DOI: 10.7409/rabdim.025.033

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Effect of foamed asphalt on the properties of the asphalt mixture with reclaimed asphalt pavement

Abstract: The paper presents the effects of foamed asphalt modified with synthetic wax (SW_{LC}) and tall oil amidopolyamine (TOA) at 1.5% m/m and 0.4% m/m, respectively, on an asphalt mixture containing reclaimed asphalt pavement (RAP). The experimental plan and research methodology for determining the properties of the innovative foamed asphalt are presented. The design called for a control asphalt mixture using hot mixture technology and containing reclaimed asphalt pavement at 20% m/m, 40% m/m and 60% m/m to mineral aggregate. The asphalt mixture with RAP made with innovative foamed asphalt was produced at temperatures characteristic of HWMA (Half Warm Mix Asphalt) technology. In order to recognise the behaviour of the asphalt mixtures with RAP, innovative foamed asphalt was added to the mixtures as part of the first stage of the study at B_{min} + 0.3%, +0.6%. According to the test plan, their: compactness of air voids V_a, water resistance *ITSR*, indirect tensile strength at –10°C, 0°C, +10°C and +20°C, and resistance to permanent deformation WTS_{AIR} and PRD_{AIR} were evaluated. The results of the study were analysed and the effect of the innovative foamed asphalt on the properties of the assessed mineral and asphalt mixtures containing RAP at 20% m/m, 40% m/m and 60% m/m in relation to the amount of mineral aggregate was assessed. The conclusion of the study is the selection of a recommended asphalt mixture in terms of the amount of RAP for further extended and functional research.

Keywords: asphalt mixture, HWMA technology, innovative foamed asphalt, RAP, physico-mechanical properties.

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1. INTRODUCTION

The dynamic development of Poland since the beginning of the 21st century would not have been possible without the expansion of the road infrastructure, which was initiated by a programme to build motorways and motorways and a network of secondary roads. The beginning of the 21st century was a period of intensive construction of new and upgrading of existing roads. During the upgrading work, during the milling of the asphalt layers, reclaimed asphalt concretes (RAP) were recovered from the road surface, which consists of two valuable materials, aggregate and asphalt binder. It should be noted that they are among the non-renewable material sources. It is therefore essential to reuse such a valuable material as RAP in accordance with the principle of a closed-cycle economy [1-4]. Using it again, its use can ensure sustainability in asphalt road surface construction. It should be noted that RAP is a very valuable material in terms of "energy" because it contains a large amount of energy, which is associated with the extraction of aggregate from rock, the production of asphalt and the manufacture of the -asphalt mixture. Initially, primarily RAP was used during the production of recycled substructures with asphalt emulsion or foamed asphalt [5-10] and to a limited extent for the production of cement concretes [11]. However, due to the valuable nature of RAP as a construction layer material, work has been carried out around the world for several years on the possibility of using it in asphalt mixtures for the upper layers of road surface structures.

Unfortunately, there are technical and technological conditions that significantly limit the possibility of using RAP for new mineral and asphalt mixtures produced using the traditional "hot" technology. Above all, they are related to the batch plants commonly used in Europe and in a large part of the world. This is because RAP cannot be directly combined with new aggregate, because if the material comes into contact with the burner flame, the asphalt contained in the RAP will be burned off, its quality will be reduced and excessive blue smoke will be emitted due to the combustion of the old binder [12]. Therefore, there is a reduction in RAP content during the production of asphalt mixtures in traditional installations, which is caused by the production process, which usually introduces the RAP material at ambient temperature and then there is a process of heating by hot new aggregates. The end result is that the RAP material dries and heats up as a result of the conduction-heat-flow process when the RAP and aggregate come into contact [12-14]. An important factor limiting the widespread implementation of RAP for the production of asphalt mixtures is its high moisture content, which is usually around 7-8% [15]. It adversely affects the process of rendering the new mineral and RAP, causing a slowing down of the production rate as a result of the need to extend its mixing time with the hot new aggregate for the required drying and heating [12], [16]. It is therefore advisable to keep the RAP as dry as possible and, to this end, it should be stored in sheds with a roof. At present, the existing restrictions allow the use of RAP of practically 20% in the composition of the mineral mixture and in special cases up to 30% [12]. To a lesser extent, there are restrictions on the amount of RAP used in drum mixer, which, 30% limit in the new mineral mixture in cyclic operations, multidirectional work is being carried out on however, are not widely used [17]. In order to enable increasing the content of RAP above the possibility of heating it or using alternative technologies for the production of mineral and asphalt mixtures.

A very important technological issue is to ensure that the asphalt mixture produced with the RAP similar or even more favourable physical and mechanical properties compared to the control mixture [18], which should ensure the required service life of the RAP. A significant factor in this aspect is the homogeneity of the reclaimed asphalt road surface [19], particularly in terms of the content and properties of the reclaimed asphalt binder. With the increase in the content of RAP in the new asphalt mix, the role of reclaimed asphalt binder becomes more important. This is all the more so as it has been subject to technological and operational ageing processes [20-21] which can increase the stiffness of the new asphalt mix. Therefore, the use of recycled asphalt may cause concerns about the properties of the new asphalt mixture with the addition of RAP. In order to counteract these effects of reclaimed asphalt, regenerative additives are used to improve the viscoelastic properties of reclaimed asphalt [22-24]. Studies have shown that the effect of these additives can be both positive, improving the fatigue life of the asphalt mixture [22], [24], and possibly negative [25].

One solution to the problems presented could be the use of water-foamed asphalt to render the asphalt mixture with an increased amount of RAP. Thanks to its characteristics, water-foamed asphalt enables the production of asphalt mixtures at temperatures between 100°C and 130°C [26-31], in addition, the moisture contained on the surface of the mineral aggregate/RAP is not a negative factor, but contributes to further foaming of the asphalt. The reduced production temperature of the foamed asphalt mixture also does not require the new aggregate to be heated to a high temperature. The negative effect of moisture contained in the RAP is also eliminated. In addition, the research carried out into the use of special additives in the asphalt prior to its foaming with water ensures high foaming parameters for the binder [32-34], which results in a very good environment for the new aggregate and RAP. The high quality of the mineral and asphalt mixture produced is guaranteed. Reducing the production temperature of the asphalt mixture also has a measurable economic as well as environmental effect as a result of reduced greenhouse gas emissions, particularly CO_2 [35-36]. Tests carried out on asphalt with the addition of tall oil amidopolyamines (TOA) and a synthetic wax with a reduced SW_{LC} carbon footprint produced a foamed asphalt with very high foaming characteristics and limited binder ageing. Studies carried out have also shown that the use of this type of binder has a regenerative effect on asphalt recovered from RAP [37-38]. The developed water-modified foamed asphalt is a binder dedicated to the production of asphalt mixtures with more than 30% RAP content at reduced production temperatures, while ensuring the required physical and mechanical properties.

2. METHODOLOGY AND MATERIALS

2.1. FOAMED ASPHALT

The study used 50/70 asphalt, which was foamed with water. Prior to foaming, LC synthetic wax SW_{LC} with a reduced carbon footprint [39] and tall oil amidopolyamine (TOA) [40] were dosed into the binder at 1.0%, 1.5%, 2.0% and 2.5% and 0.0%, 0.2%, 0.4%, and 0.6% by weight of the asphalt, respectively. The properties of the asphalt additives used are summarised in Table 1 and Table 2.

