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APPLICATION OF DYNAMIC COMPLEX STIFFNESS MODULUS MASTER CURVES OF HMA WITH RECYCLED MATERIALS IN THE MECHANISTIC-EMPIRICAL DESIGN OF ROAD PAVEMENT STRUCTURES

ZASTOSOWANIE KRZYWYCH WIODĄCYCH MODUŁU SZTYWNOŚCI MMA Z MATERIAŁAMI Z RECYKLINGU PRZY MECHANISTYCZNO-EMPIRYCZNYM PROJEKTOWANIU KONSTRUKCJI NAWIERZCHNI DROGOWYCH

STRESZCZENIE. Głównym celem artykułu jest przedstawienie możliwości i zalet zaawansowanych metod określania właściwości lepkosprężystych mieszanek mineralno-asfaltowych wyprodukowanych z użyciem materiałów z recyklingu w indywidualnym mechanistyczno-empirycznym projektowaniu konstrukcji nawierzchni. Stosowanie do produkcji MMA różnego typu materiałów może znacząco zmienić ich parametry funkcjonalne, jak np. moduł sztywności dynamicznej. Dodatkowo parametr ten zmienia się wraz ze zmianą temperatury nawierzchni oraz prędkości pojazdów. Aby w sposób świadomy i minimalizujący ryzyko błędu określić trwałość konstrukcji nawierzchni, należy jak najdokładniej zbadać i opisać tę zmienność zachowania się warstw asfaltowych na skutek zmiany właściwości materiałów wsadowych, np. przez udział materiałów pochodzących z recyklingu oraz pod wpływem zmian temperatury i prędkości obciążenia nawierzchni. Najlepszym do tego sposobem jest zastosowanie krzywych wiodących zespolonego modułu sztywności dynamicznej MMA zbudowanych na podstawie wyników badań wykonanych w różnych temperaturach i częstotliwościach obciążenia. Dzięki temu podczas projektowania konstrukcji możemy określić stan naprężeń i odkształceń nawierzchni w różnych warunkach klimatycznych, wykorzystując temperatury sezonowe lub średniomiesięczne oraz uwzględniając specyfikę pracy nawierzchni – inną prędkość pojazdów dla tras głównych, a inną dla łącznic czy skrzyżowań ulic. W artykule porównane zostały wyniki krzywych wiodących dla różnych typów MMA z i bez dodatku materiałów odpadowych lub z recyklingu, takich jak granulat asfaltowy, guma ze zużytych opon czy włókna syntetyczne oraz ich wpływ na szacowaną trwałość konstrukcji nawierzchni ze względu na różne podejście do określania warunków klimatycznych oraz prędkości ruchu.

SŁOWA KLUCZOWE: moduł sztywności MMA, krzywe wiodące, recykling, mechanistyczno-empiryczne projektowanie konstrukcji nawierzchni, trwałość nawierzchni.

ABSTRACT. The main objective of the paper is to present the possibilities and advantages of advanced methods for determining the viscoelastic properties of asphalt mixtures produced using recycled materials in individual mechanistic-empirical pavement design. The use of various types of materials in asphalt mixture production can significantly alter their functional parameters, such as the dynamic stiffness modulus. In addition, this parameter changes with the change in the temperature of the road pavement and the speed of vehicles. In order to determine the durability of the pavement structure in an informed manner and minimize the risk of error, it is necessary to investigate and describe as precisely as possible this variability in the behavior of asphalt layers as a result of changes in the properties of input materials, e.g. by the addition of recycled materials and under the influence of changes in temperature and load velocity of the pavement. The most effective approach involves the application of master curves of the dynamic complex stiffness modulus of asphalt mixture, constructed based on research results conducted at different temperatures and loading frequencies. This allows for the determination of stress and deformation states of the pavement construction under various climatic conditions, utilizing seasonal or average monthly temperatures and considering the specific characteristics of pavement operation, such as different vehicle speeds for main routes, connectors, or street intersections. The paper compares the changes in dynamic modulus master curves for different types of asphalt mixtures with and without the addition of waste or recycled materials such as reclaimed asphalt pavement (RAP), rubber from used tires, or synthetic fibres and changes impact on the estimated durability of the pavement structure due to different approaches to determining climatic conditions and movement speed.

KEYWORDS: dynamic complex stiffness modulus of HMA, master curves, recycling, mechanistic-empirical design of pavement structures, pavement durability.

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1. INTRODUCTION

Today's challenges associated with the construction and maintenance of roads require continuous improvement of their design methods and more accurate testing of the functional properties of the materials used. Climate change, the continuous increase in traffic load, and the need for more sustainable solutions force the exploration of new materials and pavement design approaches that consider various factors influencing their durability, construction costs, and maintenance.

This paper focuses on advanced methods of testing the properties of asphalt mixtures (HMA) used in road pavement and examples of practical use of this information in individual design. Its goal was to present the possibility of research on how different types of materials, including those derived from recycling, affect the functional parameters of HMA, for example the values of the complex dynamic modulus. The stiffness of asphalt mixtures, but also its variability in different climatic conditions and pavement working conditions is an important parameter determining the durability of the pavement. Due to the viscoelastic nature of HMA, it is also very strongly dependent on temperature and load time.

Recycled materials such as reclaimed asphalt pavement (RAP), scrap tire rubber or synthetic fibers have a significant influence on the properties of HMA. This has also been confirmed by research carried out by Polish scientific centers, e.g., studies on the influence of the addition of reclaimed asphalt pavement on low-temperature HMA cracking [1] or the analysis of the mechanical properties of mineral-cement-emulsion mixtures [2]. These studies confirm the importance of thoroughly investigating HMAs containing recycled materials and assessing their behavior under different temperature conditions and loading times. This information is crucial for the design of pavement structures, which should be adapted to local climatic conditions and vehicle speeds.

