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ASSESSMENT OF CRACK PROPAGATION RESISTANCE IN SMA MIXTURES WITH RECLAIMED ASPHALT PAVEMENT

OCENA ODPORNOŚCI NA PROPAGACJĘ SPĘKAŃ MIESZANEK SMA Z GRANULATEM ASFALTOWYM

STRESZCZENIE. Konieczność okresowej wymiany warstw ścieralnych w tym z mieszanek typu SMA wiąże się z możliwością pozyskania i ponownego wykorzystania wysokiej jakości destruktu asfaltowego. Dotychczas problem stosowania destruktu oraz granulatu asfaltowego do mieszanek typu SMA nie był przedmiotem szerokich analiz i badań. Wdrażanie zasad gospodarki o obiegu zamkniętym wymusi w najbliższym czasie upowszechnienie stosowania granulatu asfaltowego również do mieszanek typu SMA. W procesie wymiany warstwy ścieralnej nowa mieszanka mineralno-asfaltowa układana jest na istniejącej warstwie wiążącej, w której na skutek wcześniejszej eksploatacji mogą występować m.in. mikrospękania, które w okresie dalszego użytkowania nawierzchni będą propagować również do nowo wykonanej warstwy ścieralnej. Mieszanka SMA powinna zatem charakteryzować się odpornością na propagację spękań z niższych warstw asfaltowych. Zastosowanie w mieszance SMA materiału z recyklingu, zawierającego postarzone lepiszcze asfaltowe może przyczyniać się do zmniejszenia odporności na pękanie. Założono, że właściwości mieszanki mineralno-asfaltowej mogą być kształtowane m.in. poprzez modyfikację parametrów procesu produkcyjnego mieszanki. Analizie poddano wpływ wybranych warunków technologicznych wytwarzania mieszanek SMA z granulatem asfaltowym na ich odporność na propagacje spękań ocenianą metodą SCB. Badaniom poddano dwie mieszanki mineralno-asfaltowe typu SMA 11 o zawartości granulatu asfaltowego 20% oraz 40% m/m wytwarzane w technologii dozowania granulatu asfaltowego na gorąco. Na podstawie analizy uzyskanych wyników wykazano, że zarówno przyjęty schemat dozowania składników mieszanki, jak i zawartość granulatu asfaltowego mają istotny wpływ na uzyskiwane wartości parametrów charakteryzujących odporność na pękanie mieszanki mineralno-asfaltowej.

SŁOWA KLUCZOWE: mieszanka SMA, granulat asfaltowy, SCB, recykling, spękania.

ABSTRACT. The need for periodic replacement of wearing courses, including those made from SMA mixtures, involves the possibility of acquiring and reusing high-quality reclaimed asphalt pavement (RAP). To date, the issue of the use of RAP and asphalt granulate for SMA mixtures has not been extensively analysed and studied. The implementation of the principles of a circular economy will soon force the widespread use of asphalt granulate also for SMA mixtures. In the process of replacing the wearing course, the new asphalt mixture is laid on top of the existing binder course, in which, as a result of previous use, micro-cracks can occur, among others, which will also propagate into the newly built wearing course during the further use of the pavement. The SMA mixture should therefore be characterised by resistance to crack propagation from lower asphalt layers. The use of recycled material containing aged asphalt binder in the SMA mixture may contribute to a reduction in crack resistance. It was assumed that the properties of a mineral-asphalt mixture could be shaped, among others, by modifying the parameters of the mixture production process. The effect of selected technological conditions for the production of SMA mixtures with asphalt granulate on their resistance to crack propagation assessed by the SCB method was analysed. Two SMA 11 asphalt mixtures with a mineral-asphalt granulate content of 20% and 40% m/m produced using hot-mix asphalt granulate batching technology were tested. On the basis of the analysis of the results obtained, it was shown that both the batching scheme adopted for the mixture components and the content of asphalt granulate have a significant influence on the values obtained for the parameters characterising the resistance to cracking of the mineralasphalt mixture.

KEYWORDS: binder activation, cracking, reclaimed asphalt pavement (RAP), recycling SCB, SMA mixture.

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1. INTRODUCTION

In recent years, the focus has shifted towards developing recycling technology for asphalt pavements. Existing technologies enable using Reclaimed Asphalt Pavement (RAP) in asphalt mixtures in quantities ranging from 20% to 80%. The use of RAP in producing Stone Mastic Asphalt (SMA) mixtures is subject to more restrictions and requirements than traditional asphalt concretes due to the proportions of components used [1]. To increase the use of RAP in SMA mixtures, it is necessary to use RAP exclusively from milling the SMA layer [2]. Previous experience in use of RAP in SMA mixtures has been much poorer compared to traditional asphalt concretes with RAP. Nonetheless, current focus is on implementing circular economy technologies, which will inevitably lead to more widespread use of RAP in SMA mixtures, including wearing courses [3].

It is assumed that high durability and resistance are necessary for wearing courses due to the intensive impact of traffic loads and climatic conditions [4]. Previous limited experience shows that successful production of high-quality SMA mixtures containing RAP in amounts of up to 30% m/m and, in special cases, even up to 50% m/m is possible [1, 5–8]. Opportunities are still being explored to increase the content of RAP as well as to improve the properties of these mixtures.