Table 1. Essential characteristics of SW_{LC} synthetic wax [39]

Property	Unit	Value
Colour	–	white, yellowish
Flash point	°C	285
Solidification temperature	°C	95
Density at 25°C	Mg/m³	0.9
Molecular weight	g/mol	approx. 1,000

Table 2. Essential characteristics *TOA* [40]

Property	Unit	Value
Appearance	–	brown liquid
Density at 20°C	Mg/m³	0.88-0.98
Dynamic viscosity at 20°C Brookfield Spindle SC 4-183	mPa · s	3000
Solidification temperature	°C	<0
Flash point	°C	>218

On the basis of the research carried out, the optimum amounts of additives to ensure the most favourable characteristics of the foamed binder and its basic and rheological properties were determined. The SW_{LC} synthetic wax content is 1.5% and the tall oil amidopolyamine content is 0.4% by weight of the binder, respectively. The foaming characteristics of the 50/70 asphalt with the optimum amount of SW_{LC} and *TOA* are shown in Fig. 1. They were determined based on previous and control exploratory foaming tests of the 50/70 asphalt with SW_{LC} additions of 1.0%, 1.5%, 2.5%, and 3.0%, and *TOA* additions of 0.0%, 0.2%, 0.4%, and 0.6%, with water additions ranging from 1.5% to 2.5% [32].

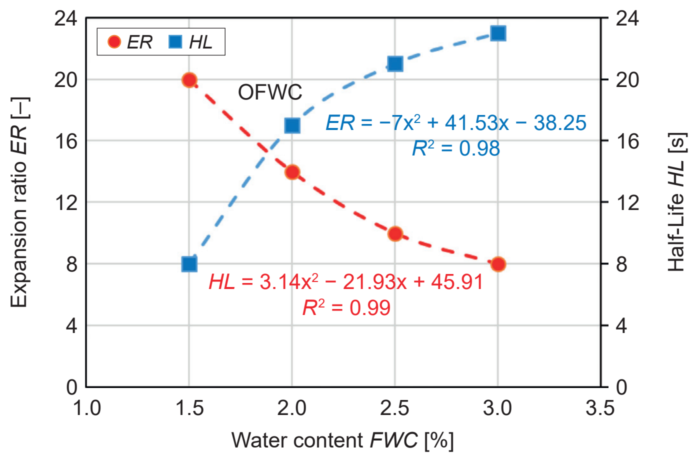

Fig. 1. Foaming characteristics of asphalt 50/70 with optimal amount of SW_{LC} and *TOA*

However, the properties of the 50/70 foamed asphalt with the optimum amount of SW_{LC} and *TOA* are summarised in Table 3, which also gives the properties of the binder after asphalt foam breakdown.

The spectrogram of 50/70 asphalt with optimum WMA additive contents before foaming and after RTFOT and RTFOT + PAV ageing is shown in Fig. 2.

The values of indices $I_{c=o}$, $I_{s=o}$ and $I_{c=c}$ are summarised in Table 4.

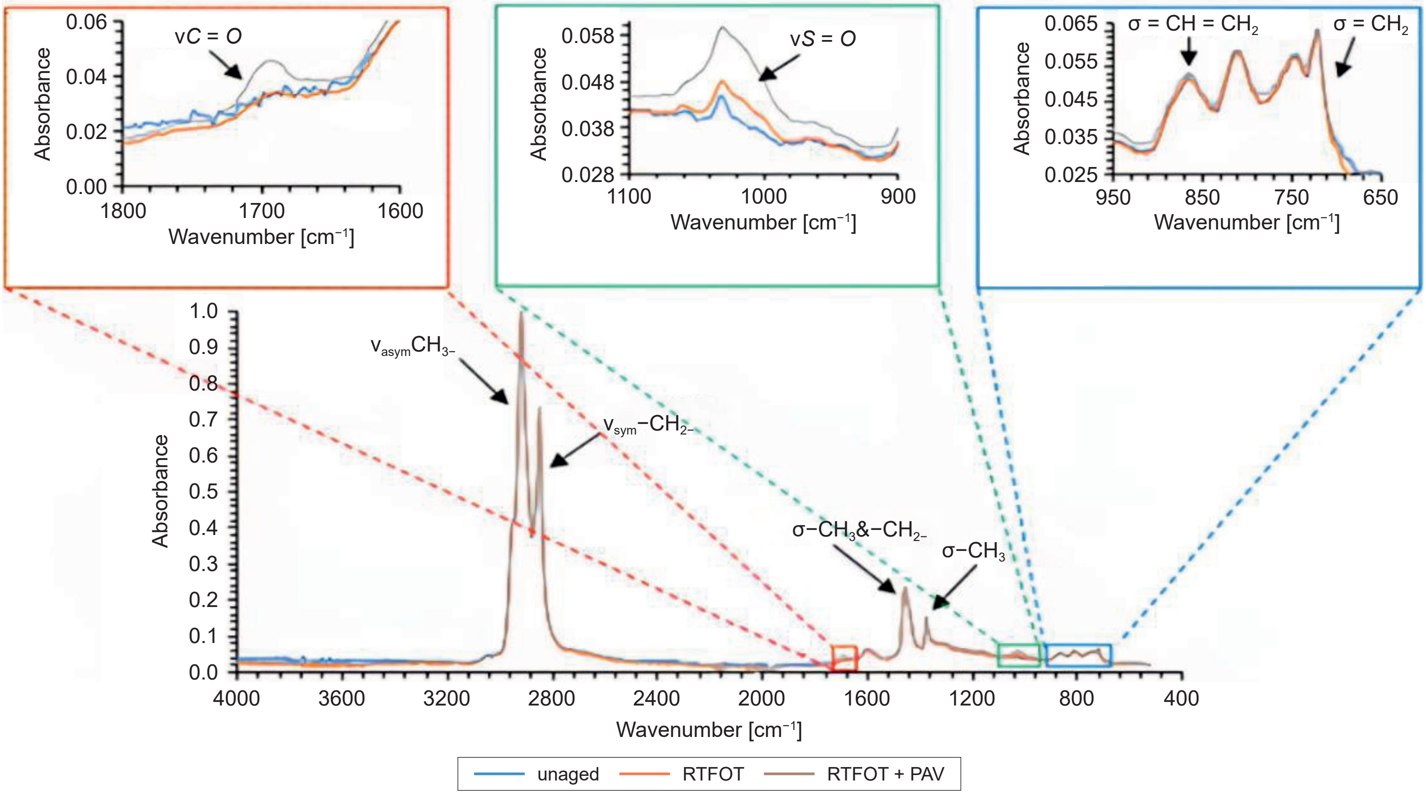

Fig. 2. FTIR spectrogram of 50/70 foamed bitumen with an optimum concentration of 1.5% SW_{LC} synthetic wax and 0.4% *TOA* tall oil amidopolyamine by weight of bitumen