With global warming and increasingly changeable weather conditions, roads must be designed considering periodic extreme temperatures and precipitation. Standard design methods that do not take these changes into account can lead to faster pavement wear, increased risk of damage, and the need for frequent road repairs.

2. THE AIM AND SCOPE OF THE RESEARCH

This publication presents the application of advanced research and design methods to the design of pavement structures with the use of recycled materials and taking into account the changes that such materials cause in the viscoelastic properties of mixtures over a wide temperature range and at different loading times.

The first part of the paper presents the methodology adopted for the design of pavement structures. The computer tools used, as well as the structure models and pavement durability criteria applied are presented. In addition, the methods used to determine the complex modulus of asphalt mixtures are presented as well as the principles and methods used to determine their master curves, which allow the value of the HMA modulus to be determined for any combination of load time and temperature.

In the second part of the paper, the results of investigations of the complex dynamic stiffness modulus of the mixtures produced with the addition of recycled materials are presented. The master curves of the obtained moduli were used to present the variability of the parameters of the tested mixes as a function of loading time and temperature in comparison with reference mixes.

The third part of the paper presents the application of the determined parameters of the tested mixtures for exemplary analyses using the individual mechanistic-empirical design of pavement structures.

3. RESEARCH AND ANALYSIS METHODOLOGY

3.1. METHODOLOGY OF MECHANISTIC-EMPIRICAL ANALYSIS OF PAVEMENT STRUCTURES

In the subsequent part of the study, the durability of the pavement structure was calculated using mechanistic-empirical methods, employing stress and strain analysis in the construction based on the theory of multi-layered elastic half-space [3]. The computer program WinJULEA was utilized to calculate the pavement state of stresses and strains [4].

The following distress criteria for pavement were considered in the calculations:

- fatigue cracking criterion for asphalt layers (AASHTO 2004 [5]),
- structural deformation criterion for pavement (subgrade),

where the durability of the pavement is determined by the smaller of the results.

The procedure during the analysis was as follows:

- adoption of the thickness of pavement structure layers,
- determination of material layer constants, E-moduli and ν-Poisson ratios,
- calculation of stress and strain states in the pavement structure,
- calculation of the fatigue durability of the pavement.

The following parameters, conditions and assumptions were adopted for the analysis:

- single standard axle load: 100 kN,
- single wheel with a pressure of: 50 kN,
- contact pressure between wheel and the pavement: 850 kPa,
- equivalent surface temperature: 13°C,
- seasonal pavement temperatures according to [13]:
  - Winter -2°C (20% of traffic)
  - Spring and Autumn 0°C (50% of traffic)
  - Summer 23°C (30% of traffic)

The model of the pavement structure adopted for the calculations is shown below in Fig. 1.

3.1.1. Criterion of the fatigue cracking of new asphalt layers AASHTO 2004 [3]

The fatigue durability of asphalt layers was calculated based on the AASHTO 2004 [5] model which is a modified version of the Asphalt Institute model. This model was used in the calculations of KTKNPiP[6]:

$$N_{FC} = D_{FC} \cdot 7.3557 \cdot (10^{-6}) \cdot C \cdot k_1' \cdot \left(\frac{1}{\varepsilon_t}\right)^{3.9492} \cdot \left(\frac{1}{E}\right)^{1.281}, \qquad (1)$$

where:

N_{FC} – the number of repetitive axle loads until fatigue cracks occur, on FC percentage of the total lane area,

D_{FC} – is the fatigue damage expressed as a decimal fraction, corresponding to the assumed quantity of fatigue cracking FC, and the thickness of asphalt layers h_{ac} calculated from the formula:

$$D_{FC} = 10^{\ln\left(\frac{100}{FC}-1\right)\cdot\frac{1}{C_2^r}}, \qquad (2)$$

C_2^r – coefficient depending on the thickness of asphalt layers, calculated using the formula:

$$C_2' = -2.40874 - 39.748 \cdot \left(1 + \frac{h_{ac}}{2.54}\right)^{-2.56}, \qquad (3)$$

h_{ac} – thickness of asphalt layers [cm],

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

$$C = 10^{M}, \qquad (4.1)$$

$$M = 4.84 \cdot \left(\frac{V_b}{V_m + V_b} - 0.69\right), \qquad (4.2)$$

V_b – effective volumetric binder content, % (v/v),

V_m – volumetric content of voids, % (v/v),

k'_1 – calibration coefficient depending on the thickness of asphalt layers, for bottom-up cracks calculated using the formula:

$$k_1' = \frac{1}{0.000398 + \frac{0.003602}{1 + e^{11.02 - 1.374 \cdot h_{ac}}}}, \qquad (5)$$

ε_t – tensile strain at a critical point,

E – modulus of stiffness of the asphalt layer [MPa].