The use of RAP is often associated with an increase in the stiffness of the mixture and a consequent decrease in its resistance to cracking [9–11]. The reduction in crack resistance for mineral-asphalt composites that contain recycled material is caused by the asphalt binder from the recycled material. As the binder undergoes aging processes, its stiffness increases, rendering it less resistant to cracking [12]. Another reason for the possible deterioration of the properties of the new composite is the lack of homogenisation. In mineral-asphalt composites, clusters of recycled material may appear, trapping the RAP binder and leading to a weaker material structure. Furthermore, the coating of asphalt binder on the grains of both new and recycled aggregate is often not complete and homogeneous, which can also degrade selected properties of the composites [13–15]. There has been a limited amount of published work investigating the fracture resistance of SMA mixtures with RAP. These reports have demonstrated that the proportion of RAP utilised has a major effect on the properties of SMA mixtures. Meanwhile, rejuvenating agents were found to be an effective method of reducing stiffness [5, 16–20].

To increase the amount of RAP content in a new composite, the properties of the recycled material must be considered, alongside the need to create a uniform mixture of all components – including RAP, RAP binder, virgin mineral aggregate, virgin binder, and any additives. Virgin binders with a lower viscosity or refreshing additives are commonly used to mitigate the adverse effects of aging in the recycled material [18, 21]. The process can be referred to as material modifications. To achieve better homogeneity of bituminous mixtures containing RAP, additives can be used to improve the workability of the mixture. Another solution to enhance the homogeneity of the mixture and the binder coating is to modify the production technology. This includes optimizing the preparation of recycled material, temperatures, and the order of adding components throughout the production of a new bituminous mixture [13, 22].

This paper presents the results of a study on the effect of modifying the technology of producing SMA mixtures with RAP on their resistance to crack propagation, tested by the Semi Circular Bend (SCB) method. The component dosage and mixture production methods applied in the analyses were aimed at differentiating the formation of the binder coating. Technological solutions have been identified to achieve the best possible resistance to crack propagation of SMA mixes with different RAP contents.

2. PURPOSE AND SCOPE OF RESEARCH

The purpose of the study was to evaluate the effect of modifying the SMA mixture production technology on its resistance to crack propagation as determined by the SCB method.

Three different ingredient dosage schemes in the production of SMA mixtures were analysed with the assumption that they could affect the way the asphalt coating is formed on grains of virgin aggregate and aggregate from RAP. It was assumed that the way in which the asphalt coating is formed from virgin binder and RAP binder on the grains of aggregates can have an impact on the final thickness and homogeneity of the asphalt coat. This, in turn, may affect the mixture's resistance to cracking.

The adopted schemes varied in the sequence of adding virgin binder, virgin aggregate and RAP to the bituminous mix.

3. RESEARCH MATERIALS

Two bituminous mixtures of SMA 11 for the KR3-6 traffic load category have been tested. One mixture had 20% RAP in its composition, while the other had 40% RAP obtained from selectively milling the SMA mixture wearing course. These mixtures were named in this paper as SMA_20RAP and SMA_20RAP. The compositions of the tested mixtures are

Table 1. Tested asphalt mixture compositions

Mixture components	Contents [%]	
	SMA_20RAP	SMA_40RAP
polimer-modified bitumen 45/80-55	5.3	4.1
limestone filler	5.6	2.8
fine aggregate 0/2 – limestone	7.5	4.7
fine aggregate (rinsed) 0/2 – limestone	7.5	4.7
coarse aggregate 2/5 – melaphyre	9.3	5.6
coarse aggregate 4/8 – melaphyre	5.6	0.0
coarse aggregate 8/11 – melaphyre	39.2	38.1
aggregates from SMA RAP	18.8	37.5
SMA RAP binder (BR rate)	1.2 (18)	2.5 (36)
stabilizer	0.3 (percent of mixture mass)	0.4 (percent of mixture mass)
adhesion agent	0.4 (percent of binder mass)	0.4 (percent of binder mass)

Table 2. Basic properties of virgin and RAP binder

Properties	PMB 45/80-55	RAP binder
penetration [0.1 mm]	63	51
softening point [°C]	56	55.5
elastic recovery [%]	76	75
viscosity at 90°C [Pa·s]	26.5	28.9
viscosity at 110°C [Pa·s]	4.9	4.4
viscosity at 135°C [Pa·s]	1.2	0.9

detailed in Table 1. The bituminous mixtures compositions were designed to ensure that, with differing RAP contents, the mixture grading curves were as alike as possible.

Table 2 shows the fundamental characteristics of the asphalt binders used in the bituminous mixtures tested – virgin polymer modified binder 45/80-55 and RAP binder.

The RAP binder has a minimal aging changes and similar properties as the virgin PMB 45/80-55. Moreover, the elastic recovery value suggested that RAP binder was a polymer-modified bitumen.

