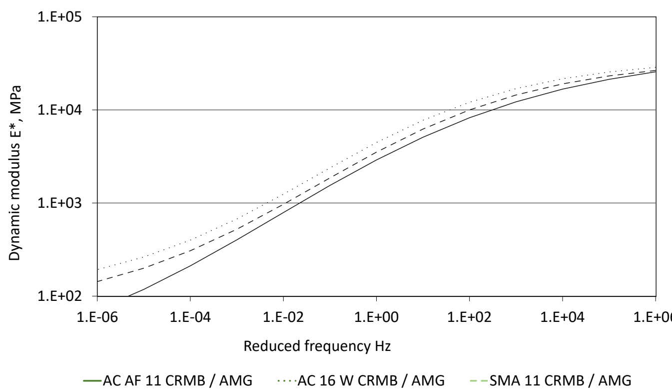


Fig. 2. Master Curve of asphalt mixtures AC AF 11 AMG and AC 22 P 35/50

Table 1. Comparison of basic parameters of asphalt mixture based on the crumb rubber modified bitumen (CRMB) used in the trial section S-19

Properties		Permanent deformation resistance P, [%]	Binders flowability BD, [%]	Water sensitivity ITSR, [%]
Test Standard		PN-EN 12697-22, large device, 60ºC, 30 000 cycles	PN-EN 12697-18	PN-EN 12697-12, 1 freezing cycle, temp. 25ºC
Result	SMA 11 CRMB / AMG	6.6	0.1	90
Requirement		$P_{10.0}$	$BD_{0.3}$	$ITSR_{90}$
Result	AC 16 W CRMB / AMG	3.2	-	81
Requirement		$P_{10.0}$		$ITSR_{80}$
Result	AC AF 11 CRMB / AMG	6.2	-	76
Requirement		$P_{10.0}$		$ITSR_{70}$

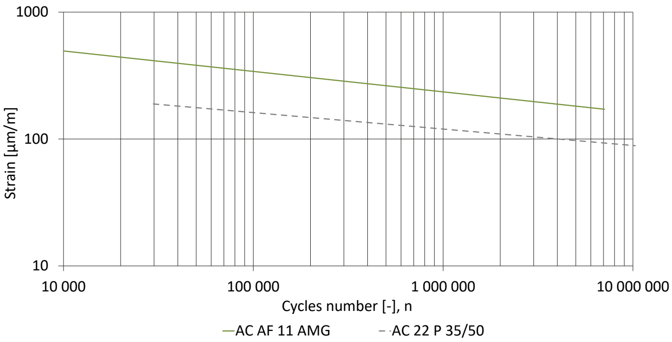


Fig. 3. The fatigue curves of the asphalt mixture AC AF 11 AMG and AC 22 P 35/50 according to PN-EN 12697-24 Annex D, temperature 10ºC, frequency 10Hz

target parameters for each mixture were selected in such a way that the functional parameters of each mixture corresponded to the function it was intended to fulfill in the construction. The basic results of the tests, along with the assumed requirements, are presented in Table 1.

Each of the asphalt mixtures based on rubber-modified asphalt, in addition to determining their basic properties, was tested for stiffness modulus at different temperatures and frequencies. The tests were conducted using a universal testing machine UTM-30. Based on the conducted tests, parameters of leading curves were determined, enabling the determination of the stiffness modulus at any temperature and frequency depending on the pavement operating conditions. The calculations were based on stiffness modulus values at a frequency of 10 Hz and a temperature

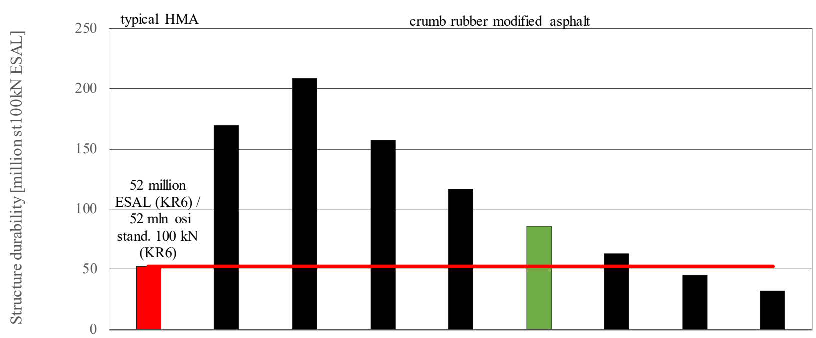
Table 2. The design of the structural layers and the materials used in the test section S-19

