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Evaluation of Fatigue Life of Asphalt Concrete Mixtures with Reclaimed Asphalt Pavement

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Featured Application: The results of the work can be used in the design of bituminous mixtures with RAP, as well as may be taken into account in the change of technical regulations in Poland regarding the use of RAP.

Abstract: The topic of this article is the evaluation of the fatigue life of asphalt concrete mixtures with reclaimed asphalt pavement (RAP). The evaluation was carried out in relation to asphalt concrete mixtures AC22P and high modulus asphalt concrete ACWMS16 with 50% contents of RAP, greater than currently permitted by technical regulations in Poland. The first stage consisted of the evaluation of laboratory results, which was followed by a mechanistic analysis of the designed life of pavement structures with reclaimed asphalt. The evaluation included the results of laboratory tests (i.e., the air voids content, effective asphalt content, properties of recovered asphalt (penetration, softening point), stiffness, and resistance to fatigue of bituminous mixtures). Calculations of the design life of the structure were made using the criteria according to the 2004 AASHTO specifications for fatigue life and the Asphalt Institute for subgrade deformation. In addition, calculations were carried out using the French method. The analyses allowed for a comprehensive evaluation of the asphalt concrete mixture in the analyzed scope. The evaluation of the fatigue life of AC22P and ACWMS16 mixtures with 50% content of reclaimed asphalt as well as the results of the calculations of design life of the structure indicated positive effects. The tests have been carried out within the framework of the research project dedicated to hot recycling entitled "Reclaimed asphalt pavement: Innovative technology of bituminous mixtures using material from reclaimed asphalt pavement".

Keywords: pavement design; fatigue life; recycling; reclaimed asphalt pavement; RAP; mechanistic method

1. Introduction

The hot recycling technology has been known and used worldwide for years. In many countries it is quite commonly used, and attempts can be noted for the maximum re-use of the reclaimed asphalt pavement (RAP) from the milling of asphalt courses [1–4]. This material is valuable—its composition contains mainly mineral aggregate and asphalt binder. Various methods of asphalt pavement recycling are known: both in hot and cold technology [5–8]. Application of the hot recycling technology in Poland is very limited for many reasons, including the lack of appropriate technical guidelines and recommendations, experience, equipment resources, consent from the project owners, availability of a good quality RAP, among others [9,10]. Taking the properties of a bituminous mixture with RAP into account, it must be ensured that it meets the technical requirements, and the application of RAP does not deteriorate the properties of the new mixture [11]. Certainly, these are the assumptions to ensure that the asphalt courses will be characterized by the appropriate durability. The first factor which has a significant impact is the uniformity of the reclaimed asphalt pavement [12], and in particular the contents and properties of asphalt binder. The larger the contents of RAP in the bituminous mixture, the more important is the role of old asphalt binder. Another very important factor is the ageing process covering the bitumen courses, and the asphalt binder [13,14]. Therefore, the application of reclaimed asphalt (i.e., the material after long- and short-term ageing) may raise concerns as to the characteristics of the bituminous mixture with the addition of that material. In general, a potentially increased rigidity and better resistance to permanent strains may be expected [15]. On the other hand, those properties where greater stiffness is not favorable (i.e., the resistance to cracking and fatigue resistance) may be deteriorated. In order to verify these characteristics, it is necessary to conduct performance tests. If necessary, regenerative (rejuvenator) additives should be used, the aim of which is to improve the viscoelastic properties [16–18]. The fatigue life is the primary characteristic determining the service life of the pavement [19]. A change of rheological properties of asphalt binder due to ageing can cause deterioration of the fatigue life of mixtures with RAP [20,21]. There are also studies showing an opposite effect [22]. This publication presents the results of fatigue tests of two bituminous mixtures for the base course with 50% contents of RAP; i.e., AC22P asphalt concrete and high modulus asphalt concrete ACWMS16. An analysis of the fatigue test results and calculations of the pavement design life were conducted. These studies and analyses have not been done in Poland so far. The results of fatigue tests and structure analysis are particularly important in the context of popularizing the use of hot recycling in Poland. They show the possibilities of using mixtures with RAP while maintaining an appropriate fatigue life of mixtures and structures.

2. Description of Test Methods

As part of laboratory tests, a number of research methods covered by European standards were applied. In the scope of binder tests, penetration (PN-EN 1426) and softening temperature (PN-EN 1427) tests were carried out. In terms of basic physical properties of mineral-bituminous mixtures, the density (PN-EN 12697-6), maximum density (PN-EN 12697-5), air void content (PN-EN 12697-8), and soluble binder content (PN-EN 12697-1) were tested.

The fatigue life was determined using the four-point bending beam test (4PB) according to PN-EN 12697-24 standard. Tests were performed in constant strain mode (several strain amplitudes), at a frequency of 10 Hz and a temperature of 10 °C. These are typical testing conditions used in Poland. Beams with size of 50 × 63 × 380 mm were cut from plates compacted by laboratory roller compactor (PN-EN 12697-33). The analysis of fatigue life most often evaluates the ε_6 parameter, which determines the strain under the fatigue test, during which the life of 1 million load cycles is obtained. A higher value means potentially better fatigue properties. Additional information is provided by the fatigue characteristic, which is described by the formula:

$$N = A \cdot \varepsilon^{b}, \quad (1)$$

where: N—fatigue life, ε—strain during fatigue test; A, b—linear regression parameters, and b is the inclination of the fatigue line.

Prior to fatigue tests, the same beams were subjected to frequency sweep test, which enabled estimation of the stiffness modulus according to PN-EN 12697-26.

3. Production at Asphalt Plant and Specimen Preparations

The framework of the project included production of the trial batch mixtures with reclaimed asphalt at asphalt plant. The mixtures were produced in the asphalt plant of the company Budimex S.A. (Warsaw, Poland) (Figure 1). The plant is one of the four plants in Poland equipped with a black mixing drum for dispensing hot reclaimed asphalt [23]. In hot recycling technology, RAP is heated in a separate drum to a temperature of over 120–140 °C. The granulate is crushed, and then in a loose form goes to the mixer. There is no need to overheat the aggregate excessively or extend the mixing time to crush and heat the asphalt granulate, as is the case with cold dosing technology. On the basis of trial production and basic tests, mixtures for further functional tests including fatigue and stiffness were selected.