Table 3. Performance of foamed asphalt with optimal amount of SW_{LC} and *TOA*

Characteristics	Unit	Value	Requirements
Maximum expansion of *ER*	–	16.6	Wirtgen [39]
Half-life of *HL*	s	14.4	Wirtgen [39]
Penetration at 25°C	0.1 mm	49.4	PN-EN 1426
Softening temperature	°C	56.6	PN-EN 1427
Modulus of rigidity *Sm* at temperature:	MPa		PN-EN 14771
−10°C		105	
−16°C		204	
−22°C		421	
Creep rate m_{value} at temperature:	–		
−10°C		0.327	
−16°C		0.290	
−22°C		0.276	

Table 4. Values of $I_{c=o}$, $I_{s=o}$ and $I_{c=c}$ indices for foamed asphalt with optimal amount of SW_{LC} and *TOA*

Index	Type of ageing		
	Unaged	RTFOT	RTFOT + PAV
Corbonyl $I_{c=o}$	0.0015	0.0024	0.0060
Sulfoxide $I_{s=o}$	0.0018	0.0025	0.0074
Aromaticity $I_{c=c}$	0.0122	0.0126	0.0135

2.2. DESIGN OF MINERAL AND ASPHALT MIXTURE WITH RAP

For the study, an AC 16W asphalt mixture was designed for the binder course of a road surface structure loaded with KR3-4 traffic according to WT-2 2014 [42]. Aggregates from the Świętokrzyskie Mountains were used in the mineral mix. Devonian limestone aggregate with grain sizes of 0/2 mm, 2/8 mm and 8/16 mm and 0/2 quartzite sandstone aggregate and limestone mineral meal were used. The grain size of the control AC 16W asphalt mixture is shown in Fig. 3.

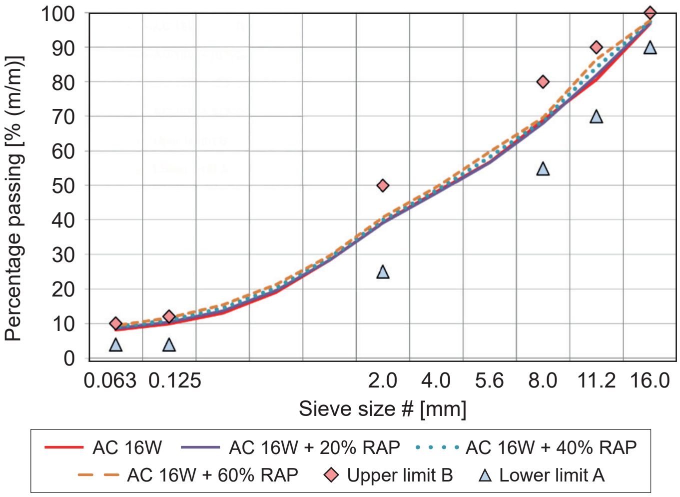

Fig. 3. Design AC 16W asphalt mixtures without and with RAP

A 50/70 asphalt was used to design the AC 16W asphalt mixture in the traditional "hot" technology. The asphalt content B_{min} = 4.5% was determined. The type tests performed for the AC 16W asphalt mixture in accordance with WT-2 2014 are summarised in Table 5.

Subsequently, mineral mixtures containing 20%, 40% and 60% RAP were designed based on the control mineral mixture AC 16W. The asphalt content of the RAP was 4.7%. The mineral mixtures were designed to have a similar grain size curve (Fig. 3), which should ensure that the asphalt mixtures made with them have similar air voids content. This will make it possible to assess the impact of the amount of RAP used in AC 16W asphalt mixtures using the developed innovative water-foamed asphalt with SW_{LC} and *TOA*. The total amount of asphalt in the AC 16W asphalt mixtures with RAP was B_{min} = 4.5%, and included innovative foamed asphalt and asphalt recovered from RAP (Table 6).

The control mixture with asphalt 50/70 produced using conventional technology was compacted at 135°C. In contrast, asphalt mixtures with RAP and innovative foamed asphalt at 100°C according to HWMA technology with foamed asphalt [43]. The RAP dosing temperature was determined experimentally, guided by the principle of achieving homogeneity in the HWMA asphalt mixture.

Table 5. Properties of the AC 16W asphalt mixture

Properties	Unit	Category	Value	Standard
Air voids content in MMA, V_a	% (v/v)	$V_{min4.0}$ $V_{max7.0}$	5.2	PN-EN 12697-8
Water resistance, *ITSR*	%	$ITSR_{80}$	92.8	PN-EN 12697-12 Annex no. 1 to WT-2 p.1.
Resistance to permanent deformation:				PN-EN 12697-22
WTS_{AIR}	mm/10³ cycles	$WTS_{AIR0.15}$	0.108	
PRD_{AIR}	%	$PRD_{AIR7.0}$	6.2	

Table 6. Composition of the AC 16W asphalt mixture with RAP

Materials	Composition [% (m/m)]							
	Reference AC 16W		AC 16W + 20% DA		AC 16W + 40% DA		AC 16W + 60% DA	
	MM	MMA	MM	MMA	MM	MMA	MM	MMA
Limestone filler	4.0	3.8	3.0	2.9	2.0	1.9	1.0	0.9
Fine aggregate, 0/2, quartz sandstone	18.0	17.2	15.0	14.3	12.0	11.5	10.0	9.6
Fine limestone aggregate, 0/2	18.0	17.2	15.0	14.3	13.0	12.4	10.0	9.6
Coarse limestone aggregate, 2/8	25.0	23.9	16.0	15.3	8.0	7.6	–	–
Coarse limestone aggregate, 8/16	35.0	33.4	31.0	29.6	25.0	23.9	19.0	18.1
RAP	–	–	20.0	19.1	40.0	38.2	60.0	57.3
Orlen 50/70	–	4.5	–	4.5 3.6 + 0.9*)	–	4.5 2.6 + 1.9*)	–	4.5 1.7 + 2.8*)
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

*) asphalt recovered from RAP

2.3. RESEARCH METHODOLOGY

The research plan developed consisted of two phases. The first involved a study of the effect of innovative foamed asphalt on the properties of asphalt recovered from RAP.

The change in the following properties of the recovered asphalt was analysed:

- penetration Pen at 25°C according to EN-PN 1426,
- softening temperature $T_{R\&B}$ in accordance with EN-PN 1427,
- viscosity η at 60°C, 90°C and 135°C according to EN-PN 13302,
- blanc curves according to EN-PN 14770.

The PAV ageing process, which characterises changes in the binder over the life of the asphalt road surface, was also included in the study of the binder combination properties. The study was carried out on nine samples [44].

The second stage of the study involved an AC 16W asphalt mixture with RAP at 20%, 40% and 60% in the mineral mixture composition. In view of the fact that there is a lack of research on asphalt mixtures with RAP made with foamed asphalt, the research was extended to include total asphalt content B_{min} + 0.3% and +0.6% by weight of the binder.

The test programme for the asphalt mixture with RAP included the determination of the following properties:

- air void content V_a [%] according to EN-EN 12697-8,
- water sensitivity *ITSR* [%] according to EN-PN 12697-12, Annex 1 to WT-2 p.1,
- resistance to permanent deformation according to EN-PN 12697-26:
  - WTS_{AIR} [mm/103 cycles],
  - PRD_{AIR} [%],
- indirect tensile strength *ITS* according to EN-PN 12697-23, at −10°C, 0°C, +10°C and +20°C.