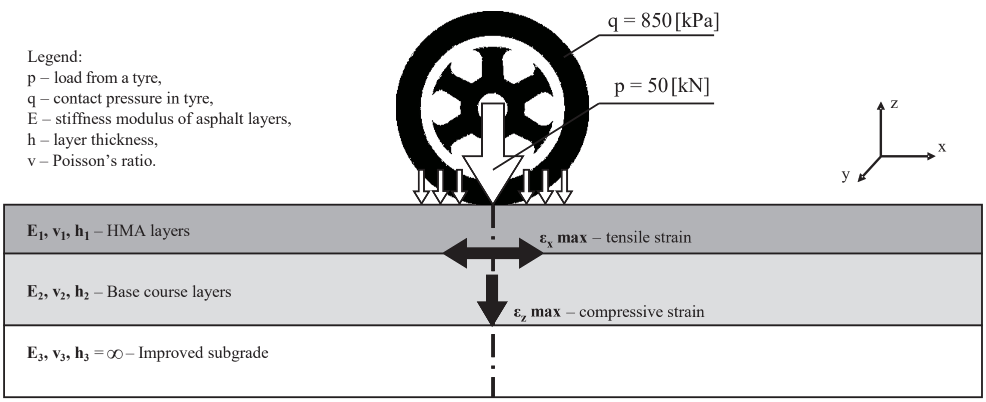

Fig. 1. Pavement structure model assumed for calculations

3.1.2. Criterion of the structural deformation of the pavement (subgrade)

The durability due to deformations of the subsoil, according to the Asphalt Institute method, was calculated using the following formula:

$$\varepsilon_p = k \cdot \left(\frac{1}{N_f}\right)^m, \tag{6}$$

where:

ε_p –vertical compressive strain caused on the upper surface of the subsoil,

N_f –number of permissible loads on standard axles,

k, m – empirical coefficients with values:

$k = 1.05 \cdot 10\text{-}2$,

$m = 0.223$.

3.2. METHODOLOGY FOR DETERMINATION OF THE MASTER CURVES

Due to the viscoelastic nature of asphalt mixtures, their response to applied load in the form of the complex modulus of stiffness depends, among other factors, on their temperature and loading time. To avoid the need to determine parameters for every possible combination of these loading conditions, the equation of master curves of the dynamic complex stiffness modulus is used.

The determination of the master curve involves, in the first stage, conducting a series of tests to establish the complex modulus of stiffness for various temperatures and frequencies (inverse loading time). The methodology used for determining these moduli is based on the approach developed within the NCHRP 9–19 project [8]. This method involves compressing cylindrical samples using a force with a haver-sinusoidal waveform. The tests were conducted using a universal testing machine, IPC Controls UTM-30, equipped with a pressure chamber allowing for the confinement of specimens (Fig. 2).

As part of the described task, the determination of the dynamic complex stiffness modulus was carried out at temperatures of [-10, 4, 20, 40, 55°C] and frequencies of [25, 10, 5, 1, 0.1 Hz], with a lateral confinement of the specimens at 138 kPa. Additionally, for the highest temperature, tests were conducted at a frequency of 0.01 Hz to determine the modulus corresponding to the creep phenomenon of the mixture. The study was repeated for 6 specimens, and the subsequent analysis involved the averaged results of individual temperature and frequency combinations after discarding significantly deviating values. The results of the stiffness modulus tests for a representative mixture are presented in Fig. 3 in the form of isotherms on a frequency-dependent chart.

Master curves utilize the principle of time-temperature superposition, which is applicable to thermo-rheologically simple materials, such as mineral-asphalt mixtures [9]. It has been observed that for such materials, it is possible to achieve the same complex stiffness modulus at a given temperature and load frequency, as in tests for a suitably chosen combination of progressively higher temperatures and frequencies, and vice versa—for progressively lower temperatures and frequencies. This means that for thermo-rheologically simple materials, the effect of temperature change can be compared to a change in loading time. By applying this principle, test results conducted at different temperatures and frequencies can be shifted to a single temperature and presented for new corresponding frequency values. To create a master curve, the results of modulus tested at different temperatures are presented on a graph of modulus-frequency dependence on a double logarithmic scale.

The results from individual temperatures are then horizontally shifted relative to the chosen reference temperature in such a way

Fig. 2. On the left, the IPC Global UTM-30 machine used in the tests, on the right, a sample during the testing of the dynamic complex stiffness modulus

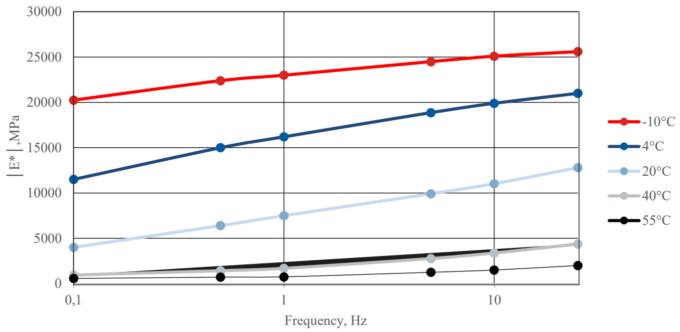

Fig. 3. Results of determination of complex modulus of stiffness in the form of isotherms

that the obtained results can be approximated as a single smooth curve (Fig. 4). At each temperature, the amount of required offset to form a master curve describes the material's temperature dependence, expressed as the value of the time shift factor. This shift of individual isotherms results in a change of the frequency scale to a new reduced frequency.

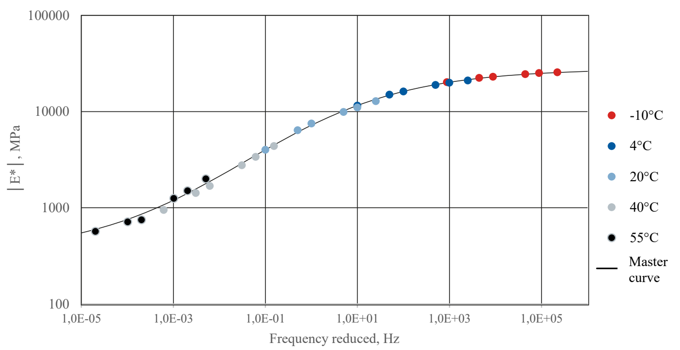

Fig.4. Example of a master curve model after shifting data for individual temperatures

To describe the obtained modulus values on the time axis in the following calculations, a sigmoidal curve model was adopted in accordance with the AASHTO R 62–13 standard [10] with the following formula:

$$\log\left|E^*\right| = \delta + \frac{(\alpha)}{1+e^{\beta+\gamma\log f_r}} , \qquad (7)$$

where:

$\left|E^*\right|$ – dynamic modulus [psi],

$\alpha, \beta, \delta, \gamma$ – fitting parameters,

f_r – reduced frequency [Hz].