4. DESCRIPTION OF THE TECHNOLOGY FOR TESTING MIXTURE PRODUCTION

4.1. GENERAL COMMENTS

Due to the higher quantities of RAP utilized in the studied SMA mixtures, a mixture production technology was assumed, in which the RAP is dosed using hot dosage technology. To vary the formation of the binder coating in the mixtures analysed, three different component dosing schemes were used in the study. These schemes differed in the sequence of dosing of the bituminous mixture components and their mixing time. As the samples were prepared in laboratory conditions, the mixing times of the ingredients were comparatively longer than the ones utilized in asphalt mixing plant.

4.2. ANALYSED METHODS OF DOSING AND MIXING THE COMPONENTS OF SMA MIXTURES

The three dosing and mixing schemes for SMA mixture components utilized in the study are presented in Fig. 2–4. All SMA mixture components were prepared identically, regardless of the dosing and mixing scheme used: aggregate was heated to 200°C, RAP to 140°C and virgin binder to 160°C.

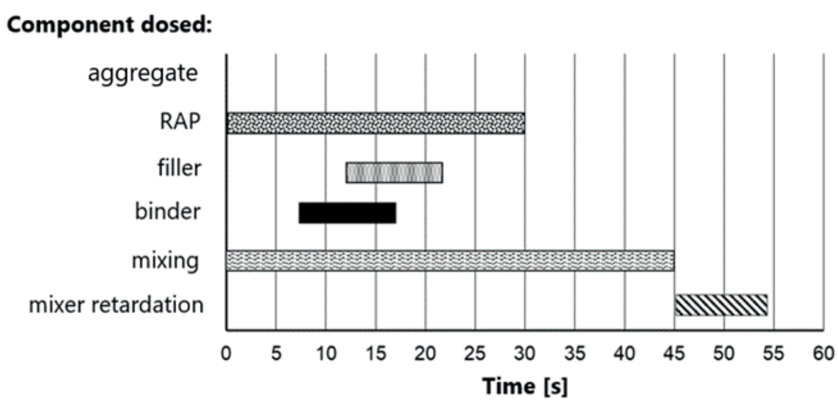

Fig. 1. Standard process for dosing and mixing the components of a hot mix asphalt with RAP [22]

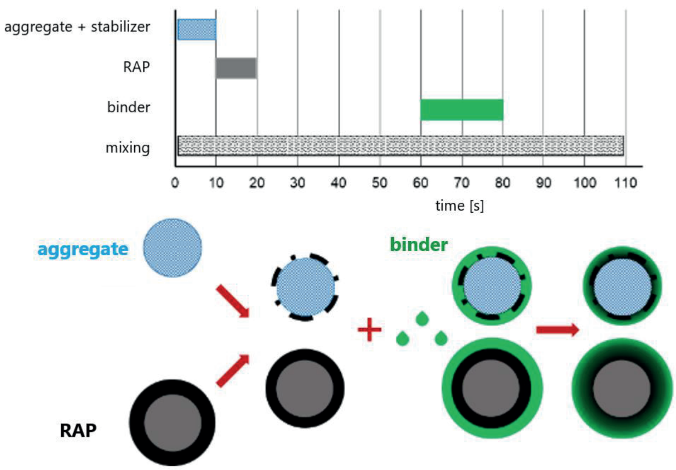

Fig. 2 The first scheme used in the study (scheme_1) for dosing and mixing bituminous mix components (with RAP)

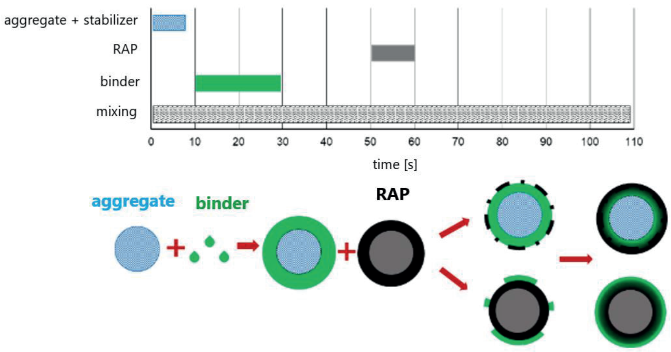

Fig. 3 The second scheme used in the study (scheme_2) for dosing and mixing bituminous mix components (with RAP)

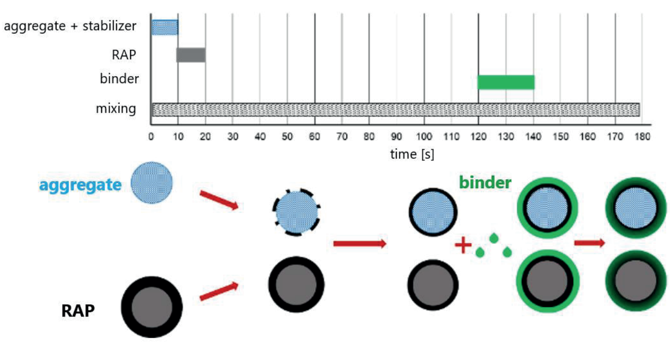

Fig. 4 The third scheme used in the study (scheme_3) for dosing and mixing bituminous mix components (with RAP)

The first scheme (Fig. 2) presents a standard approach to dosing mix components, where virgin aggregate and RAP are initially combined, followed by the dosing of virgin asphalt binder. In this case, partial activation of the granulate binder may occur. The RAP binder will be partially redistributed onto the surface of the virgin aggregate [13]. The aggregate and RAP mixture is then coated with a film of virgin binder.