The results obtained were statistically analysed to determine their reliability and to determine the significance of the effect of the innovative foamed asphalt on the properties of the binder obtained from asphalt recovered from the RAP and the properties of the asphalt mixtures with RAP using ANOVA analysis of variance [44, 45]. The results of the study were visualised using Statistica softwear [46].

3. RESULTS OF THE STUDY AND DISCUSSION OF THE FINDINGS

3.1. INFLUENCE OF FOAMED ASPHALT ON THE PROPERTIES OF ASPHALT RECOVERED FROM RAP

The essential characteristics of asphalt recovered from RAP are summarised in Table 7.

Table 7. Essential characteristics of asphalt recovered from RAP

Characteristics	Unit	Value	Requirements
Penetration *Pen* at 25°C	0.1 mm	15.7	PN-EN 1426
Softening temperature $T_{R\&B}$	°C	68.8	PN-EN 1427

Due to the fact that 20%, 40% and 60% of the RAP was used in the asphalt mixtures, so the composition of the binder in the asphalt mixtures was as follows:

- asphalt mixtures with 20% RAP: −3.6% foamed asphalt +0.9% recycled asphalt (L 20),
- asphalt mixtures with 40% RAP: −2.6% foamed asphalt +1.9% recycled asphalt (L 40),
- asphalt mixtures with 60% RAP: −1.7% foamed asphalt +2.8% recycled asphalt (L 60).

The effect of foamed asphalt on the penetration and softening point of the binder with asphalt recovered from RAP is shown in Fig. 4.

Based on the analysis of the characteristics shown in Fig. 4, it can be concluded that the use of an innovative foamed asphalt containing 1.5% SW and 0.4% *TOA* for both penetration at 25°C (Fig. 5a) and softening temperature (Fig. 5b) has a positive effect on the properties of the binder containing foamed asphalt and asphalt recovered from RAP. Innovative foamed asphalt contributes to the rejuvenation of asphalt recovered from RAP. At the same time, the intensity of the impact depends on its quantity in the binder used in the tests. The PAV ageing process of the binder adversely affects penetration at 25°C and the softening temperature. In general, the more asphalt recovered from the RAP in the binder tested, the lower the recovery of its properties. Analysing from a quantitative aspect the asphalt content of the RAP in the tested binder, it can be concluded that a practically limiting value is its content of up to 40%, for which the rejuvenation effect is still significant.

The effect of the innovative foamed asphalt on the dynamic viscosity at 60°C, 90°C and 135°C of the asphalt recovered from the RAP was then analysed (Fig. 5).

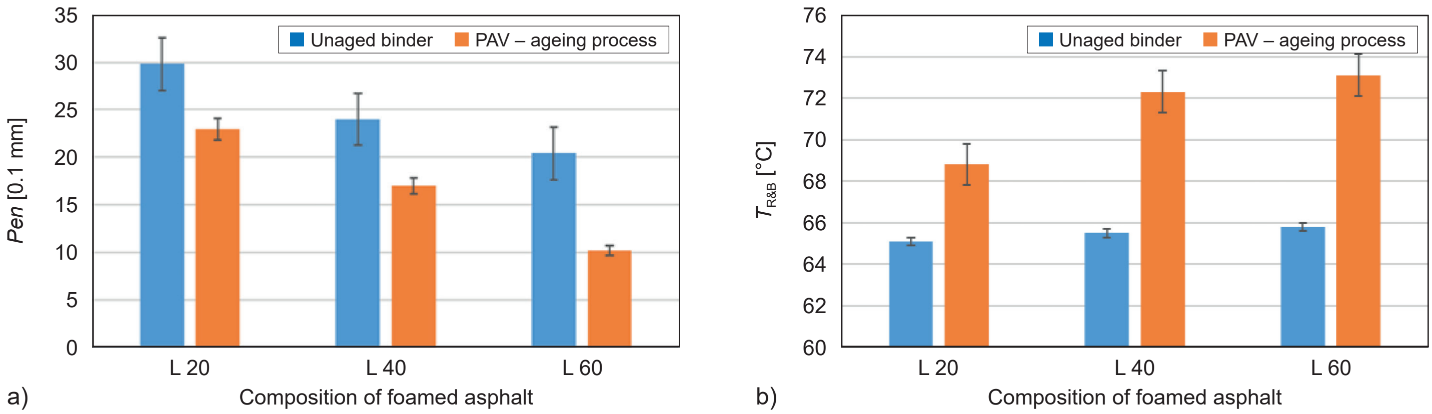

Fig. 4. Influence of foamed asphalt on penetration and softening point of binder with asphalt recovered from RAP: a) penetration *Pen* at 20°C, b) softening point $T_{R\&B}$