The Arrhenius equation was used to determine the shift factor. This is one of the standard solutions in superposition modeling, as presented for example in American and European standards [11]. The equation for reduced frequency using the Arrhenius formula is as follows:

$$\log f_r = \log f + \frac{\Delta E_a}{19{,}14714}\left(\frac{1}{T} - \frac{1}{T_r}\right) , \qquad (8)$$

where:

f_r – reduced frequency at the reference temperature [Hz],

f – loading frequency at test temperature [Hz],

ΔE_a – activation energy (fitting parameter),

T – test temperature [°K],

T_r – reference temperature [°K].

The determination of the master curve involves simultaneous numerical optimization of the curve function parameters and the shift factor to minimize the model error in relation to the measured values [12]. The calculations were carried out using the Microsoft Excel Solver add-in for this purpose. After determining the parameters, it is possible to transform any combination of loading time and temperature into reduced frequency, which, when inserted into the optimized curve formula, allows for the determination of the averaged dynamic modulus value of the tested mixture.

4. TESTED MATERIALS

The conducted analyses utilized the results of complex stiffness modulus of seven mineral-asphalt mixtures that meet the technical requirements of WT-2 2014 [7]. The list of mixtures, along with the type of aggregates and the type of recycled material used, is presented in Table 1.

The tested materials were selected in such a way that when comparing mixtures in individual layers, they exhibited as close as possible volumetric asphalt content and air void content. An exception is made for SMA because mixtures with the addition of rubber-modified asphalt typically have more asphalt (~0.5%) and a higher content of air voids. Mixtures with the addition of RAP (corresponding to items 4 and 7) were chosen for analysis so that mixtures without their addition would serve as the basis for their type of research (corresponding to items 3 and 6), and their grain size curves and air void content would be similar. This allows for determining the influence of recycled materials while minimizing the impact of changes in the volumetric properties of mineral-asphalt mixtures.

Table 1. Summary of the tested mixtures

No.	HMA layer	Type of HMA	Aggregate type	Type of recycled material
1	Wearing	SMA 11 PMB 45/80-55 KR3-KR7	Melaphyr	–
2		SMA 11 AMG KR3-KR7	Melaphyr	Rubber Asphalt
3	Binder	AC WMS 16 W PMB 25/55-60 KR3-KR6	Melaphyr	–-
4		AC WMS 16 W PMB 25/55-60 KR3-KR6 +0.5% SF	Melaphyr	Synthetic fibers 0.5%*
5		AC WMS 16 P/W PMB 25/55-60 KR3-KR7	Limestone	RAP 10%*
6	Subbase	AC 22 P 35/50 KR3-KR7	Dolomite	–
7		AC 22 P 35/50 KR3-KR7 + 20% RAP	Dolomite	RAP 20%*

* percentage share in the mass of asphalt mixture

5. RESULTS OF THE DETERMINED MASTER CURVES AND THEIR DISCUSSION

For the above-mentioned mixtures, a series of determinations of the dynamic complex stiffness modulus were carried out using the UTM-30 apparatus. These results were then used to determine the corresponding parameters of the master curves according to the methodology presented earlier.

The analysis of the master curve allows us to assess the asphalt mixture in terms of its behavior across a wide range of temperatures and traffic speeds. The schematic comparison of two exemplary mixtures is shown in the figure below.

The exemplary mixtures exhibited the same response to traffic loading in the form of a complex stiffness modulus at a certain reduced frequency. However, analyzing the material's reaction to an increase in temperature or a decrease in traffic speed, it is observed that mixture A shows a higher modulus value, which can correspond to a greater resistance to permanent deformation. Similarly, evaluating the behavior of mixtures at increased traffic speed or reduced temperature, we can assess that mixture A potentially exhibits greater resistance to low-temperature damage.

Such a comparison on one graph is possible only when the influence of temperature change is identical, i.e., both curves have the same time shift factor. In other cases, master curves can be used to determine and compare values corresponding to a constant temperature or frequency.

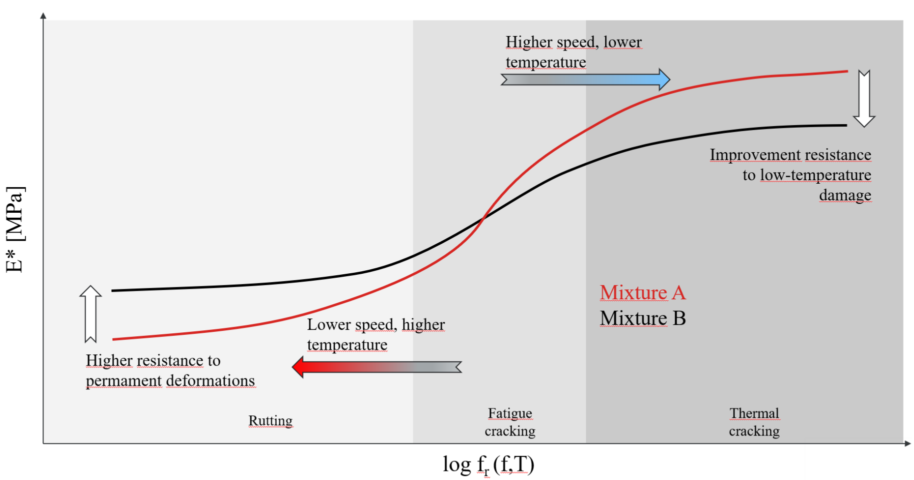

Fig. 5. Interpretation of differences in shapes of master curve plots for stiffness modulus between different HMA mixtures