Figure 1. Asphalt plant with a reclaimed asphalt pavement (RAP) drum on the top and view of the RAP pile.

The produced mixes were packed in portions of about 25 kg in paper bags and delivered to the IBDiM laboratory (Warsaw, Poland). The portion of the mixture was then heated again in the laboratory oven to the compaction temperature, then it was put to the laboratory mixer. Subsequently, plates with dimensions of 50 × 18 × 10 cm were compacted using a standardized steel roller method. Thereafter, the degree of compaction was controlled, which should be in the range 98–100%. Then, beams for fatigue and stiffness tests were cut from each plate (Figure 2).

Figure 2. Beam for four-point bending beam test (4PB) fatigue and stiffness test.

4. Tests Results

4.1. Basic Properties of Asphalt Binders and Bituminous Mixtures

In addition to the mixtures analyzed in this publication (i.e., AC22P and ACWMS16), mixtures for the wearing course and the binder course were also produced and tested. Properties of these mixtures are necessary for the analysis of the pavement structure. In order to determine the stiffness of a bituminous mixture using the empirical method, it is necessary to know the basic properties of the asphalt binder (penetration, softening point) and the selected physical properties of the bituminous mixture (binder and aggregate content by volume). To determine these properties of asphalt binders, laboratory tests were carried out on binders recovered from mixtures containing reclaimed asphalt. Table 1 presents the mixtures, their basic properties, and the properties of the recovered binders. All mixes were designed according to the technical requirements [24] based on PN-EN 13108-1 (asphalt concrete) and PN-EN 13108-5 (SMA). There are two mixtures for base course: AC22P and AC WMS 16. The first one is conventional asphalt concrete, while the second is high modulus asphalt concrete (HMAC). The main differences are due to the composition of these mixtures and volume properties. ACWMS has a lower air voids content, finer grading, and higher binder content. The mixture obtained in this way is characterized by high resistance to fatigue and at the same time good resistance to rutting [25–27]. In order to increase stiffness, harder binders are used (e.g., 20/30 or 10/40-65). HMAC is often used in Poland for heavily trafficked roads. Mixture AC16W is typical asphalt concrete for binder course, while AC11S and SMA11 are designed for wearing course. Grading curves of all mixtures are presented in Figure 3.

4.2. Results of Fatigue Tests

Table 2 presents the fatigue characteristics parameters of the mixtures of asphalt concrete AC22P 35/50 and high modulus asphalt concrete ACWMS16 25/55-60 with reclaimed asphalt. Additionally, the same parameters of that type of mixture, but without the reclaimed asphalt content, were included for comparison. The results come from the research works carried out in the Road and Bridge Research Institute in recent years.

Table 1. Properties of recovered binders and bituminous mixtures with reclaimed asphalt.

Mixture	AC22P 35/50 50%RAP	AC16W 25/55-60 50%RAP	ACWMS16 25/55-60 50%RAP	AC11S 45/80-55 30%RAP	SMA11 45/80-55 15%RAP
Added (fresh) asphalt binder	35/50	25/55-60	25/55-60	45/80-55	45/80-55
Contents of reclaimed asphalt, % m/m	50	50	50	30	15
Properties of recovered asphalt					
Penetration at 25 °C, 0.1 mm	28	28	32	49	52
Softening point according to ring and ball method, °C	62.3	66.5	64.5	60.5	58.9
Properties of bituminous mixtures					
Density, kg/m^3	2431	2417	2430	2419	2379
Maximum density, kg/m^3	2540	2518	2500	2480	2429
Contents of soluble asphalt, % *m*/*m* (by weight)	3.7	4.4	5.0	5.2	6.3
Contents of aggregate mixture, % *m*/*m* (by weight)	96.3	95.6	95.0	94.8	93.7
Air voids content, % *v*/*v* (by volume)	4.3	4.0	2.8	2.5	2.1
Contents of soluble asphalt, % *v*/*v* (by volume)	8.7	10.3	11.8	12.2	14.6
Contents of aggregate, % *v*/*v* (by volume)	87.0	85.7	85.4	85.3	83.4

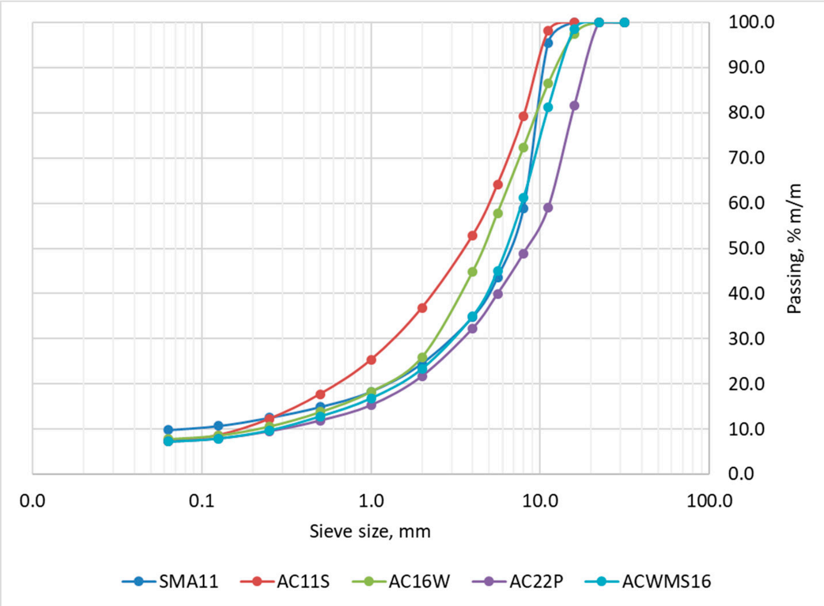

Figure 3. Grading curves.

Table 2. Results of the mixture fatigue test.