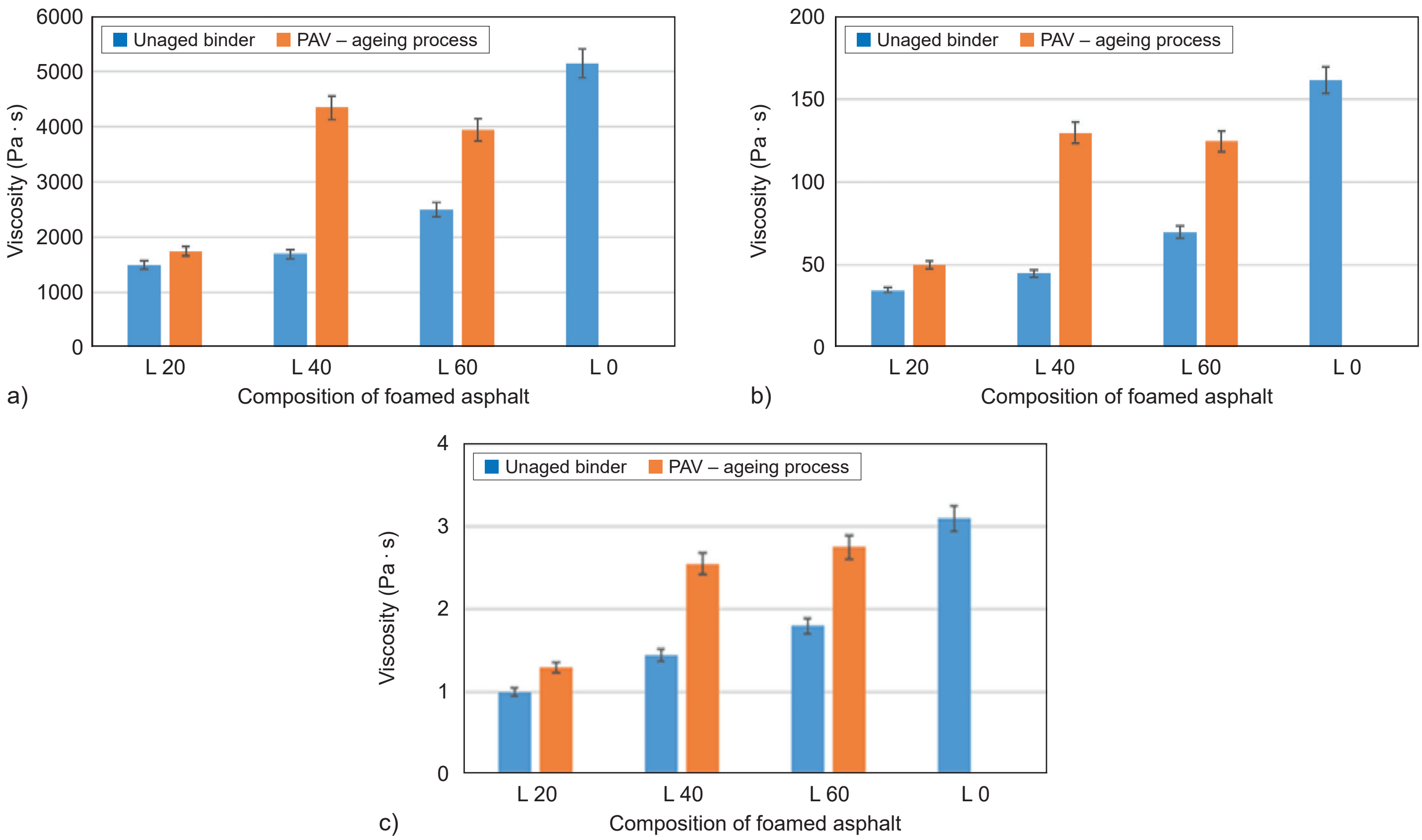

Fig. 5. Results of dynamic viscosity tests of the analysed asphalt binders at: a) 60°C, b) 90°C, c) 135°C

Based on the analysis of the tested asphalt binders shown in Fig. 5, it can be concluded that the use of innovative foamed asphalt in the formulation of the tested binders similarly influences the rejuvenation of the asphalt from the RAP in terms of penetration at 25°C and softening temperature. The use of innovative foamed asphalt has the effect of lowering the viscosity of the binders tested in the experiment. They will thus surround the aggregate and RAP grains more efficiently when the AC 16W asphalt mixture is rendered. As the amount of asphalt recovered from the RAP increases, the rejuvenating effect of the innovative foamed asphalt is reduced regardless of the temperature of the viscosity test. It should be noted that the aging process of PAV has a negative effect on the developed binder consisting of RAP and innovative foamed asphalt regardless of their proportional content and test temperature. Taking into account the rejuvenating effect of the innovative foamed asphalt for the unaged and post-PAV binder under development, it can be assumed that 40% of the asphalt recovered from the RAP in its formulation is the borderline value.

Black's curves were drawn from the oscillation tests performed on the binders in the DHR rheometer. Fig. 6 shows the Black curve for the asphalt recovered from the RAP. On the other hand, Fig. 7, Fig. 8 and Fig. 9 show the Black curves for a binder containing innovative foamed asphalt and asphalt recovered from RAP in the following proportions of 80% : 20%, 60% : 40% and 40% : 60%, respectively.

By analysing Black's curves showing the dependence of the binder's composite modulus in terms of the phase shift angle, it is clear that the innovative foamed asphalt has a positive effect on the asphalt from the RAP and the developed binder. A particularly favourable effect of the innovative foamed asphalt can be seen in the case of the 20% asphalt content of the RAP in the binder under development, which can be judged by the fore-run and curvature of the characteristics shown in Fig. 6 compared with those of the RAP in Fig. 7. As the asphalt content of the RAP increases to 40% and 60% in the developed binder, the rejuvenating effect of the innovative foamed asphalt decreases, the characteristics of the Black curve becoming similar to that shown in Fig. 6. The ageing process of PAV adversely affects the course of the analysed Black characteristics of the tested binders (innovative foamed asphalt + asphalt from the RAP), but they are still more favourable than those presented for asphalt recovered from the RAP (Fig. 6). It should be noted that the Black curves for the developed binder containing 40% and 60% asphalt from the RAP are close to each other.

In summary, the rejuvenating effect of the innovative foamed asphalt with the addition of 1.5% synthetic wax and 0.4% tall oil amidopolyamine is observed up to a compactness of 40% of the recovered asphalt in the composed binder.

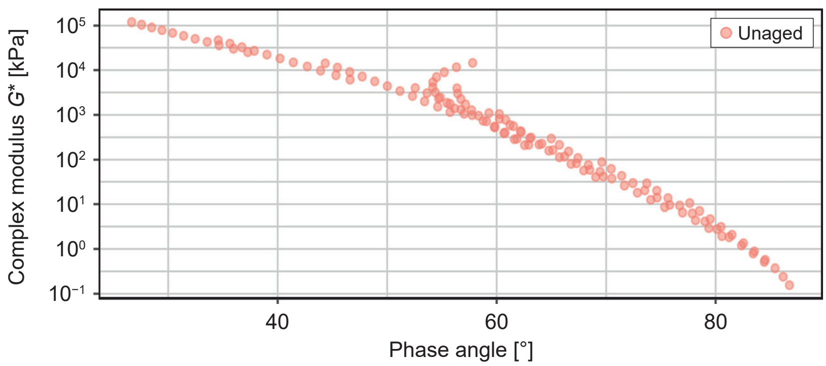

Fig. 6. Black curves for asphalt binder recovered from RAP

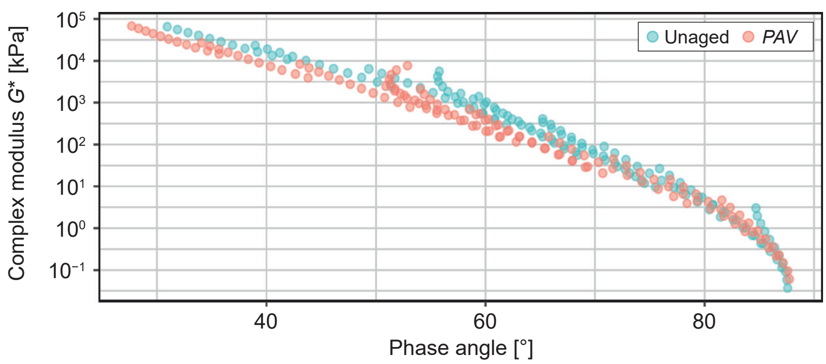

Fig. 7. Black curves for an asphalt binder of composition:
80% innovative foamed bitumen 50/70 and 20% binder recovered from RAP

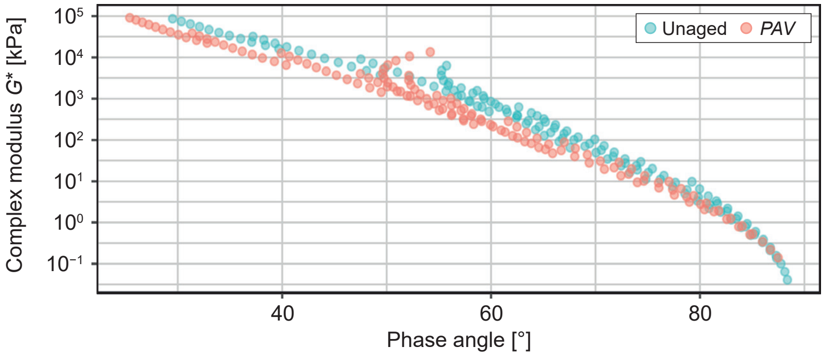

Fig. 8. Black curves for an asphalt binder of composition:
60% innovative foamed asphalt and 40% binder recovered from RAP