Layer	Type of material	Layer thickness [cm]
wearing	SMA 11 CRMB / AMG	4
binder	AC 16 W CRMB / AMG	13
anti-fatigue	AC AF 11 CRMB / AMG	8
lower base	unbound mixture $C_{90/3}$	23
subbase	hydraulically bound mixture $C_{5/6}$	15
capping	mineral or anthropogenic soil with CBR>=35%	20
improved subgrade	soil stabilized with hydraulic binder $C_{0.4/0.5}$	25
original soil G4		∞

of 13ºC, reduced by a safety factor constituting 85% of the resulting stiffness modulus value. Leading curves for all applied mixtures are presented in Figure 2. Additionally, the AC AF 11 mixture was tested for fatigue resistance using the 4PB-PR method according to PN-EN 12697-24, Appendix D, at a temperature of 10ºC and a frequency of 10Hz. For comparative purposes, Fig. 3 shows the fatigue curve for AC AF 11 AMG along with the result of the tests for a typical AC 22 P 35/50 mixture.

The course of the leading curves indicates that the composite stiffness modulus of the mixture for the binder layer is the highest compared to the mixture intended for the wearing and anti-fatigue layers. At the same time, this layer is characterized by the highest resistance to permanent deformations. Meanwhile, the fatigue resistance of the mixture for the anti-fatigue layer AC AF 11 AMG is higher than the fatigue resistance of the standard mixture for the subbase layer, AC 22 P 35/50.

According to the contractual documents, the durability of the pavement construction of the experimental section could not be less than the durability of the typical construction for KR6 traffic, which is 52 million equivalent single axle loads (ESAL) of 100kN. Using the presented pavement construction design methodology, the impact of changing the type of asphalt mixtures from typical to those using rubber-modified asphalt was analyzed. The mere replacement of typical mixtures with those using rubber-



Layer thickness

wearing	4cm	4cm	4cm	4cm	4cm	4cm	4cm	4cm	4cm
binder	8cm	8cm	16cm	15cm	14cm	13cm	12cm	11cm	10cm
anti-fatigue	16cm	16cm	8cm	8cm	8cm	8cm	8cm	8cm	8cm
lower unbound base	20cm	20cm	20cm	21cm	22cm	23cm	24cm	25cm	26cm

Fig. 4. The impact of changing the type of asphalt mixtures and the thickness of individual layers on the fatigue durability of the pavement structure

modified asphalt allowed for more than a threefold increase in the fatigue durability of the entire pavement construction. Then, it was examined how the proportions of thicknesses of individual layers and the reduction of their thickness affect the change in construction durability. The calculation results presented in Figure 4 indicate the possibility of reducing the thickness of the asphalt layer package from 28 cm to as low as 24 cm when using the designed asphalt mixtures with rubber-modified asphalt for the specific experimental section. The target thickness of the asphalt layers, to achieve an additional safety factor, was set at 25 cm. The construction layer arrangement adopted for the experimental section is presented in Table 2.

According to the prepared traffic forecast, the expected traffic intensity in the assumed operational period is 49 million ESAL of 100 kN. Assuming one equivalent temperature of 13ºC, the fatigue durability of the construction is 86 million ESAL of 100 kN, which is greater than the planned cumulative load over the 50-year operational period. The designed construction durability is also higher than the durability of the typical construction for KR6 traffic, which is 52 million ESAL of 100kN.

Fig. 5. Testing the pavement load-bearing capacity using a Falling Weight Deflectometer (FWD)

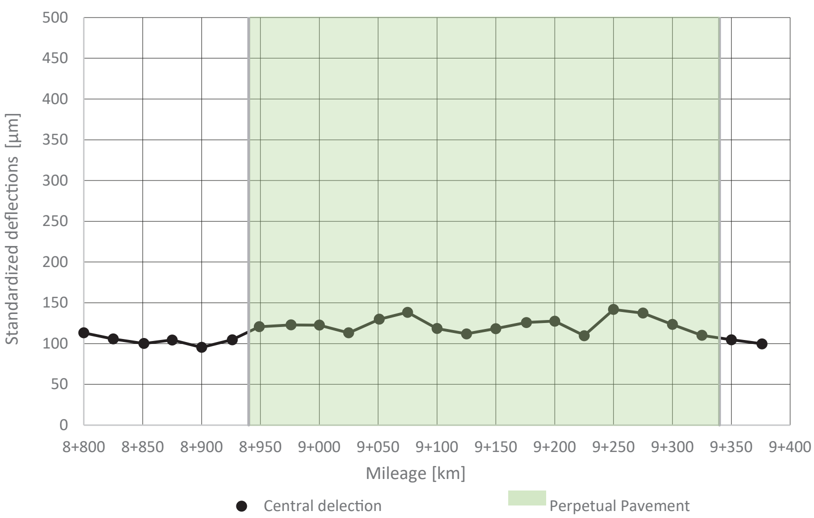


Fig. 6. Standardized value of the measured deflections on the trial section on the S19 expressway