Mixture	Fatigue Curve Parameter			Fatigue Resistance
	A	*b*	R^2	ε_6, μm/m
AC22P 35/50 50%RAP	1.7×10^{19}	−6.2	0.91	134
AC22P 35/50 ref. 1 *	4.7×10^{20}	−7.1	0.88	117
AC22P 35/50 ref. 2 **	3.2×10^{18}	−6.1	0.91	116
ACWMS16 25/55-60 50%RAP	5.3×10^{18}	−5.7	0.86	176
ACWMS16 25/55-60 ref. 1 ***	5.9×10^{22}	−7.4	0.95	185
ACWMS16 25/55-60 ref. 2 *	7.9×10^{20}	−6.4	0.94	214

* The results of tests under the research project RID I/25, ** the results of tests under the research work described in [25], *** the results of tests under the research work described in [26].

Evaluation of the durability of AC22P and ACWMS16 mixtures with reclaimed asphalt must be carried out separately, because these are mixtures of different types and with different binders (unmodified asphalt and polymer-modified asphalt). Therefore, it is not surprising that those mixtures significantly differ in terms of fatigue resistance with an indication of the better properties of ACWMS16. It should be noted that the addition of reclaimed asphalt in a relatively large amount of 50% did not affect the scatter of results. The regression correlation coefficient R^2 at the level of 0.9 is the result proving small scatter of results, and does not deviate from the values obtained for mixtures without reclaimed asphalt.

The AC22P 35/50 asphalt concrete is one of the basic mixtures for base courses according to the Technical Recommendations in Poland [24], and is very often used for different traffic categories. It is designed using the empirical method and the requirements in terms of fatigue resistance were not specified. Therefore, it is not possible to determine the suitability of the AC22P 35/50 mixture with reclaimed asphalt with respect to the applicable technical requirements. However, the results obtained for this mixture may be referred to the results from other research. Hence, Table 2 and Figures 4 and 5 provide the results for two AC22P 35/50 reference mixtures. The comparison of the ε_6 parameter indicates higher results of the fatigue life of the mixture with reclaimed asphalt compared to the reference mixtures. This effect is also visible in diagrams of fatigue characteristics. Characteristics of AC22P mixtures have similar incline; however, the line of the mixture with RAP is shifted in the direction of longer fatigue lives. The obtained results can also be referred to slightly older results of tests of asphalt concrete BA 0/25 D50 [28], where the results of ε_6 from ca. 100 to 130 µm/m were obtained for the six variants of the mixture with various asphalt contents and asphalt binder origins (suppliers). On this basis, it was possible to state that the results for the AC22P 35/50 mixture and the results described above are the typical and expected results. Taking this into account, the results for the mixture with reclaimed asphalt look positive and do not allow conclusions to be drawn about the deterioration of the fatigue life.

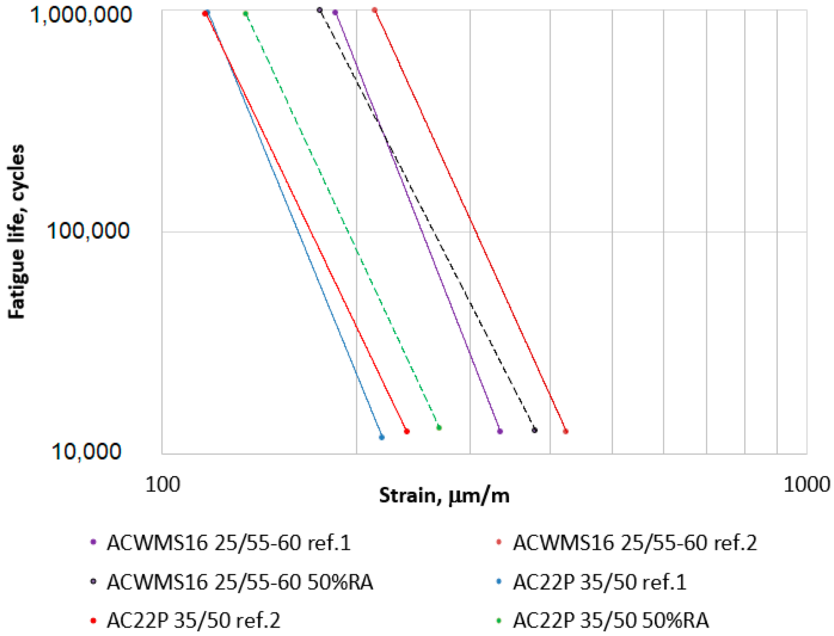

Figure 4. Graphical representation of the fatigue characteristics of mixtures with reclaimed asphalt and reference mixtures.

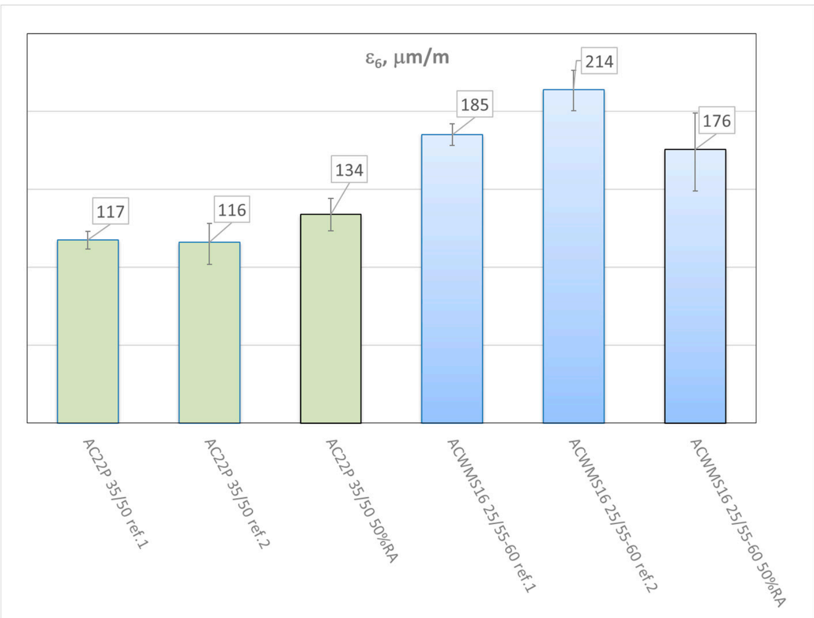

Figure 5. Comparison of the ε_6 parameter of the individual mixtures and the 95% confidence intervals.