5.1. ANALYSIS OF DATA OBTAINED FROM THE MASTER CURVES OF THE MIXTURE MODULUS

In order to objectively evaluate the parameters of the tested mixtures, they were divided based on their location in the construction layers. For each group, the results of the relation of the complex stiffness modulus to temperature were plotted in the range from -15°C to 60°C, assuming a constant frequency of f=10 Hz corresponding to the vehicle speed of (≈60 km/h) and for a frequency of f=0.8 Hz, which corresponds to slow vehicle movement (≈5 km/h) in the area of intersections. To compare the variability of mixtures with recycled materials, the results were presented in the form of charts showing the percentage change in the modulus of mixtures with the addition of recycled materials compared to the mixture without it, identified at the frequency of loading corresponding to vehicle traffic at a speed of 60 km/h.

5.1.1. Master curves for asphalt mixtures designed for the wearing course

Figure 5 shows the values of the complex modulus of the mixtures used in the wearing course at varying temperatures for two traffic speeds. For traffic speed corresponding to 60 km/h, the rubber-modified asphalt mix has a lower modulus at temperatures lower than 13°C, compared to the mixture with polymer modified asphalt. However, above this temperature, the rubber-modified asphalt mixture shows higher stiffness.

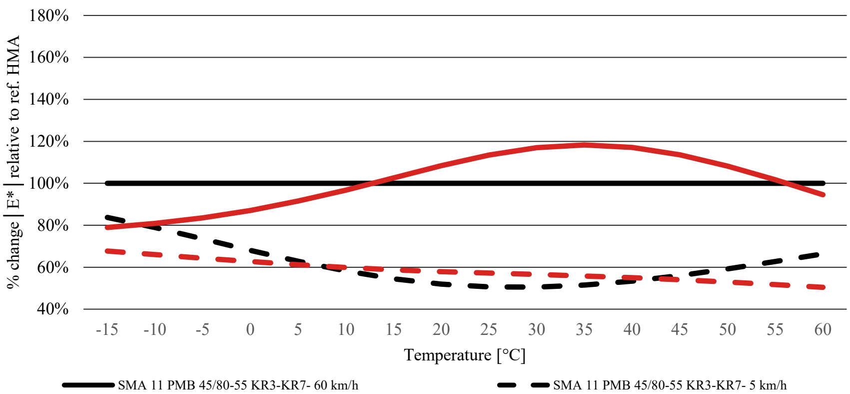

Fig. 6. Comparison of the percentage change in the value of stiffness moduli for wearing course with rubber-modified asphalt in relation to SMA 11 PMB 45/80-55 KR3-KR7 at ≈60 km/h motion speed

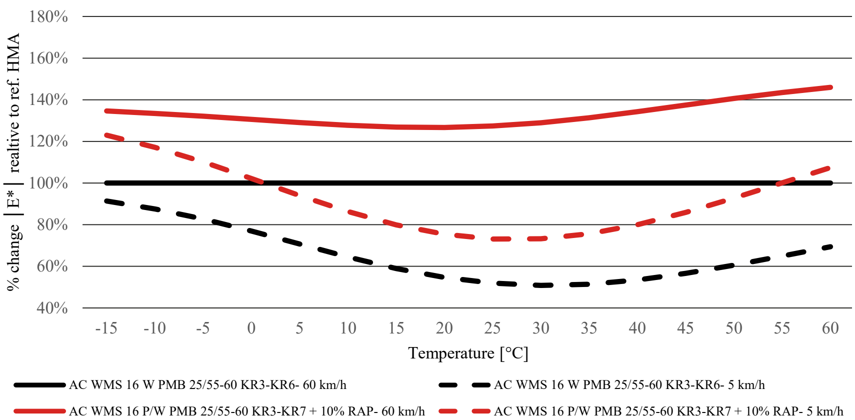

Fig.7. Comparison of the percentage change in the value of stiffness modulus for binder course mixture with RAP in relation to AC WMS 16 W PMB 25/55-60 KR3-KR6 at ≈60 km/h motion speed

A closer analysis of the difference between the mixtures shows that at -15°C, the SMA with PMB is more than 20 percentage points stiffer than its AMG counterpart. Almost by the same amount, i.e. by about 20 p.p., the same mixture is less rigid in the range of 30 to 40°C. As the temperature continues to rise, the graph shows a critical point at 55°C, where the rubber-modified bitumen begins to have a lower modulus value. In a wide temperature range of up to 55°C, the asphalt rubber mixture has more favorable characteristics than the standard polymer-modified asphalt mix.

In the case of reducing the speed to 5 km/h and the temperature dropping below 5°C, there is a tendency for an increased difference in the stiffness of the compared mixtures, with AMG bitumen becoming increasingly more flexible compared to PMB. A more detailed comparative analysis for lower speeds indicates a shift in the intercept points towards lower temperatures compared to higher speeds. Moreover, the observed difference in stiffness between the mixtures at 20°C is 5 percentage points lower than in the case of faster movement. A critical observation is the shift of the intercept point, above which AMG begins to exhibit a lower modulus of stiffness than polymer-modified bitumen.