Mixture production following the second scheme (Fig. 3) comprises an initial phase of dosing virgin aggregate and virgin binder, pre-mixing these components, and subsequently adding RAP to the mixture. It was presumed that utilizing this approach would result in the virgin aggregate being covered with a thicker layer of binder than in scheme 1, as the virgin binder would not be as readily absorbed by the grain surface of RAP.

The third method (Fig. 4) follows the same sequence of adding ingredients as method 1. However, the mixing duration for virgin aggregate and RAP was extended. This augmented the activation and redistribution of RAP binder, leading to a more uniform coverage of virgin and RAP binders over all mixture grains.

The cellulose stabilizer dosage was applied before the virgin binder dosage in each scheme.

Fig. 5 illustrates a view of virgin aggregate mixed with RAP as they produce SMA mixture, comprising 20% RAP, at intervals of 1 and 2 minutes of mixing.

In the instance of a mixture containing 20% RAP, there was an absence of visible binder redistribution from the RAP despite the length of time it was mixed with virgin aggregate – as depicted in Fig. 5a and 5b.

Fig. 6 displays virgin aggregate mixed with RAP, as part of the process for producing SMA mixture containing 40% RAP. The mixing process is shown after 1 and 2 minutes.

In the case of a mixture with 40% RAP, there is a noticeable redistribution of the binder from the RAP after extending the mixing time to 2 minutes – Fig. 6b.

a) b)

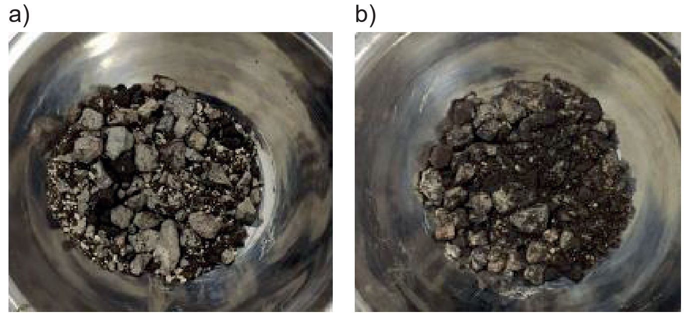

Fig. 5. SMA_20RAP mixture before virgin binder dosing:
a) after 1 minute of mixing virgin aggregate with RAP,
b) after 2 minutes of mixing virgin aggregate with RAP

a) b)

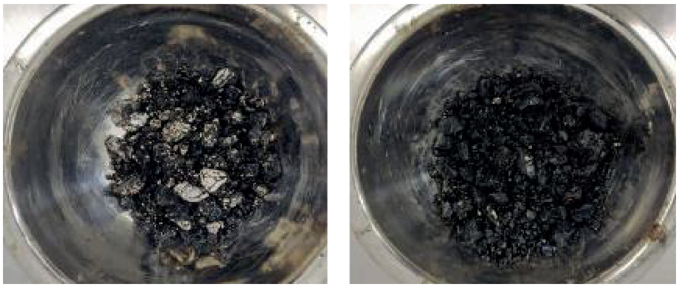

Fig. 6. SMA_40RAP mixture before virgin binder dosing:
a) after 1 minute of mixing virgin aggregate with RAP
b) after 2 minutes of mixing virgin aggregate with RAP

5. RESEARCH METHODOLOGY

5.1. PREPARATION OF SPECIMENS

Samples of each asphalt mixture were compacted using a gyratory compactor by applying a pressure of 0.6 MPa and a compaction temperature of 145±5°C. The specimens were compacted until reaching reference volumetric densities of 2.380 g/cm^3 and 2.376 g/cm^3 for the SMA_20RAP and SMA_40RAP mixtures respectively, which corresponded to an average of 65 specimen rotations in the gyratory compactor. Cylindrical samples, with a diameter and height of 150 mm, were created from the asphalt mixtures produced. The reference densities were determined during the mixture design phase using samples compacted with a Marshall compactor.

Four semi-cylindrical samples with a thickness of 50 ± 5 mm were cut from each of the cylindrical samples. The next step involved creating a notch with a width of 1.5 mm at the midpoint of the specimen's diameter. In order to measure the strain energy and the critical strain energy release rate value Jc, three different notch depths of 5, 10 and 15 mm were used in the tests.

5.2. CRACK PROPAGATION RESISTANCE TEST (SCB METHOD)

The test for crack propagation resistance was carried out following the methods described in EN 12697–44 "Asphalt Mixtures – Hot Testing Methods for Asphalt Mixtures – Part 44: Crack Propagation in the Semi-Circular Bend Test" and ASTM D8044 "Standard Test Method for Evaluation of Asphalt Mixture Cracking Resistance using the Semi-Circular Bend (SCB) Test at Intermediate Temperatures" [23, 24].