5. CONDITION OF PAVEMENT STRUCTURE AND WARRANTY REQUIREMENTS

Before opening the road for use, measurements of pavement deflections were conducted on the perpetual pavement section using a dynamic Falling Weight Deflectometer (FWD) (Fig. 5). Figure 6 shows the values of maximum deflections (under the central load) of the analyzed trial section on the S19 expressway, adjusted to a load of 50 kN and converted to an equivalent temperature of 20°C.

It can be observed that the central deflection values within the experimental section are slightly higher than those of the standard sections. This is related to the use of more flexible layers of mixtures with crumb rubber-modified bitumen (AMG) and the application of a thinner package of asphalt layers (the thickness of the asphalt layers package on the trial section was 25 cm, while on the remaining part of the S19 expressway, it was 28 cm). It should be noted that the pavement deflection values are not a direct reflection of the technical condition of the pavement, especially when evaluating the construction of the pavement made using new, innovative technology. The analysis of the results of pavement deflection measurements was conducted by contractual documents based on [33].

One of the required parameters used in load classification is a representative deflection index, calculated as the sum of the mean value and standard deviation of standardized deflections. The value of the representative deflection index is calculated using the following formula:

$$U = \frac{\sum_{i=1}^{n} us_i}{n} + Du, \tag{10}$$

where:

U – representative deflection index [μm],

us_i – standardized value of the measured single deflection [μm] – maximum deflection corrected to standard conditions, according to the formula:

$$us = D \cdot \frac{50}{F} \cdot f_T \cdot f_S \cdot f_P, \tag{11}$$

where:

D – maximum deflection [μm],

F – load [kN],

f_T – temperature correction factor for deflections, according to the formula:

$$f_T = 1 + 0.02 \cdot (20 - T), \tag{12}$$

where T represents the temperature of asphalt layers during the FWD test;

f_S – coefficient due to the season during the measurement [-],

f_P – coefficient due to the type of base course [-],

n – number of standardized deflections along the section [-],

Du – standard deviation of standardized values of individual deflection measurements along the section [μm].

The representative surface curvature index of the pavement was also calculated according to the following formula:

$$SCI300 = \frac{\sum_{i=1}^{n} sci_i}{n} + D_{sci}, \tag{13}$$

where:

sci_i – surface curvature index [μm],

n – number of standardized deflections along the section [-],

D_{sci} – standard deviation of standardized values of individual surface curvature index measurements along the section [μm],

standardized values of individual surface curvature index:

$$sci = \mathrm{D0} - \mathrm{D300}, \tag{14}$$

where:

D0 – deflection at the central point [μm],

D300 – the deflection at a point located 300 mm away from the central point [μm].

In Table 3, the required permissible values of parameters are presented. Meanwhile, Table 4 shows the measurement results obtained in the trial section after the completion of construction.

Table 3. Required pavement bearing capacity values

Parameter	Traffic classification				
	KR1-2	KR3	KR4	KR5	KR6-7
Representative deflection index U, μm	≤550	≤390	≤300	≤250	≤205
Representative surface curvature index SCI300, μm	≤115	≤70	≤50	≤40	≤30

Table 4. Pavement bearing capacity parameters on the analyzed section of the S19 expressway

Standardized value of the measured single deflection [μm]	Standard deviation [μm]	Representative deflection index [μm]
123.3	9.9	133.2
Standardized values of individual surfa-ce curvature index [μm]	Standard devia-tion of standard-ized values of individual surface curvature index [μm]	Representative surface curvature index [μm]
20.5	1.9	22.5

Analyzing the deflection measurement results, it can be stated that the required load-bearing parameters for the pavement of the analyzed experimental section are met. The presented results were taken before opening the trial section of the expressway to traffic and should be regularly continued.