It is important to note that the analyzed mixtures, under standard test conditions of temperature and frequency (10–13°C, f=8–10Hz), show a relatively similar modulus value. According to the methodology described in KTKNPiP, the presented variability in the mixture's characteristics due to temperature and load time would not be considered at all.

5.1.2. Master curves for HMA designed for binder course

The analysis of the binder course mixtures indicates a stiffening effect of the addition of the analyzed recycled materials (Fig. 7), when examining dynamic moduli for both analyzed frequencies. The use of RAP in the studied case stiffened the mixture in the range of 30 to 60 percentage points, with an increasing trend in terms of temperature. It should be noted that with a decrease in the loading frequency, the mixture shows an

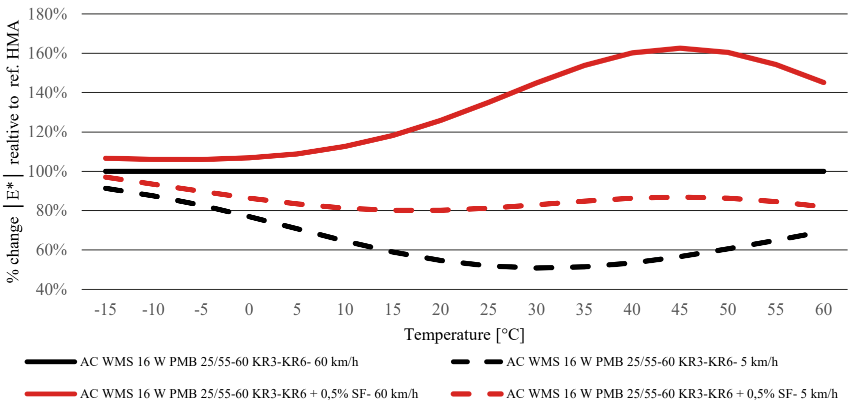

Fig. 8. Comparison of the percentage change in the values of stiffness modulus for binder course mixture with synthetic fibers in relation to AC WMS 16 W PMB 25/55-60 KR3-KR6 at ≈60 km/h motion speed

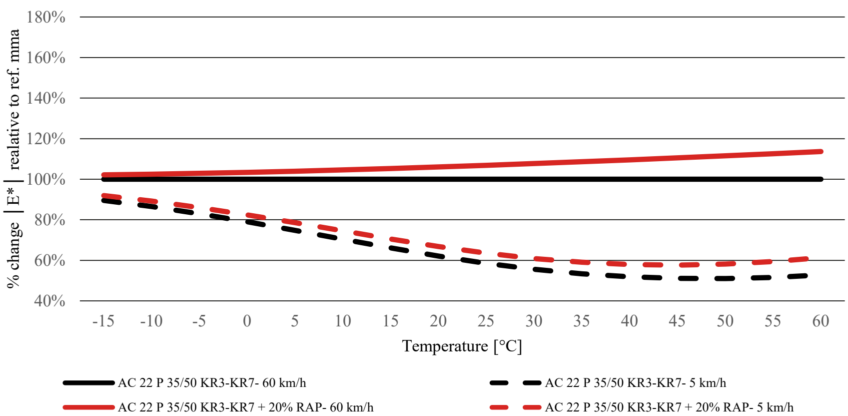

Fig. 9. Comparison of the percentage change in the value of stiffness modulus for base courses mixture with RAP against AC 22 P 35/50 KR3-KR7 at motion speed ≈60 km/h

increase in stiffness compared to the mixture without the addition of RAP (approximately 10%).

The addition of synthetic fibers also contributes to the observed increase in the stiffness of the tested mixtures (Fig. 8). The growing influence of fiber addition on increasing stiffness with temperature is evident. For high-speed movement, it can be observed that the mixture with fiber addition at 45°C reaches a difference of up to 60 percentage points.

If the speed of traffic is lowered, the maximum difference in stiffening the mixture moves to a temperature of 33°C, reaching a similar value of change (~33 p.p.) in relation to the mixture without the addition of fibers. The increased stiffness of the mixture at higher temperatures will translate into their potentially greater resistance to permanent deformation and lower deflections of the surface from traffic loads.

5.1.3. Master curves for HMA for asphalt base course

The analysis of mixtures designed for the base course confirms the observations of the effect of the addition of reclaimed asphalt pavement from the binder course mixes (Fig. 9).

For both frequencies, increased stiffness is observed compared to the mixture without the addition of RAP, with a tendency for the increase of difference in stiffness with rising temperature. This confirms the observations described in the paper cited in the introduction regarding the influence of adding RAP on the stiffness of asphalt mixtures [1].

The analyses presented above allow for a deeper assessment of the impact of the recycled material, taking into account its characteristics over a wide range of working conditions, both in terms of climate and loading speed. This enables its optimal application utilizing the individual structural design methodology.

6. ANALYSIS OF THE INFLUENCE OF DIFFERENCES IN STIFFNESS MODULUS OF DIFFERENT HMA ON THE DURABILITY OF PAVEMENT STRUCTURES

The aim of the conducted analyses is not to promote any specific types of pavement structures, types of HMA or any particular type of waste materials, but only to draw attention to the differences in the range of crucial parameters of asphalt layers they can exhibit due to the specific features and properties of component materials (including waste and recycled materials) and varied working conditions of pavements, such as asphalt layer temperatures and the vehicle speeds.

6.1. CONSTRUCTION AND CALCULATION SCHEME ADOPTED FOR PAVEMENT DURABILITY ANALYSES

For further calculations and analyses, a typical flexible pavement structure was adopted according to the guidelines of KTKNPiP [6], designed for traffic category KR6, which is intended to carry between 22 and 52 million standard axles of 100 kN. The construction scheme is presented in Fig. 10.