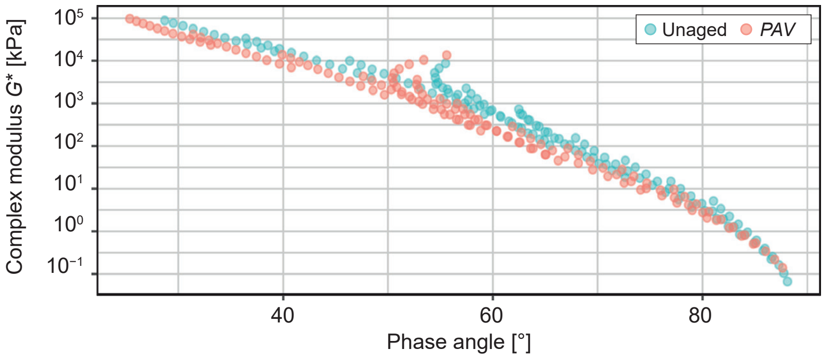

Fig. 9. Black curves for an asphalt binder of composition:
40% innovative foamed bitumen 50/70 and 60% binder recovered from RAP

3.2. INFLUENCE OF FOAMED ASPHALT ON THE PROPERTIES OF THE ASPHALT MIXTURE WITH RAP

The basic parameter of an asphalt mixture on which all its other characteristics depend is the air void content V_a (%). It shapes the water susceptibility *ITSR* and the resistance to the formation of permanent deformations characterised by the WTS_{AIR} and PRD_{AIR} parameters. The first phase of the research has just analysed the effect of the RAP content of the AC 16W asphalt mixture using innovative foamed asphalt.

The effect of the amount of RAP on the void content V_a of the AC 16W asphalt mixture with innovative foamed asphalt is shown in Fig. 10.

The air voids content of the AC 16W asphalt mixture should be between 4% and 7% according to WT-2 [40]. By analysing the V_a characteristics shown in Fig. 10, it can be seen that practically only for B_{min} does the void content meet this criterion, regardless of the amount of RAP in the asphalt mixture. Increasing the binder content to B_{min} + 0.3% and +0.6% has the effect of significantly reducing the void content, which is the result of overfilling by the binder. The use of an RAP in the range of 20% to 40% in the asphalt mixture results in a slight reduction in the void content compared to the control asphalt mixture. This is most likely the result of the effect of the foamed asphalt on the very good surrounding of the aggregate grains and the RAP with the binder [9], which ensures improvements in the compaction of the asphalt mixture. In the asphalt mixture containing 60% RAP, there was a slight increase in void content, most likely caused by the excessive use of recycled asphalt, which increased the binder's viscosity and hindered compaction at low temperatures.

Another parameter analysed for the AC 16W asphalt mixture with RAP was the susceptibility to water impact characterised by the *ITSR* index in terms of the innovative foamed asphalt content, which is shown in Fig. 11.

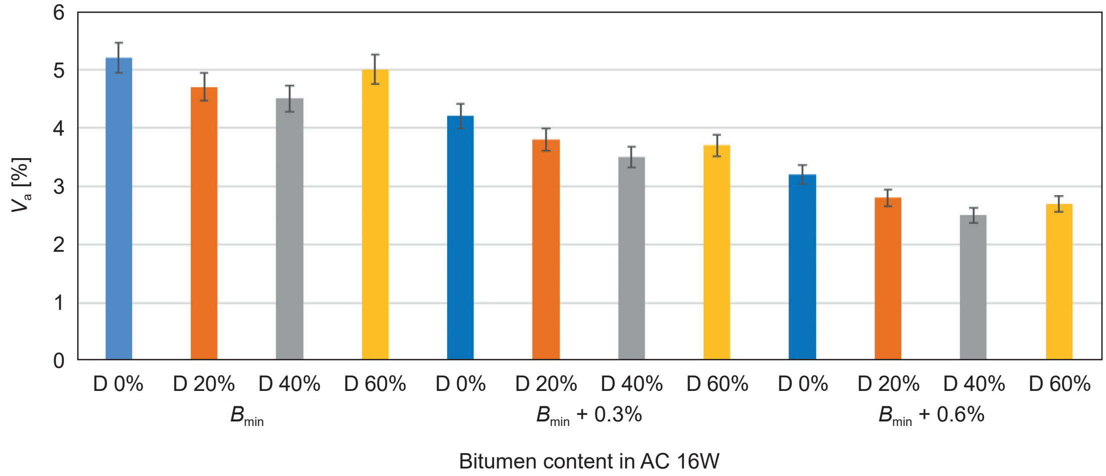

Fig. 10. Influence of the binder on the voids content V_a in the asphalt mixture in terms of the quantity of RAP (D)

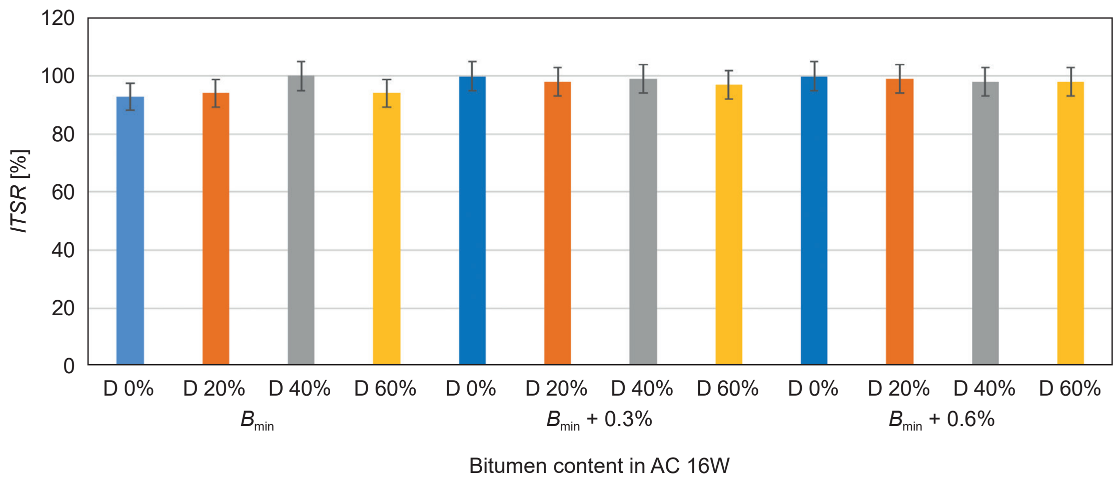

Fig. 11. Influence of the binder on the effect of *ITSR* water in the asphalt mixture in terms of the amount of RAP (D)

Analysis of the results shown in Fig. 11 indicates that as the amount of asphalt recovered from RAP and the amount of binder (innovative foamed asphalt + asphalt recovered from RAP) in the asphalt mixtures increases, the *ITSR* parameter practically approaches 100%. It can be concluded that, by the same token, the AC 16W asphalt mixtures with RAP used behave in the same way as hot-mixed asphalt when the bitumen quantity is increased to B_{min} + 0.6%.

A very important parameter of asphalt mixtures is their resistance to the formation of permanent deformations characterised by the WTS_{AIR} and PRD_{AIR} parameters, which are shown in Fig. 12 and Fig. 13.