6. SUMMARY AND CONCLUSIONS

On the main carriageway of the S19 expressway between Kraśnik and Janów Lubelski, a 400-meter pavement trial section, fully aligned with the strategy of sustainable development, was designed and constructed. The pavement structure was developed following the American concept of perpetual pavement, incorporating a stiff and rut-resistant binder layer along with a flexible and fatigue-resistant base layer. This layer arrangement extends the service life of the pavement while reducing the thickness compared to the standard asphalt layers for the given traffic category.

Recycled crumb rubber-modified bitumen from used vehicle tires was applied to all asphalt layers. The utilized mixtures differ not only in the alternative bitumen but also in the individual approach to aggregate composition and volumetric. These differences impact mixture parameters, such as the stiffness modulus, which must be considered in the individual design of such pavement constructions.

The utilization of waste materials, such as used vehicle tires, not only brings ecological benefits but also positively influences the material properties of bituminous binders. The constructed pavement structure enables the reduction of natural resource consumption, elongation of the periods between maintenance, and the utilization of fully valuable waste, like used car tires. Moreover, this type of structure is entirely recyclable, allowing for its use in the construction of new roads after its designated service life.

The implementation of the trial section confirmed the feasibility of constructing such pavement structures on the expressway under traffic. The completed pavement meets load-bearing requirements. Experiences gained from its execution should be used to verify technological recommendations for the construction of such pavement structures. The surface condition of the pavement and changes in the load-bearing capacity of the trial section should be regularly monitored to assess its performance and further validate the applied technology.

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REFERENCES

[1] *Park H., Kim J., Kim Y., Lee H-J.*: Determination of the Layer Thickness for Long-Life Asphalt Pavement. Proceedings of the Eastern Asia Society for Transportation Studies, **5**, 2005, 791–802

[2] *Buncher M.M., Newcomb D.E., Huddleston I.J.*: Perpetual pavements. Asphalt: The Magazine of the National Asphalt Institute, **15**, 3, 2000, 20–22

[3] *Newcomb D.E, Willis R., Timm D.H*: Perpetual Asphalt Pavements – A Synthesis. Asphalt Pavement Alliance, IM-40, 2004, 1–45

[4] *Yang Y., Gao X., Lin W., Timm D.H., Priest A.L., Huber G.A., Andrewski D.A.*: Perpetual pavement design in China. International Conference on Perpetual Pavement, Ohio Research Institute for Transportation and the Environment, 2006, 1–17

[5] *Uzarowski L., Moore G., Gamble P.*: Innovative, comprehensive design and construction of perpetual pavement on the Red Hill Valley Parkway in Hamilton. TAC/ATC 2008 – 2008 Annual Conference and Exhibition of the Transportation Association of Canada – Transportation: A Key to a Sustainable Future, 2008

[6] *Maher M.L.J.*: From Theory to Practice: Rich Bottom Layer Design

[7] *Walubita L.F., Scullion T.*: Texas Perpetual Pavements – New Design Guidelines. Texas Transportation Institute (December 2009), 2010

[8] *Lee S.I., Walubita L.F., Hu S., Scullion T.*: Sustainable Perpetual Asphalt Pavements and Comparative Analysis of Lifecycle Cost to Traditional 20-Year Pavement Design: Technical Report FHWA/TX-18/0-6856-1. Texas A&M Transportation Institute College Station, Texas, 2018

[9] *Button J.W.*: Perpetual Bituminous Pavements. Transportation Research Circular, Number 503, 2001

[10] *Grajewska A., Matraszek K., Ruttmar I.*: Koncepcje zastosowania nowoczesnych lepiszczy w długowiecznych nawierzchniach asfaltowych. XXVIII Seminarium Techniczna PSWNA, Falenty, 25–27 marca 2013

[11] *Sybilski D.*: TN-249: Nawierzchnie asfaltowe długowieczne i tanie w utrzymaniu. Zadanie 1 – Analiza doświadczeń nawierzchni długowiecznych w świecie. Warszawa, 2009

[12] *Grajewska A., Pełczyńska K., Ruttmar I.*: Długowieczna nawierzchnia drogi ekspresowej S8 Opacz – Paszków zaprojektowana na 50 lat. Materiały Budowlane, 4, 2016, 10–12, DOI: 10.15199/33.2016.04.02

[13] *Szwed A., Kamińska I.*: Two-step Method of Designing Distribution of Material Stiffness in Perpetual Pavement to Prevent Structural Rutting and Fatigue. Procedia Engineering, **153**, 2016, 706–714, DOI: 10.1016/j.proeng.2016.08.230