The high modulus asphalt concrete is the only mixture in Poland for which the requirements of fatigue life are specified in the recommendations [24]. The value of the ε_6 parameter of the ACWMS16 25/55-60 mixture with reclaimed asphalt is much higher than the required 130 μm/m, which allows for positive evaluation of its properties in terms of fatigue life. The other two ACWMS16 25/55-60 reference mixtures without the RAP exhibit better fatigue properties in terms of the ε_6 parameter and the fatigue characteristics. This difference is due to the use of "fresh" polymer-modified asphalt and RAP containing unmodified asphalt binder. As we know, the use of modified binders and the extent of modification have a beneficial effect on the fatigue resistance of the mixtures. The mixture with reclaimed asphalt combines the unmodified asphalt binder and polymer-modified binder. Therefore, a lesser extent of modifications of the polymer contents was obtained than in the case of reference mixtures without RAP.

4.3. Determination of the Stiffness of Bituminous Mixtures

Knowledge of the stiffness modulus of bituminous mixtures is necessary for calculations of the design life of the structure using the mechanistic method. Stiffness was determined using the empirical method and the BANDS software (Shell, The Hague, The Netherlands, 1998) by using the previously specified parameters of recovered asphalts and bituminous mixtures [29]. The values were determined at a load time of 0.02 s and temperatures 10 and 13 °C. The value of stiffness at 13 °C is required in the design using the 2004 AASHTO method in accordance with the rules specified in the Polish Catalogue [30], while the result at 10 °C is necessary for the design using the French method [31]. In addition, the values of stiffness were determined at the frequency of 10 Hz and the temperature of 10 °C, which were compared with the results obtained in the laboratory tests using the four-point bending beam method. Figure 6 indicates a good correlation between the calculated values and values obtained in the laboratory, with the latter being approximately 5–10% higher (Table 3).

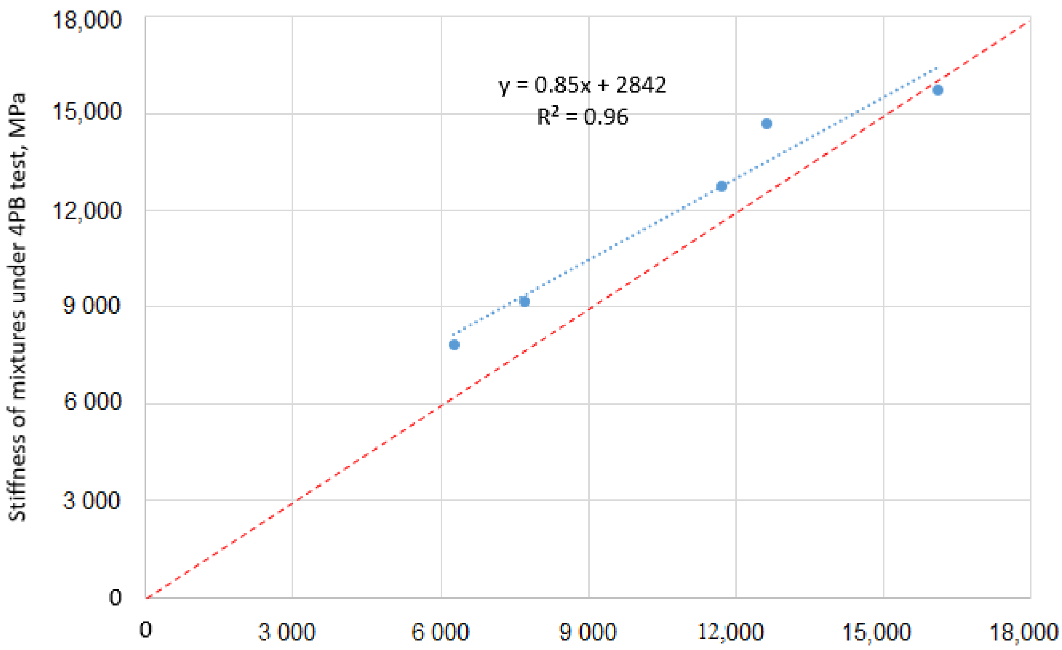

Figure 6. Comparison of the stiffness of trial batch mixtures obtained from laboratory tests and those calculated using the empirical method.

Table 3. Stiffness modulus.

Mixture	AC22P 35/50 50%RAP	AC16W 25/55-60 50%RAP	ACWMS16 25/55-60 50%RAP	AC11S 45/80-55 30%RAP	SMA11 45/80-55 15%RAP
Stiffness (0.02 s, 13 °C) under empirical estimation, MPa	13,900	10,600	9230	5900	4700
Stiffness (0.02 s, 10 °C) under empirical estimation, MPa	15,600	12,300	11,300	7260	5880
Stiffness (10 Hz, 10 °C) under empirical estimation, MPa	16,100	12,600	11,700	7700	6260
Stiffness (10 Hz, 10 °C) under laboratory tests 4PB, MPa	15,716	14,690	12,722	9189	7853

5. Analyses of Pavement Design Life

5.1. Purpose of the Analyses

The purpose of the calculations is to determine the usability of the bituminous mixtures with reclaimed asphalt for typical pavement structures in terms of calculated fatigue life. Fatigue durability is the basic parameter determining the quality of pavement structures. According to the general principle of using bituminous mixtures with RAP, they cannot reduce the durability of the structure. The analysis uses the mechanistic method, which is used in the individual design of road pavement structures in Poland. This method uses selected parameters of asphalt mixtures and recognized fatigue criteria. Therefore, the results of laboratory tests are used in the analysis. The analyses were carried out on typical flexible pavement structures according to the Catalogue [30]. Results of the analyses were compared to the required number of equivalent axle loads for given traffic load category.

5.2. Pavement Structures

The thicknesses of the pavement courses were left unchanged in relation to those specified in the Catalogue. Figure 7 presents upper parts of pavement structures consisting of asphalt layers and the range of equivalent axle loads for each traffic load category. The SMA11 mixture was used for the traffic load category KR3-7 wearing course, while asphalt concrete AC11S was used for KR1-2. The KR1-7 binder course and the base course adopt AC16W and AC22P mixtures, and KR5-7 structures additionally introduce variants using the ACWMS16 mixture. The lower structural layers were adopted uniformly and consisted of an unbound aggregate subbase with a thickness of 20 cm and 15 cm cement treated base course.