In this research, a general purpose testing machine was used which allows testing under static and dynamic loading conditions in the range of 0 to 130 kN and in the temperature range of -50 to + 40°C. Before testing, specimens were placed in the machine's chamber and thermostatically controlled to a test temperature of 0°C for a period of 4 hours. The specimen was subjected to mid-span loading using a piston speed of 5 mm/min. The specimen was loaded until it reached the maximum force, at which point the specimen was destroyed. Fig. 7 illustrates the specimens before loading and after the test.

For analysing the resistance to crack propagation in SMA mixtures with RAP, the following independent variables were defined:

– two RAP content for the mixture: 20% and 40%,
– three dosing and mixing schemes for the components: scheme 1, scheme 2, scheme 3,
– three different notch depths in the specimens: 5 mm, 10 mm, and 15 mm.

The following parameters, which characterize the fracture resistance of bituminous mixtures, have been identified as dependent variables:

– strain at maximum force,
– maximum stress at failure,
– fracture toughness K_{ic},
– critical strain energy release rate Jc,
– pre-crack slope.

The strain at maximum force Ɛ was calculated from the formula [23]:

$$\varepsilon_{\max,i} = \frac{\Delta W_i}{W_i} \cdot 100\%, \tag{1}$$

where:

W_i – height of specimen i (i=1,2,3,4) (mm),

ΔW_i – vertical displacement at maximum force of specimen i (i=1,2,3,4) in (mm).

The maximum stress at failure σ was calculated from the formula [23]:

a) b)

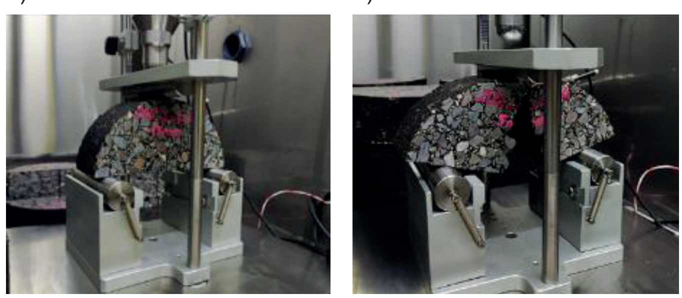

Fig. 7. a) Sample view before testing, b) after damage

$$\sigma_{\max,i} = \frac{F_{\max,i}}{D_i \cdot t_i}\left[\frac{N}{mm^2}\right], \tag{2}$$

where:

$F_{\max,i}$ – maximum force of specimen i (i = 1,2,3,4) in newtons (N),

D_i – diameter of specimen i (i = 1,2,3,4) (mm),

t_i – thickness of specimen i (i = 1,2,3,4) (mm).

The fracture toughness K_{Ic}, was calculated from the formula [23]:

$$K_{Ic,i} = \sigma_{\max,i} \cdot Y_1 \cdot \sqrt{\pi \cdot a_i}\left[\frac{N}{mm^{1.5}}\right], \tag{3}$$

where:

$\sigma_{\max,i}$ – stress at failure of specimen i (i=1,2,3,4) $\left[\frac{N}{mm^{1.5}}\right]$,

a_i – notch depth of specimen i (i=1,2,3,4) (mm),

Y_1 – normalized mode I stress intensity factor (see formula 4):

$$Y_{Ic,i} = 4.782 - 1.219\left(\frac{a_i}{r_i}\right) + 0.63\exp\left(7.045\left(\frac{a_i}{r_i}\right)\right)\left[\frac{N}{mm^{1.5}}\right]. \tag{4}$$

The critical strain energy release rate Jc was utilized in the analyses to describe the strain energy release rate, while the crack propagation occurred. Various notch depths were analysed in order to obtain the critical strain energy release rate. Formula (5) was used to determine the J-integral value.

$$J_c = -\left(\frac{1}{b}\right)\frac{dU}{da}\left[\frac{kJ}{m^2}\right], \tag{5}$$

where:

U – strain energy to failure (kJ),

a – notch depth (m),

b – sample thickness (m),

$\frac{dU}{da}$ – change of strain energy with notch depth (kJ/m).

In addition to analyzing standard parameters that characterize resistance to crack propagation, as defined in the standards [23–24], the force-displacement relationship was further analysed for each specimen by determining the tangent of the slope angle of the force-displacement curve in the phase before the maximum force is reached and the specimen is destroyed (pre-crack slope) [25]. The following points were identified: maximum force Pmax, 40% of maximum force, and 80% of maximum force.

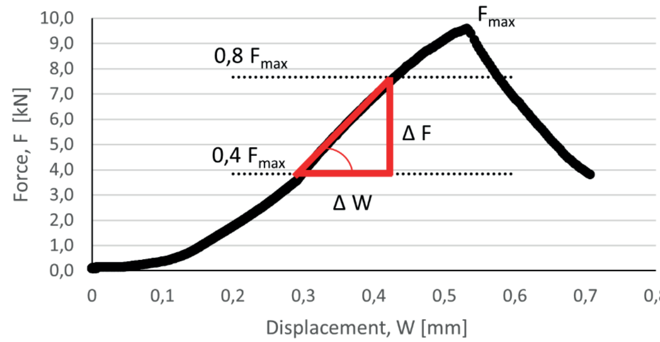

Fig. 8: The technique for calculating the gradient of the force-displacement graph during the pre-crack phase [25]

The tangent of α's angle of slope was calculated from equation (6):

$$tg\alpha_i = \frac{\Delta F_{0.4-0.8}}{\Delta W_{0.4-0.8}}\left[\frac{kN}{mm}\right], \tag{6}$$

where:

$\Delta F_{0.4-0.8}$ – the difference between the forces obtained in the range 0,4 F_{max} to 0,8 F_{max} (kN),

$\Delta W_{0.4-0.8}$ – difference in the vertical displacements obtained for forces 0,4F_{max} and 0,8 F_{max} (mm).