The analysis of the rut growth rate parameter WTS_{AIR} presented in Fig. 12 shows that increasing the total binder content of the tested AC 16W asphalt mixtures with RAP above B_{min} results in a significant increase in the value of the analysed characteristic and its permissible value of 0.15 mm/10^3 cycles is exceeded. Only asphalt mixtures with a total binder content of B_{min} meet the criterion for an acceptable WTS_{AIR} limit. It should be noted that the use of innovative foamed asphalt and asphalt recovered from RAP in the binder composition has a positive effect on the value of the WTS_{AIR} parameter. Which is most likely due to the stiffening role of the asphalt from the RAP. The rut growth rate in asphalt mixtures containing 20%, 40%, and 60% RAP is lower than in the control mixture made with 50/70 hot-mix asphalt.

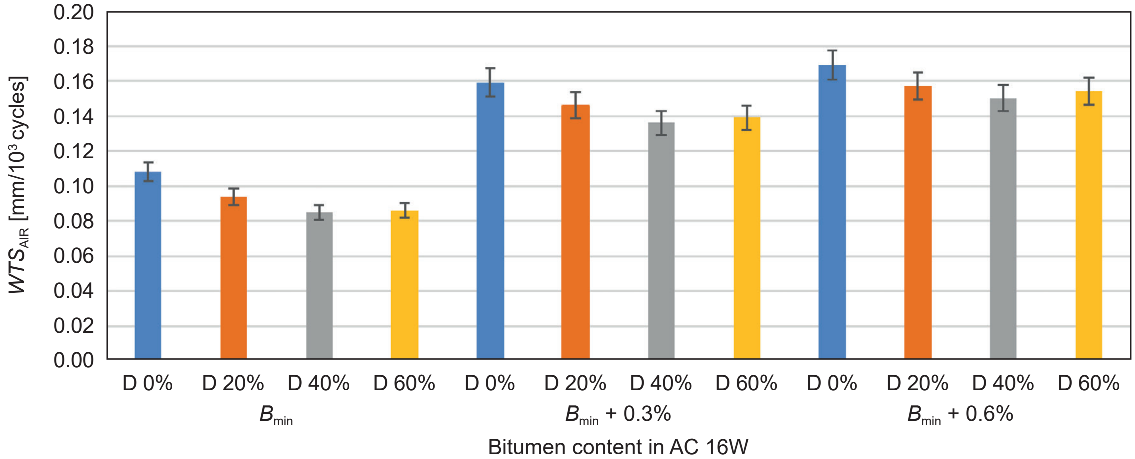

Fig. 12. Influence of the binder on the resistance to permanent deformation of WTS_{AIR} in an asphalt mixture in terms of the amount of RAP (D)

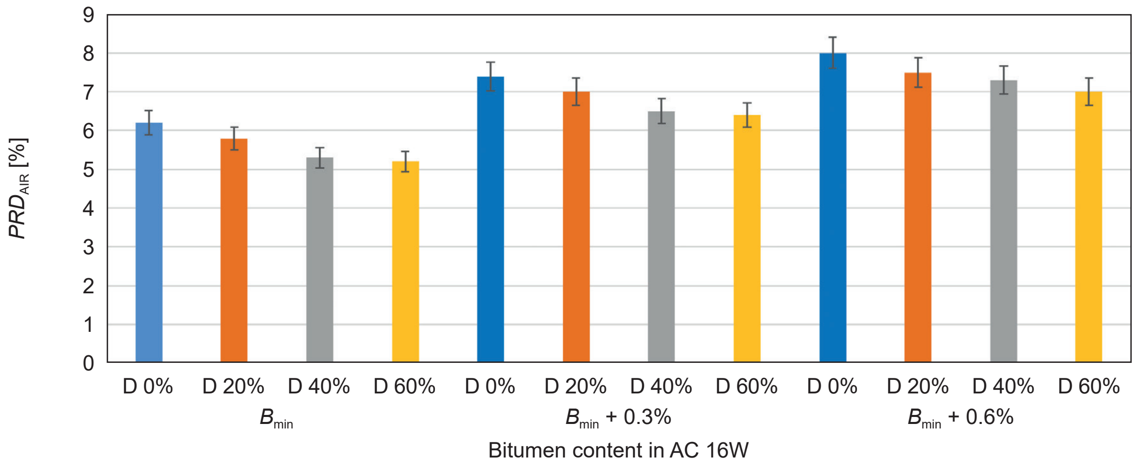

Fig. 13. Influence of the binder on the resistance to permanent deformation of PRD_{AIR} in an asphalt mixture in terms of the amount of RAP (D)

A similar trend to WTS_{AIR}, is found for the PRD_{AIR} parameter of the analysed asphalt mixtures with RAP. With a total binder content of B_{min}, the limit value of 7.0% for the analysed parameter is exceeded for practically all asphalt mixtures. On the other hand, in terms of B_{min} in asphalt mixtures, the beneficial effect of the use of an innovative foamed asphalt that renews the asphalt from the RAP. However, as the proportion of recycled asphalt increases relative to the innovative foamed asphalt, the stiffening effect of the aged asphalt from the RAP becomes apparent.

Another parameter analysed is the indirect tensile strength *ITS* of the AC 16W asphalt mixture containing RAP and foamed asphalt determined in accordance with PN-EN 12697-23:2017-12 in terms of test temperatures, which is shown in Fig. 14.

The test results shown in Fig. 14 indicate that there is an increase in the indirect tensile strength of the AC 16W asphalt mixture as the test temperature decreases. And increasing the binder content of the asphalt mixture has the effect of reducing the indirect tensile strength in the temperature range +10°C and +20°C. In contrast, a reduction in intermediate tensile strength is observed across the binder dosage range at −10°C and 0°C at 20% and 40% RAP, respectively, due to the use of an innovative foamed binder containing 1.5% synthetic wax and 0.4% *TOA*. On the other hand, there is an increase in the intermediate tensile strength values of AC 16W at a content of 60% of the RAP, which may be a consequence of the fact that asphalt recovered from the RAP and not the innovative water-foamed binder plays a predominant role in the total binder content of the asphalt mixture.