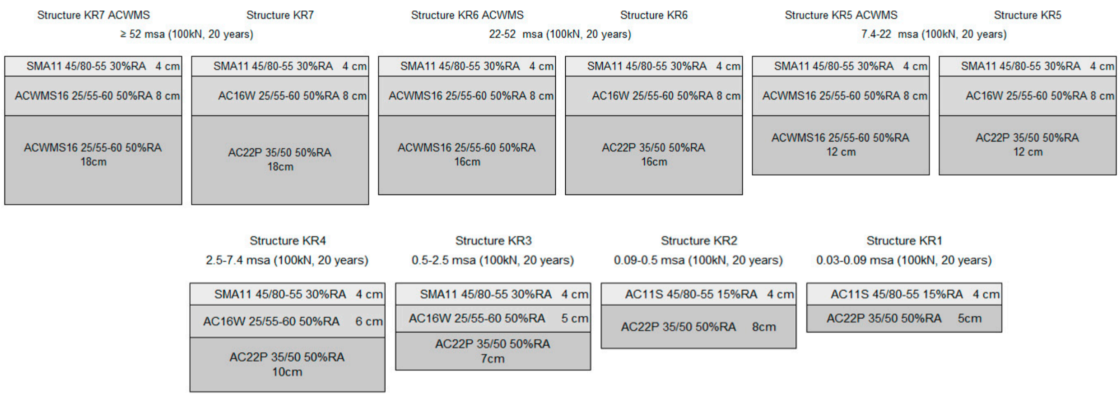

Figure 7. Upper layers of pavement structures for fatigue analyses for different traffic load categories.

5.3. Numerical Method

The mechanistic pavement design method consists of determining the fatigue life of the structure on the basis of a stress–strain state analysis. For this purpose, the surface is treated as a system of courses with specific thicknesses on the subgrade with infinite thickness. The most common model is the model of elastic layers located in the elastic half-space. The individual courses are characterized by thickness (h), the modulus of elasticity (stiffness) (E), and Poisson's ratio (ν). The asphalt layers' stiffness modulus were adopted in accordance with the results of tests and calculations stated above. The remaining parameters were selected in accordance with the instructions specified in the Catalogue [30]:

- subgrade modulus of elasticity G1 equal to 80 MPa, Poisson's ratio 0.35,
- modulus of elasticity of the cement treated sub-base 200 MPa, Poisson's ratio 0.3,
- modulus of elasticity of the unbound subbase 400 MPa, Poisson's ratio 0.3,
- Poisson's ratio of asphalt courses 0.3.

In order to make the design life calculations of the analyzed flexible pavement structure, it is necessary to determine horizontal tensile strains in the bottom of the asphalt layers and the compressive vertical strains in the upper surface of the subgrade.

Calculations of the stress–strain states in the structure were performed using the NOAH 2.0 software (Nynas NV, Stockholm, Sweden, 1996). The following assumptions were made in accordance with the provisions adopted during the development of the Catalogue [31]:

- equivalent axle load 100 kN (wheel load 50.0 kN),
- contact pressure q = 850 kPa,
- equivalent temperature 10 (French method) or 13 °C (AASHTO method).

Two criteria of pavement failure were considered; i.e., the criterion of fatigue of the asphalt layers and the criterion of the subgrade deformation.

The calculations were carried out using the criteria recommended for use in Poland [31]; i.e., the 2004 AASHTO method in relation to the fatigue life of asphalt layers and the method of the Asphalt Institute with respect to the subgrade.

The fatigue life of asphalt layers according to the 2004 AASHTO criterion is described with the following equations [32]:

$$N_{asf} = 7.3557 \cdot (10^{-6}) \cdot C \cdot k_1' \cdot (\varepsilon_t^{-3.9492}) \cdot E^{-1.281}, \quad (2)$$

where:

$$C = 10^M, \quad (3)$$

$$M = 4.84 \cdot \left(\frac{V_b}{V_a + V_b} - 0.69 \right), \quad (4)$$

N_{asf}—fatigue life (number of equivalent standard axles), ε_t—tensile strain (μm/m), E—stiffness (MPa), V_b—asphalt content by volume (% v/v), V_a—air voids (% v/v), h_{ac}—total thickness of bituminous layers (cm).

k_1' is a parameter according to the formula:

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

The criterion of subgrade strain according to the equation of the Asphalt Institute is:

$$\varepsilon_P = 0.0105 \cdot Ngr^{-0.223}, \quad (6)$$

where: N_{gr}—life (number of equivalent standard axles), ε_p—subgrade strain (μm/m).

The structure durability N_{min} is the lower of the N_{asf} and N_{gr} values.

In addition, the fatigue calculations of the asphalt course were carried out using the so-called French method [33]. It allows for using the parameters of fatigue life of the bituminous mixture determined in the laboratory tests, unlike the 2004 AASHTO method. The equation includes the inclination of the Wöhler curve and the ε_6 value (value of strain under the fatigue test, during which durability is 10^6 cycles). In France, a two-point bending trapezoidal beam method is used, which is different from the four-point bending beam method used in Poland. However, based on the experience of the Road and Bridge Research Institute from comparative fatigue tests within the framework of the RILEM committee [34,35] (which demonstrated compliance of the results obtained using those methods), it was established that the results of 4PB tests can be used in the French method.

In the French method, the relation between the elastic strain in the bottom of asphalt layers and the life of the structure is as follows:

$$\varepsilon_t = \varepsilon_6 \cdot \left(\frac{N_{asf}}{10^6}\right)^b \cdot \left(\frac{E(10\ ^\circ\mathrm{C})}{E(\theta)}\right)^{0.5} \cdot k_c \cdot k_r \cdot k_s, \tag{7}$$

where: ε_6—strain under the fatigue test, during which durability is 10^6 cycles; E (10 °C)—stiffness at 10 °C (MPa); $E(\theta)$—stiffness at equivalent temperature (MPa); b—inclination of fatigue line, see Equation (1); k_c—coefficient dependent on mixture type; k_s—coefficient dependent on the pavement subgrade modulus; k_r—risk level coefficient.