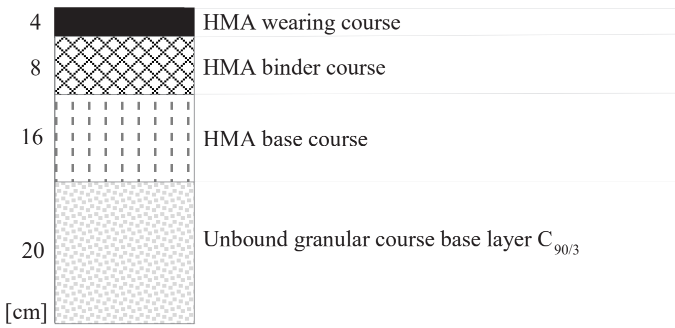

Fig.10. Pavement structure for traffic category KR6 according to KTKNPiP [6]

6.2. CALCULATION PARAMETERS USED TO DETERMINE THE DURABILITY OF THE PAVEMENT STRUCTURE

Each of the analyzed asphalt mixture (Table 1) was characterized in terms of dynamic modulus at various temperature and frequency values as described in section 3.2. Additionally, their basic volumetric and functional properties were determined in accordance with WT-2 2014 [6]. Based on the conducted tests, parameters of master curves were determined, allowing the determination of the stiffness modulus at any temperature and frequency depending on pavement operating conditions. The calculations were based on modulus values reduced by a safety factor of 85% of the resulting values from the obtained master curve models.

6.3. VARIANTS OF PAVEMENT STRUCTURES ACCORDING TO THE TYPES OF MIXTURES USED IN PARTICULAR ASPHALT LAYERS

To better illustrate the influence of differences in the moduli of asphalt layers and differences in the shape of their master curves on the pavement's behavior under variable operating conditions, several variants of the upper part of the structure were selected for comparison. These variants are characterized by the use of relatively similar types of asphalt mixtures in the specific asphalt layers (similar aggregate types and mineral skeleton gradation, binder type, and volumetrics), but with different additives from recycled waste materials (as presented in Table 1). Another assumption was to adopt an identical layout and thickness of layers according to KTKNPiP [6]. In all adopted variants, the thickness and modulus of elasticity of the main base layer made of an unbound granular mixture C90/3 are the same, namely h = 20 cm and E = 400 MPa, respectively. The modulus of elasticity of the subgrade at the surface of the lower layers of the pavement structure and the improved subgrade was set at a constant level of E = 120 MPa. Table 2 presents various variants of the asphalt layers package adopted for further analysis.

Table 2. Summary of the analyzed variants of the asphalt layers package

Variant of the KR 6 pavement structure	
Variant 1	**h [cm]**
SMA 11 PMB 45/80-55 KR3-KR7	4
AC 16W 35/50 KR3-4+0%RAP	8
AC 22 P 35/50 KR3-KR7 + 0% RAP	16
Variant 2	**h [cm]**
SMA 11 PMB 45/80-55 KR3-KR7	4
AC WMS 16 W PMB 25/55-60 KR 3-6 + 0% RAP	8
AC 22 P 35/50 KR3-KR7 + 0% RAP	16
Variant 3	**h [cm]**
SMA 11 AMG KR3-KR7	4
AC WMS 16 W PMB 25/55-60 KR 3-6 + 0% RAP	8
AC 22 P 35/50 KR3-KR7 + 20% RAP	16
Variant 4	**h [cm]**
SMA 11 AMG KR3-KR7	4
AC WMS 16 W PMB 25/55-60 KR 3-6 + 0.5% SF	8
AC 22 P 35/50 KR3-KR7 + 20% RAP	16
Variant 5	**h [cm]**
SMA 11 AMG KR3-KR7	4
AC WMS 16 P/W PMB 25/55-60 KR3-KR7 + 10% SF	8
AC 22 P 35/50 KR3-KR7 + 20% RAP	16

6.4. IMPACT OF VARIABILITY IN STIFFNESS MODULI AND PAVEMENT OPERATING CONDITIONS ON ESTIMATED STRUCTURE DURABILITY

From the perspective of pavement mechanics, differences in the stiffness moduli of asphalt layers can significantly affect the durability of the structure and its lifecycle, including the degradation curve and the associated scope and intensity of required heavy maintenance procedures. The moduli of asphalt mixtures depend on the properties of the materials they are made of, but they also change to a considerable extent during road operation, depending on the pavement temperature and loading speed.

Currently, according to KTKNPiP [6], in the case of individual pavement structure design, it is sufficient to determine the moduli of asphalt layers at an equivalent temperature of 13°C for flexible pavements and 15°C for semi-rigid pavements, with a loading time of 0.02 s, corresponding to the movement of a heavy-duty vehicle at a speed of 60 km/h.

To determine the impact of modulus changes due to differences in mechanistic analysis methodology on pavement durability, the calculations for various structural variants were carried out with the following assumptions:

- An equivalent temperature of 13°C throughout the entire service life at a vehicle speed of 60 km/h.
- Three temperatures (-2, 10, 23°C) for four seasons, considering different traffic volumes during these periods (winter 20% traffic, spring and autumn 50%, summer 30%) and at a vehicle speed of 60 km/h.