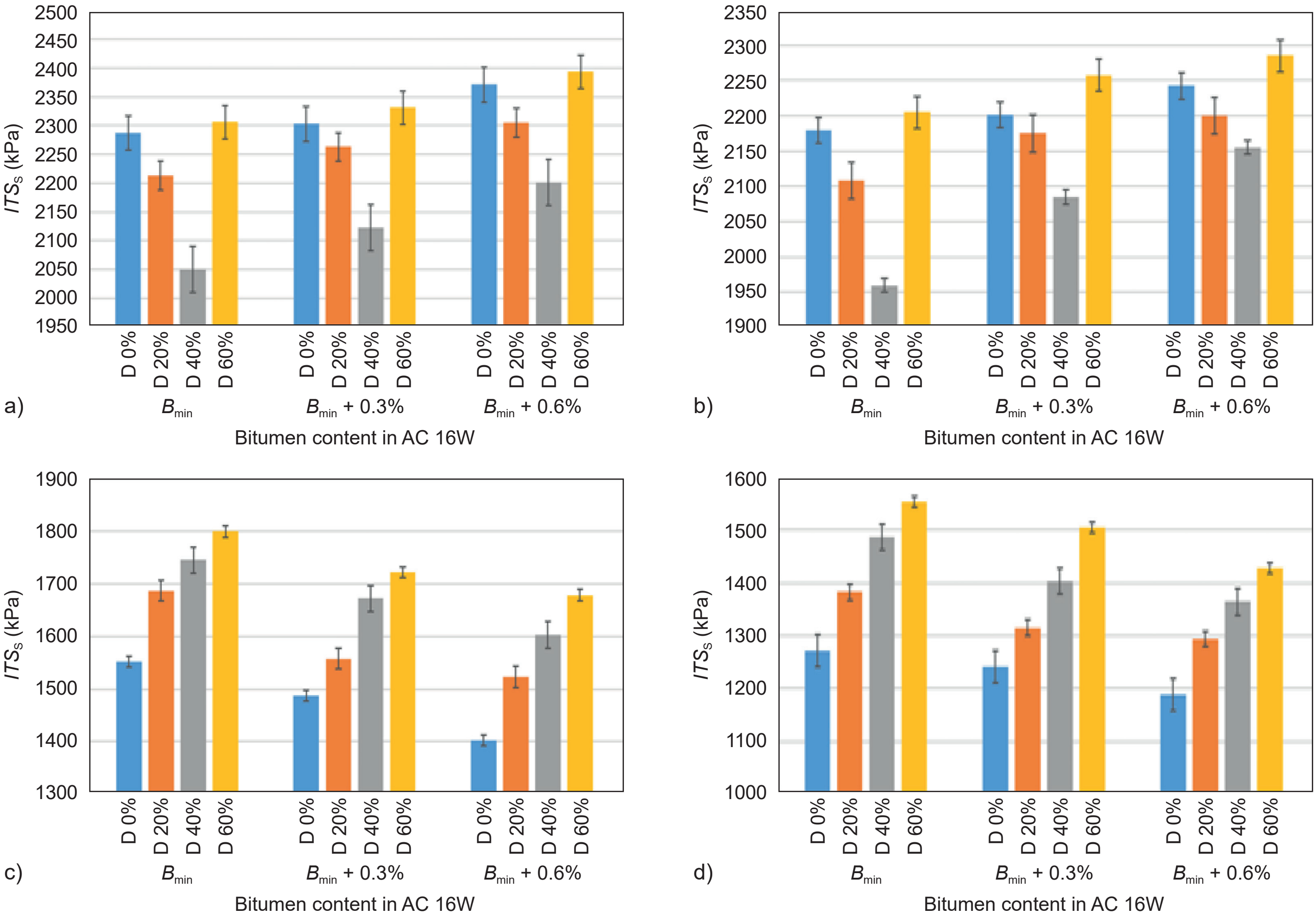

Fig. 14. Indirect tensile strength *ITS*s of the asphalt mixture with RAP (D) at: a) −10°C, b) 0°C, c) +10°C, d) +20°C

In summary, it can be concluded that the most favourable indirect tensile strength of *ITS*s in the temperature range −10°C to +20°C is characterised by the asphalt mixture containing 40% RAP as compared to the control at B_{min} content. In the temperature range −10°C and 0°C the indirect tensile strength of this asphalt mixture is more than 10% lower than the indirect tensile strength of control asphalt mixture with 50/70 asphalt. Thus, it will be more resistant to the cracking process. However, in the temperature range +10°C and +20°C, its indirect tensile strength is more than 10% higher than that of the control A mix, which will ensure that the road surface made from it will last longer in the summer temperature range.

4. CONCLUSIONS

On the basis of the studies carried out on the effect of foamed asphalt with the addition of 1.5% synthetic wax and 0.4% tall oil amidopolyamine on the properties of the AC 16W asphalt mixture with RAP, the following conclusions can be drawn:

1. Innovative foamed asphalt has a rejuvenating effect on the properties of asphalt recovered from RAP. The intensity of its impact depends on the amount of bitumen recovered and decreases as its proportion in the composed binder increases. The most favourable binder composition contains 60% innovative foamed asphalt and 40% recycled asphalt.
2. The developed asphalt mixture containing RAP and an innovative binder composition behaves in the same way when increasing the binder quantity above B_{min} as a traditional hot asphalt mixture.
3. The innovative foamed asphalt combined with asphalt recovered from RAP at B_{min} yields more favourable

basic physical and mechanical properties for the asphalt mixture than for the traditional asphalt mixture.

4. The use of innovative foamed asphalt ensures that the required parameters of the asphalt mixture with RAP are achieved at the reduced compaction temperature of 100°C.

The positive results obtained for the basic physico-mechanical properties of the asphalt mixture with RAP and innovative foamed asphalt indicate the need for further research into its complex rheological parameters. Obtaining a comprehensive study will indicate the potential feasibility of implementing this type of asphalt mixture into road practice.

ACKNOWLEDGEMENTS

The authors would like to thank the National Centre for Research and Development for funding the research under the LIDER XIII grant project No. 0068/L-13/2022.

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Efekt oddziaływania asfaltu spienionego na właściwości mieszanki mineralno-asfaltowej z destruktem asfaltowym

Streszczenie: W referacie przedstawiono wpływ asfaltu spienionego modyfikowanego woskiem syntetycznym (SW_{LC}) i amidopolaminą oleju talowego (TOA) odpowiednio w ilości 1,5% m/m i 0,4% m/m na mieszankę mineralno-asfaltową z destruktem asfaltowym. Przedstawiono plan eksperymentu oraz metodykę badawczą dotyczącą oznaczenia właściwości innowacyjnego asfaltu spienionego. Projekt zakładał wykonanie kontrolnej mieszanki mineralno-asfaltowej w technologii „na gorąco" oraz zawierającej destrukt asfaltowy w ilości 20% m/m, 40% m/m i 60% m/m w stosunku do kruszywa mineralnego. Mieszankę mineralno-asfaltową z destruktem asfaltowym wykonaną z innowacyjnym asfaltem spienionym wytwarzano w temperaturze charakterystycznej dla technologii HWMA (ang. Half Warm Mix Asphalt). W celu rozpoznania zachowania mieszanek mineralno-asfaltowych w destruktem w ramach pierwszego etapu badań dodawano do nich innowacyjny asfalt spieniony w ilości B_{min} + 0,3%, +0,6%. Zgodnie z planem badań dokonano oceny ich: zwartości wolnych przestrzeni V_a, odporności na oddziaływanie wody *ITSR*, wytrzymałość na pośrednie rozciąganie w temperaturze −10°C, 0°C, +10°C i +20°C oraz odporność na deformacje trwałe WTS_{AIR} i PRD_{AIR}. Dokonano analizy wyników badań i oceniono wpływ innowacyjnego asfaltu spienionego na właściwości ocenianych mieszanek mineralno-asfaltowych zawierających destrukt asfaltowy w ilości 20% m/m, 40% m/m i 60% m/m w stosunku do ilości kruszywa mineralnego. Podsumowaniem pracy jest wybór rekomendowanej mieszanki mineralno-asfaltowej w aspekcie ilości destruktu asfaltowego do dalszych rozszerzonych i funkcjonalnych badań.

Słowa kluczowe: innowacyjny asfalt spieniony, mieszanka mineralno-asfaltowa, RAP, technologia HWMA, właściwości fizyko-mechaniczne.