Parameters were taken from laboratory tests or were chosen according to French recommendations. Parameter k_s was taken as 0.9 (KR1-KR4) or 1.0 (KR5-KR7). Parameter k_c is 1.0 for ACWMS base course or 1.1 for typical asphalt concrete base course. Risk level coefficient was calculated with probability level 98% for KR5-KR7 structures, and 95% for other pavements.

5.4. Calculations of Structure Fatigue Life

Tables 4 and 5 summarize the results of calculations of strains in the asphalt base course and in the subgrade according to the individual structural variants and the results of structure durability calculations according to the 2004 AASHTO criteria (Equation (2)) and the Asphalt Institute criteria (Equation (6)). Regardless of the method used for determining the stiffness or the fatigue criterion, the results of the structure durability calculations were higher than the upper limit of the range of the design number of equivalent standard axles for the specific traffic category (red dashed lines in Figures 8 and 9). In general (with some exceptions), the results obtained according to the 2004 AASHTO criterion were higher than the results according to the French method. In the case of ACWMS structures, AASHTO results were two to four times higher than those obtained using the French method. For the corresponding constructions with typical asphalt concrete, the relation is reversed. From the designer's point of view, on this basis, it can be indicated as a safer application of the French method to the structures of ACWMS, and AASHTO methods for structures with classic asphalt concrete. The smallest differences between these methods were in the case of medium thickness structures (KR4-KR5) with AC.

Table 4. The results of calculations of design life of the structures (stiffness of the asphalt layers according to calculations).

Configuration	KR7 ACWMS	KR7	KR6 ACWMS	KR6	KR5 ACWMS	KR5	KR4	KR3	KR2	KR1
ε_{asf}, μm/m	55.3	36.5	61.5	49.5	78.2	64.0	73.0	84.7	139.0	175.0
ε_{gr}, μm/m	149	133	164	149	206	192	218	251	411	538
N_{gr}, MSA* (100 kN)	193.4	321.9	125.8	193.4	45.3	62.1	35.1	18.7	2.0	0.6
2004 AASHTO method										
N_{asf}, MSA (100 kN)	153.6	111.0	101.8	33.6	40.0	12.3	7.3	4.4	0.7	0.4
N_{min}, MSA (100 kN)	153.6	111.0	101.8	33.6	40.0	12.3	7.3	4.4	0.7	0.4
The French method										
N_{asf}, MSA (100 kN)	62.6	465.1	35.3	70.3	9.6	14.3	5.6	2.2	0.1	0.02
N_{min}, MSA (100 kN)	62.6	465.1	35.3	70.3	9.6	14.3	5.6	2.2	0.1	0.02

* MSA–millions of standard axle loads.

Table 5. The results of calculations of design life of the structures (stiffness of the asphalt layers according to laboratory tests).

Configuration	KR7 ACWMS	KR7	KR6 ACWMS	KR6	KR5 ACWMS	KR5	KR4	KR3	KR2	KR1
ε_{asf}, µm/m	43.8	38.3	49.1	43.1	62.8	55.6	63.6	73.9	125.6	162
ε_{gr}, µm/m	133	117	141	131	179	168	192	223	404	502
N_{gr}, MSA (100 kN)	321.9	567.6	247.7	344.6	85.0	112.3	62.1	31.7	2.2	0.8
2004 AASHTO method										
N_{asf}, MSA (100 kN)	255.8	78.4	164.3	49.6	63.0	18.4	10.8	6.4	0.9	0.5
N_{min}, MSA (100 kN)	255.8	78.4	164.3	49.6	63.0	18.4	10.8	6.4	0.9	0.5
The French method										
N_{asf}, MSA (100 kN)	127.6	241.3	68.9	116.1	18.2	23.9	9.2	3.6	0.1	0.03
N_{min}, MSA (100 kN)	127.6	241.3	68.9	116.1	18.2	23.9	9.2	3.6	0.1	0.03

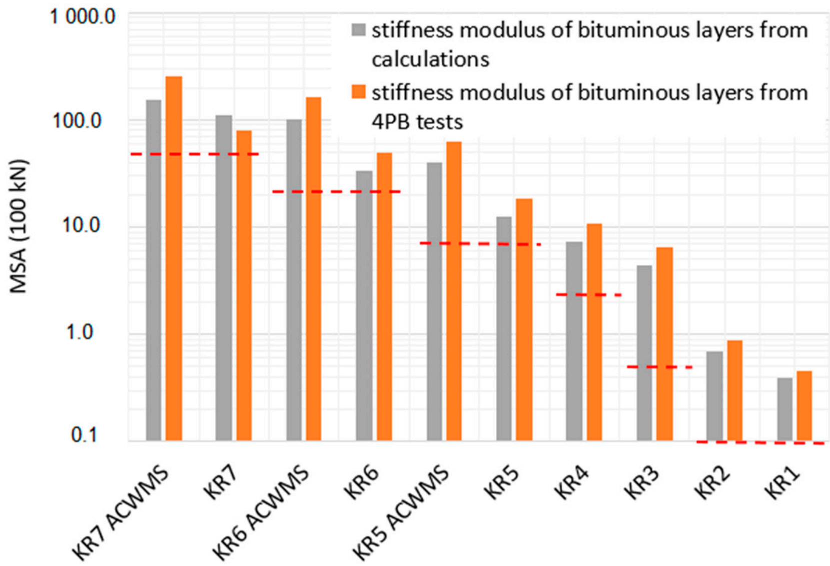

Figure 8. Results of calculations of pavement structure durability according to the 2004 AASHTO criterion.