For each parameter identified, an analysis of variance was performed to verify the significance of the influence of each variable. To achieve this, a level of significance of α=0,05 was adopted. The decision on the impact of each factor's significance was based on the following assumption:

- if $\rho \leq 0.01$ then there is a very significant influence of the independent variable,
- if 0.01 0.05 $< \rho \leq$ then there is a significant influence of the independent variable,
- if 0.05 0.1 $< \rho \leq$ then there is a negligible effect of the independent variable,
- if $\rho > 0.1$ means that the influence of the independent variable is negligible.

5.3. TEST RESULTS

Figure 9–11 illustrate the deformation values at failure for specimens containing 20% and 40% RAP, tested at various notch depths, and using three different dosing and mixing schemes for SMA-type mix components.

On the basis of on the results depicted in Fig. 9–11, it is apparent that during the notch depth increases the strain of the sample decreases. Approximately 80% of the analysed mixtures and notch depths show higher deformations in mixtures containing 40% RAP than in mixtures with 20% of RAP. The influence and correlation of component dosing and mixing methodology on the strain values cannot be conclusively determined. The analysis of variance conducted confirms a significant impact of the RAP content on the strain value. Table 3 displays the results of analysis of variance.

The variance analysis conducted revealed no significant impact of the mixing process or the interaction between the mixing process and RAP content on the strain at failure.

Figure 12–14 show average maximum stress values obtained during specimen failure in mixtures containing 20% and 40% RAP produced with three different component dosing and mixing schemes.

As with the deformation analysis, it is clear that the RAP content has a significant impact on the determined stress values at failure. The analysis showed that approximately 70% of the samples with a RAP content of 20% achieved higher stress values, on average by approximately 6%, compared to the mix samples with a RAP content of 40%. The effect of RAP content on the stress value was confirmed through the analysis of variance – Table 4. The analysis of variance revealed minimal impact on the analysed parameter by modifying the mixing scheme. However, this effect is only discernible for the smallest notch depth (5 mm), where the stress values obtained for scheme number 2 are significantly higher than those obtained for the other schemes.

Figure 15–17 illustrate the average slope values of the force-displacement diagram before reaching the maximum force (pre-crack slope) [25]. This pertains to mixtures with 20% and 40% RAP content produced by three different component dosing and mixing procedures. The parameter indicates the rate of specimen strain increase relative to the designated displacement.

Based on the analysis of the data presented in Fig. 15–17, it is evident that the RAP content variable significantly impacts the slope parameter of the force-displacement diagram. In most analysed samples, SMA mixtures with 20% RAP content achieved a higher slope value. This proves that mixtures with a lower RAP content needs a higher critical stress-strain state to obtain the same displacements than mixtures with a higher RAP content. Furthermore, it is noteworthy that scheme two obtained the lowest slope of the graph for each examined notch depth of the SMA_40RAP mixture. Given that the maximum forces

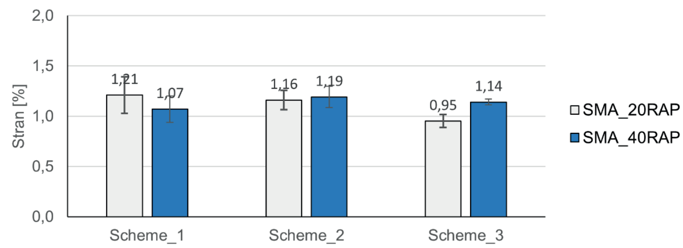

Fig. 9. Comparison of average strain values for three mixing methods and varying RAP content, with a notch depth of 5 mm

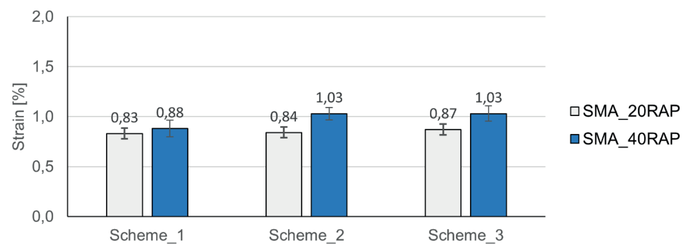

Fig. 10. Comparison of average strain values for three mixing methods and varying RAP content, with a notch depth of 10 mm