[14] *Ruttmar I., Grajewska A., Pełczyńska K.*: Perpetual pavement design and construction using anti-fatigue base layer on expressway S8 in Poland. E&E Congress 6th Eurasphalt & Eurobitume Congress, 1–3 June 2016, Prague, Czech Republic

[15] *Ruttmar I., Mularzuk R., Radziszewski P., Piłat J., Sarnowski M.*: Odcinek doświadczalny wykonany z mieszanek mineralno-gumowo-asfaltowych. Nawierzchnie Asfaltowe, 3, 2013

[16] *Mashaan N.S., Ali A.H., Karim M.R., Abdelaziz M.*: A review on using crumb rubber in reinforcement of asphalt pavement. The Scientific World Journal, 4, 2014, DOI: 10.1155/2014/214612

[17] *Lo Presti D.*: Recycled Tyre Rubber Modified Bitumens for road asphalt mixtures: A literature review. Construction and Building Materials, **49**, 2013, 863–881, DOI: 10.1016/j.conbuildmat.2013.09.007

[18] *Mashaan N.S., Ali A.H., Karim M.R., Abdelaziz M.*: An overview of crumb rubber modified asphalt. International Journal of Physical Sciences, **7**, 2, 2012, 166–170, DOI: 10.5897/IJPSX11.007

[19] *Radziszewski P., Sarnowski M., Król J., Kowalski K.J., Ruttmar I., Zborowski A.*: Recycled Tyre Rubber Modified Bitumens for road asphalt mixtures. Wydawnictwa Komunikacji i Łączności, Warszawa, 2017

[20] *Radziszewski P.*: Modelowanie trwałości zmęczeniowej modyfikowanych kompozytów mineralno-asfaltowych. Rozprawy Naukowe nr 45, Wydawnictwa Politechniki Białostockiej, Białystok 1997

[21] *Zborowski A., Klimaszewski P.*: Efektywne, ekonomiczne i ekologiczne nawierzchnie z asfaltu modyfikowanego gumą w technologii na mokro. Materiały Budowlane, 4, 2016, DOI: 10.15199/33.2016.04.03

[22] *Zborowski A., Klimaszewski P., Zawadzka A.*: Asfalt modyfikowany gumą szansą na trwalsze drogi samorządowe. Drogi Gminne i Powiatowe, 6(29), 2016

[23] *Uzan J.*: JULEA (Jacob Uzan Layered Elastic Analysis) code developed at Technion University, Haifa, Israel, 1976

[24] *Uzan J.*: The Influence of the Interface Condition on Stress Distribution in a Layered System. Transportation Research Record, **616**, 1976, 71–73

[25] *Judycki J., Jaskuła P., Pszczoła M., Alenowicz J., Dołżycki B., Jaczewski M., Ryś D., Stienss M.*: Katalog Typowych Konstrukcji Nawierzchni Podatnych i Półsztywnych. Politechnika Gdańska, Gdańsk, 2014

[26] *Judycki J., Jaskuła P., Pszczoła M., Ryś D., Jaczewski M., Alenowicz J., Dołżycki B., Stienss M.*: Analizy i projektowanie konstrukcji nawierzchni podatnych i półsztywnych. Wydawnictwa Komunikacji i Łączności, Warszawa, 2014

[27] *Corté J.F.*: French Design Manual for Pavement Structures. Guide technique. LCPC, SETRA, 1997

[28] *Corte J.F., Goux M.T.*: Conception et dimensionnement des structures de chaussee. Guide technique. LCPC, SETRA, 1994

[29] *Jaczewski M., Judycki J.*: Adaptacja francuskich kryteriów zmęczeniowych do projektowania nawierzchni podatnych w warunkach polskich. Drogownictwo, 5, 2012, 164–170

[30] *Sybilski D.*: Mechanistic-Empirical Pavement Design Guide. Podręcznik Mechanistyczno-Empirycznego Projektowania Nawierzchni Drogowych w warunkach polskich. Warszawa, 2013

[31] *Corté J.F., Goux M.T.*: Design of pavement structures: The French technical guide. Transportation Research Record, 1539, 1996, 116–124 DOI: 10.3141/1539-16

[32] *Sybilski D., Bańkowski W., Maliszewski M., Maliszewska D., Zofka A.*: Katalog Przebudów i Remontów Nawierzchni Podatnych i Półsztywnych. Warszawa, IBDiM, 2014

[33] *Radzikowski M.*: Diagnostyka stanu nawierzchni i wybranych elementów korpusu drogi. Warszawa, GDDKiA, 2019