Table 3. Summary of relative durability results of the analyzed design variants

Pavement structure Variants – KR6		HMA modules according to Table B1 KTKNPiPT= 13°C; V= 60 km/h	Master Curve HMA modules T= 13°C; V= 60 km/h	HMA modules with Seasonal T-Master Curves; V= 60 km/h	HMA modules with Seasonal T-Master Curves; V= 5 km/h
Variant 1	**h [cm]**				
SMA 11 PMB 45/80-55 KR3-KR7	4	100%	147%	113%	59%
AC 16 W 35/50 KR3-4 + 0% RAP	8				
AC 22 P 35/50 KR3-KR7 + 0% RAP	16				
Variant 2	**h [cm]**				
SMA 11 PMB 45/80-55 KR3-KR7	4	-	137%	105%	52%
AC WMS 16 W PMB 25/55-60 KR 3-6 + 0% RAP	8				
AC 22 P 35/50 KR3-KR7 + 0% RAP	16				
Variant 3	**h [cm]**				
SMA 11 AMG KR3-KR7	4	-	143%	110%	55%
AC WMS 16 W PMB 25/55-60 KR 3-6 + 0% RAP	8				
AC 22 P 35/50 KR3-KR7 + 20% RAP	16				
Variant 4	**h [cm]**				
SMA 11 AMG KR3-KR7	4	-	154%	119%	63%
AC WMS 16 W PMB 25/55-60 KR 3-6 + 0.5% SF	8				
AC 22 P 35/50 KR3-KR7 + 20% RAP	16				
Variant 5	**h [cm]**				
SMA 11 AMG KR3-KR7	4	-	160%	122%	62%
AC WMS 16 P/W PMB 25/55-60 KR3-KR7 +10% RAP	8				
AC 22 P 35/50 KR3-KR7 + 20% RAP	16				

Additionally, to determine the impact of different vehicle speeds on the durability of the structure, calculations were performed for the stiffness moduli of the asphalt mixtures determined based on their master curves at the loading frequency corresponding to a vehicle speed of 5 km/h.

For structure Variant 1, calculations were also performed assuming typical parameters for asphalt mixtures given in Table B1 of KTKNPiP [6] for one temperature and one vehicle speed. The calculated durability of this structure was assumed as a reference against which the durability of the other variants and options were determined. Table 3 presents the durability results of different structure variants under various working conditions expressed as a percentage of the reference durability of Variant 1.

The calculated relative durability results for different analyzed structural variants indicate significant differences ranging from 37 to 60 percentage points compared to the reference variant in the case of analysis based on only one equivalent temperature. The use of analysis based on moduli determined for several seasonal temperatures results in much smaller differences, although they still reach 20–22 percentage points for variants using a relatively large amount of recycled materials in each asphalt layer. It should be emphasized that in the analysis at the same vehicle speed (60 km/h), all considered structure variants achieved higher durability than the reference variant. Analyses of structures simulating the operation of different pavement variants in the intersection area (speed of 5 km/h) indicate a drastic reduction in durability ranging from 38 to even 48 percentage points compared to the reference variant calculated at a speed of 60 km/h.

The results of the above calculations, analyses, and observations lead to the conclusion that in the case of designing pavement structures using mechanistic-empirical methods, it is crucial and necessary to accurately determine the properties of the materials assumed in the analysis, primarily their stiffness moduli, and to precisely determine the working regime of the structure – pavement temperature and loading time. It can be stated, that such an approach is particularly recommended in the situation of increasingly frequent use of various types of recycled materials.

7. SUMMARY AND CONCLUSIONS

The paper compares the results of stiffness modulus tests and estimates the durability of several pavement structure variants using different types of HMA, considering the presence of various types of recycled materials (reclaimed asphalt pavement, rubber from scrap tyres, synthetic fibers) and different pavement working conditions.

The presented master curves of dynamic stiffness modulus, indicating the behavior of the mixture under diverse climatic conditions and traffic loads show significant variations in this parameter between mixtures of the same type designed for the same pavement layer, but differing in the type and quantity of recycled materials added. Consequently, significant differences in the durability of various analyzed pavement variants were obtained – ranging from a decrease of 48% for Variant 2 under long-term loading to an increase of 60% for Variant 5, which uses modulus values determined for one equivalent temperature and a standard speed of 60 km/h. These differences are particularly visible and significant at lower vehicle speeds (~5 km/h) within intersections, resulting in a reduction in durability ranging from 38–48% depending on the variant. The obtained results allow for a deeper assessment of the impact of the applied waste material, considering its characteristics over a wide range of working conditions, including climate and traffic speed, enabling its optimal use in the individual pavement design procedure.

Effective use of public funds through the design of cost-effective and environmentally friendly road pavements involving waste and recycled materials necessitates the design of pavement structures divided into sections according to different traffic load characteristics and better adapted to locally occurring climatic conditions. This, in turn, implies the need for more advanced characterization of asphalt layer stiffness, for example, by studying the complex modulus of asphalt layers and determining their master curves. Specific structures using materials with appropriate properties should be designed on highway sections between interchanges, where the traffic speed is, for example, 60 km/h. Different pavement structures using materials with slightly different properties should be used at intersections and approaches to intersections (speed ~ 5 km/h), while yet another set of materials with different properties should be employed on road connectors, where, in addition to the unfavorable working regime caused by lower traffic speed, additional shear stresses occur due to the tilt on the road curve and its high longitudinal inclination.

The presented methodology of advanced research on asphalt materials and their use in mechanistic-empirical pavement design can be crucial for road designers and process engineers dealing with asphalt mixtures. It enables a conscious selection of materials to achieve the required design parameters for pavement structures. The correct implementation of an individualized approach in road construction design, considering the changing climate and the use of recycled materials, can contribute to the increased durability of road pavements and help to protect the environment by reducing the consumption of natural resources while simultaneously lowering the construction and maintenance costs of roads during their life cycle.

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