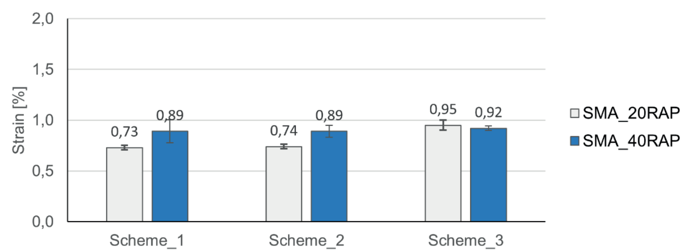

Fig. 11. Comparison of average strain values for three mixing methods and varying RAP content, with a notch depth of 15 mm

Table 3. Analysis of variance results for maximum stress at failure

Sl. No.	Independent variables	p (probability)	Impact
1	RAP content	0.042127	Significant
3	Mixing scheme	0.671366	Non-significant
5	RAP content * Mixing scheme	0.580578	Non-significant

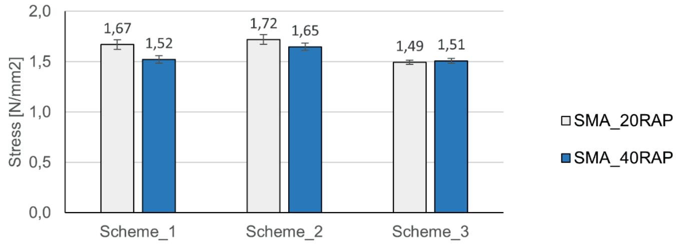

Fig. 12. Comparison of average stress values for three mixing techniques and varying RAP content, with a notch depth of 5 mm

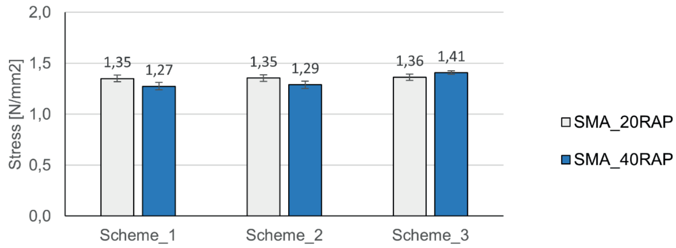

Fig. 13. Comparison of average stress values for three mixing techniques and varying RAP content, with a notch depth of 10 mm

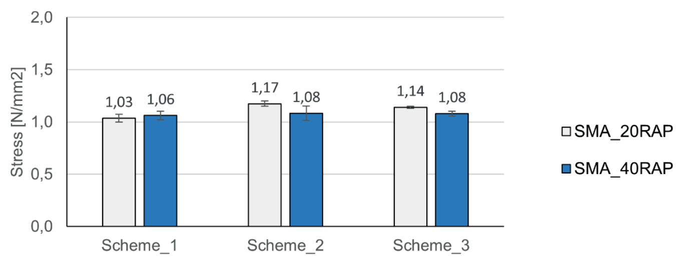

Fig. 14. Comparison of average stress values for three mixing techniques and varying RAP content, with a notch depth of 15 mm

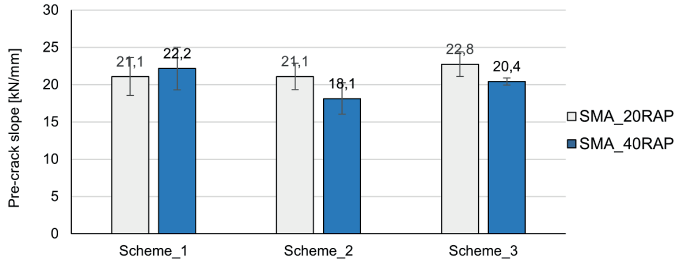

Fig. 15. Comparison of slope values in the force-deformation dependence diagram for three mixing techniques and varying RAP content at a notch depth of 5 mm

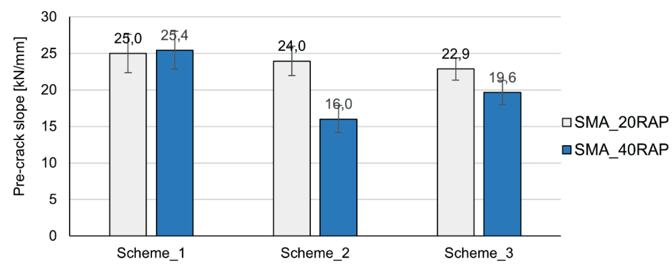

Fig. 16. Comparison of slope values in the force-deformation dependence diagram for three mixing techniques and varying RAP content at a notch depth of 10 mm

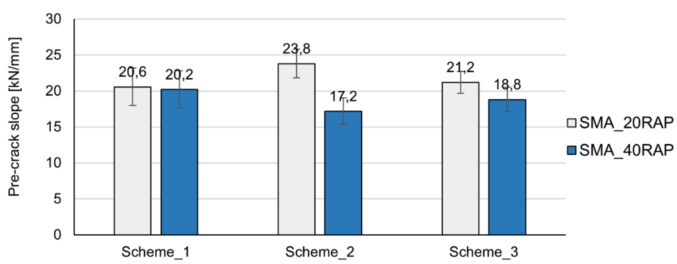

Fig. 17. Comparison of slope values in the force-deformation dependence diagram for three mixing techniques and varying RAP content at a notch depth of 15 mm