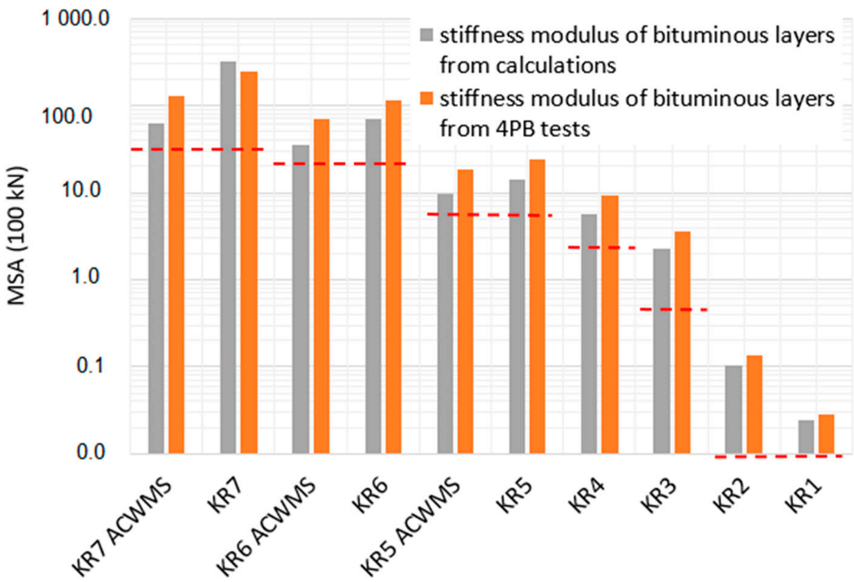

Figure 9. Results of calculations of pavement structure according to the French method for asphalt courses.

6. Summary

Hot recycling of asphalt pavement is currently a very trendy topic in Poland. This article presents the results of the research projects carried out in this field in Poland. As part of the work, tests and analyses were carried out to verify the suitability of bituminous mixtures with an increased content of RAP with regard to fatigue life. Fatigue life was evaluated in terms of mixture durability as well as pavement structure life. The results of laboratory tests of the basic properties of binders and mixtures, as well as the results of advanced tests such as fatigue life and stiffness, are presented. The test results were analyzed and the design life of the pavement structure was calculated by known calculation methods.

The evaluation of the fatigue life of AC22P and ACWMS16 mixtures with 50% content of reclaimed asphalt indicated their positive properties in this regard. Laboratory tests indicate good fatigue properties of mixtures with RAP. In the case of asphalt concrete AC22P 35/50, fatigue properties were obtained in the range typical for this type of mixture and this binder. However, in the case of ACWMS16 25/55-60, the addition of RAP slightly deteriorated the fatigue properties. The reason for this was unmodified binder in RAP, which largely replaced polymer modified binder (PMB) in the final mixture. Ultimately, the properties of the mixture in terms of fatigue were closer to the results typical for asphalt concrete with unmodified binder. Nevertheless, the mixture fulfilled the requirements of fatigue life according to Polish technical requirements. Regardless of the method used for determining the stiffness or the fatigue criterion, the results of the calculations of the structure design life were higher than the upper limit of the range of the design number of equivalent standard axles for the specific traffic category. The use of bituminous mixtures with reclaimed asphalt developed as part of the project allows the appropriate fatigue life of the pavement structure to be obtained. The results of analyses and tests also indirectly indicate the advantages of an asphalt plant with a separate drum for RAP. With this technology, it is possible to reduce RAP overheating, to limit technological aging process and proper mixing of materials. As a result, a mixture with parameters comparable to a mixture without RAP is obtained.

In the further part of the project, test sections were made and subjected to testing and observations. This will be described in subsequent publications.

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References

1. Al-Qadi, I.L.; Elseifi, M.A.; Carpenter, S.H. *Reclaimed Asphalt Pavement—A Literature Review*; Research Report FHWA-ICT-07-001; Illinois Center for Transportation, University of Illinois at Urbana-Champaign: Rantoul, IL, USA, 2007.
2. Zaumanis, M.; Mallick, R.; Frank, R. 100% Hot mix asphalt recycling: Challenges and benefits. *Transp. Res. Procedia* **2016**, *14*, 3493–3502. [CrossRef]
3. Elkashef, M.; Williams, R.C.; Cochran, E. Investigation of fatigue and thermal cracking behavior of rejuvenated reclaimed asphalt pavement binders and mixtures. *Int. J. Fatigue* **2017**, *11*, 90–95. [CrossRef]
4. Visintine, B.; Khosla, P.N.; Tayebali, A. Effects of higher percentage of recycled asphalt pavement on pavement performance. *Road Mater. Pavement Des.* **2013**, *14*, 432–437. [CrossRef]
5. Buczyński, P. The Frost Resistance of Recycled Cold Mixes with Foamed Bitumen and Different Types of Road Binders. *Procedia Eng.* **2016**, *161*, 54–59. [CrossRef]
6. Iwański, M.; Buczyński, P.; Mazurek, G. Optimization of the road binder used in the base layer in the road construction. *Constr. Build. Mater.* **2015**, *125*, 1044–1054. [CrossRef]
7. Dołżycki, B.; Jaczewski, M.; Szydłowski, C. The long-term properties of mineral-cement-emulsion mixtures. *Constr. Build. Mater.* **2017**, *156*, 799–808. [CrossRef]

8. Kukiełka, J. Recykling głęboki na zimno nawierzchni asfaltowych dróg samorządowych. *Materiały Budowlane* **2014**, *12*, 11–13. (In Polish)
9. Bańkowski, W.; Sybilski, D.; Król, J.; Kowalski, K.; Radziszewski, P.; Skorek, P. Wykorzystanie destruktu asfaltowego–konieczność i innowacja. *Budownictwo i Architektura* **2016**, *15*, 157–167. (In Polish)
10. Michalski, W. Methods of batching of RAP, Polish Association of Asphalt Pavement Contractors. *Asphalt Pavements* **2014**, *2*, 16–19. (In Polish)
11. Król, J.; Włodarski, P.; Jackowski, Ł. Właściwości mieszanek mineralno-asfaltowych ze zwiększoną ilością granulatu asfaltowego. *Drogownictwo* **2014**, *11*, 373–379. (In Polish)
12. Sybilski, D. On the need to use reclaimed asphalt pavement in Poland. *Road Eng.* **2011**, *1*.
13. Radziszewski, P. *Zmiany Właściwości Lepkosprężystych Lepiszczy Modyfikowanych i Mieszanek Mineralno-Asfaltowych w Wyniku Procesu Starzenia*; Wydawnictwo Politechniki Białostockiej: Poland, Białystok, 2007.
14. Woo, W.J.; Chowdhury, A.; Glover, C. Field aging of unmodified asphalt binder in three Texas long-term performance pavements. *Transp. Res. Rec. J. Transp. Res. Board* **2008**, *2051*, 15–22. [CrossRef]
15. Mogawer, W.; Bennert, T.; Daniel, J.; Bonaquist, R.; Austerman, A.; Booshehrian, A. Performance characteristics of plant produced high RAP mixtures. *Road Mater. Pavement Des.* **2014**, *13* (Suppl. 1), 183–208. [CrossRef]
16. Mogawer, W.; Booshehrian, A.; Vahidi, S.; Austerman, A. Evaluating the effect of rejuvenators on the degree of blending and performance of high RAP, RAS, and RAP/ RAS mixtures. *Road Mater. Pavement Des.* **2014**, *14* (Suppl. 2), 193–213. [CrossRef]
17. Kowalski, K.; Król, J.; Bańkowski, W.; Radziszewski, P.; Sarnowski, M. Thermal and Fatigue Evaluation of Asphalt Mixtures Containing RAP Treated with a Bio-Agent. *Appl. Sci.* **2017**, *7*, 216. [CrossRef]
18. Tran, N.; Taylor, A.; Willis, R. *Effect of Rejuvenator on Performance Properties of HMA Mixtures with High RAP and RAS Contents*; NCAT Report 12-05; National Center for Asphalt Technology: Auburn, AL, USA, 2012.
19. Mackiewicz, P. *Fatigue Life of Bituminous Mixtures Used in Road Pavements*; Publishing House of Wrocław University of Technology: Poland, Wrocław, 2016.
20. Walubita, L.; Epps Martin, A.; Jung, S.; Glover, C.; Park, E.; Chowdhury, A.; Lytton, R. *Comparison of Fatigue Analysis Approaches for Two Hot Mix Asphalt Concrete Mixtures (FHWA/TX-05/0-4468-2)*; Texas Transportation Institute: College Station, TX, USA, 2008.
21. Daniel, J.; Gibson, N.; Tarbox, S.; Copeland, A.; Andriescu, A. Effect of long-term ageing on RAP mixtures: Laboratory evaluation of plant-produced mixtures. *Road Mater. Pavement Des.* **2013**, *14* (Suppl. 2), 173–192. [CrossRef]
22. Tapsoba, N.; Benedetto, H.; Sauzeat, C.; Baaj, H.; Ech, M. Behaviour of asphalt mixtures containing reclaimed asphalt pavement and asphalt shingle. *Road Mater. Pavement Des.* **2014**, *15*, 330–347. [CrossRef]
23. Szyller, A.; Król, J.; Bańkowski, W. Współczesne doświadczenia ze stosowania recyklingu na gorąco w wytwórni mieszanek mineralno-asfaltowych w Polsce. *Nawierzchnie Asfaltowe* **2017**, *1*, 12–19. (In Polish)
24. WT-2 2014 Część 1—Mieszanki Mineralno-Asfaltowe—Wymagania Techniczne. General Directorate for National Roads and Motorways, 2014. Available online: https://www.gddkia.gov.pl/userfiles/articles/z/zarzadzenia-generalnego-dyrektor_13901/zalacznik%20do%20zarz%2047.pdf (accessed on 31 December 2017).
25. Bańkowski, W.; Gajewski, M.; Sybilski, D. Analysis of Fatigue Damage on Test Sections Submitted to HVS Loading. *Balt. J. Road Bridge Eng.* **2013**, *8*. [CrossRef]
26. Sybilski, D.; Bańkowski, W.; Horodecka, R.; Czajkowski, P. Laboratoryjna ocena przydatności polimeroasfaltu z dodatkiem gumy do zastosowania w mieszance AC WMS. *Road Eng.* **2014**, *9*, 300–306. (In Polish)
27. Sybilski, D.; Bańkowski, W. Beton o wysokim module sztywności w Polsce. *Drogownictwo* **2011**, *66*, 232–238. (In Polish)
28. Bańkowski, W. Comparison of the conventional and energetic fatigue failure criterion for bituminous mixes. In Proceedings of the International ISAP Symposium, Zurich, Switzerland, 18–20 August 2008.
29. Hunter, R.; Self, A.; Read, J. *The Shell Bitumen Handbook*, 6th ed.; Shell: The Hague, The Netherlands, 2015.
30. Judycki, J.; Jaskuła, P.; Pszczoła, M.; Jaczewski, M.; Ryś, D.; Alenowicz, J.; Dołżycki, B.; Stienss, M. *Katalog Typowych Konstrukcij Nawierzchni Podatnych i Półsztywnych*; General Directorate for National Roads and Motorways/Gdańsk University of Technology: Gdańsk/Warsaw, Poland, 2014.
31. Judycki, J.; Jaskula, P.; Pszczoła, M.; Stienss, M. *Analiza i Projektowanie Konstrukcji Nawierzchni Podatnych i Półsztywnych*; WKiŁ: Warsaw, Poland, 2014.

32. Adhikari, S.; Shen, S. Evaluation of fatigue models of hot-mix asphalt through laboratory testing. *J. Transp. Res. Board* **2009**, *2127*, 36–42. [CrossRef]
33. Corte, J.F. *French Design Manual for Pavement Structures*; SETRA/LCPC: Bagneux, France, 1997.
34. Di Benedetto, H.; de La Roche, C.; Baaj, H.; Pronk, A.; Lundström, R. Fatigue of bituminous mixtures: Different approaches and RILEM group contribution. In *PTEBM'03 6th Rilem Symposium*; Partl, M.N., Ed.; RILEM Publications: Zurich, Switzerland, 2003; pp. 15–38.
35. Bańkowski, W.; Sybilski, D.; Soenen, H.; Gajewski, M.; Chailleux, E. *Binder Testing: Chapter 2 in Advances in Laboratory Testing and Evaluation of Bituminous Materials*; State-of-the-Art Report of the RILEM Technical Committee 206-ATB; Springer: Berlin, Germany, 2012; Volume IX, pp. 15–83.