Table 4. Results of analysis of variance for maximum stress

Sl. No.	Independent variables	p (probability)	Impact
1	RAP content	0.010298	Significant
3	Mixing scheme	0.022658	Insignificant
5	RAP content * Mixing scheme	0.179837	Non-significant

Table 5. Results of the analysis of variance for the slope of the force-deformation relationship

Sl. No.	Independent variables	p (probability)	Impact
1	RAP content	0.013755	Significant
2	Mixing scheme	0.012044	Significant
3	RAP content * Mixing scheme	0.012551	Significant

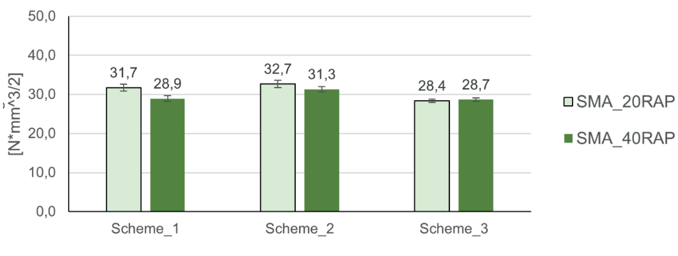

Fig. 18. Comparison of K_{ic} fracture toughness values for three mixing methods and a notch depth of a=5 mm for mixtures with 20% and 40% RAP

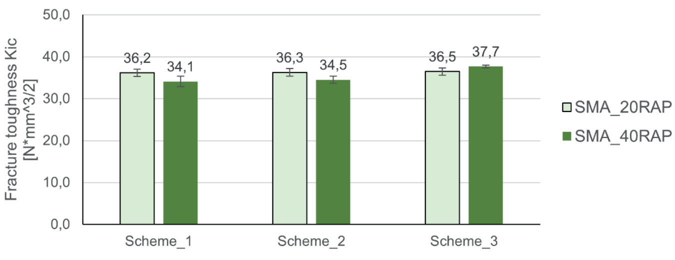

Fig. 19. Comparison of K_{ic} fracture toughness values for three mixing methods and a notch depth of a=10 mm for mixtures with 20% and 40% RAP

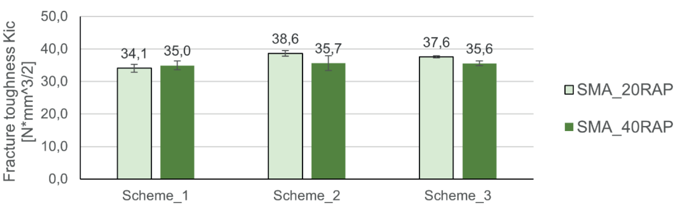

Fig. 20. Comparison of K_{ic} fracture toughness values for three mixing methods and a notch depth of a=15 mm for mixtures with 20% and 40% RAP

Table 6. Results of analysis of variance for K_{ic} fracture toughness

Sl. No.	Independent variables	p (probability)	Impact
1	RAP content	0.000000	**Very significant**
2	Mixing scheme	0.018391	**Significant**
3	RAP content * Mixing scheme	0.008127	**Significant**

did not significantly differ between the manufacturing schemes, it can be inferred that the mixture formulated under scheme 2 demonstrates greater deformation at the same level of loading compared to mixtures created under schemes 1 and 3. At the same time, it is worth mentioning that a comparable dependence was not observed for a mixture with a decreased RAP content of 20%.

The analysis of variance, as presented in Table 5, confirms that the RAP content has a significant effect on the slope parameter of the force-displacement relationship. In addition, the variance analysis demonstrated a noteworthy impact of the mixing method applied to the value of the parameter analysed, as well as a significant impact of the interaction between the mixing method and the RAP content. As for stress, the most significant impact of the mixing scheme was noticed in the specimens with a notch depth of 5 mm. In this case, both SMA_20RAP and SMA_40RAP combinations resulted in notably higher slope values for scheme number 2 than the other two mixing schemes.

The average values of K_{ic} fracture toughness for mixtures containing 20% and 40% RAP produced using three different mix designs and notch depths of 5mm, 10mm and 15mm are shown in Fig. 18 to 20.

Based on analysing of the average K_{ic} fracture resistance values, it can be concluded that the mixture containing 20% RAP content obtained significantly higher fracture resistance than mixture with 20% of RAP for almost 80% of the samples produced according to first and second dosing and mixing schemes. However, when using the third scheme, the mixture with a 40% RAP content only showed slightly higher fracture resistance for specimens with notch depths of 5 and 10 mm.

The analysis of variance conducted (Table 6) demonstrated a very significant impact of modifying RAP content and a significant impact of changing the dosing and mixing process of the components on the K_{ic} fracture resistance value.

It is worth mentioning that the SMA_40RAP mixture created under the second scheme showed no reduction in fracture toughness. Furthermore, there was a slight increase in fracture toughness observed when the notch depths were 5 and 15 mm. Based on the slope of force-displacement graph analysed earlier for scheme 2, which was the smallest among the three analysed schemes, it can be concluded that mixture produced according to scheme 2 demonstrated a better ability to transfer deformation and maintain material integrity compared to mixtures produced using the other two schemes.

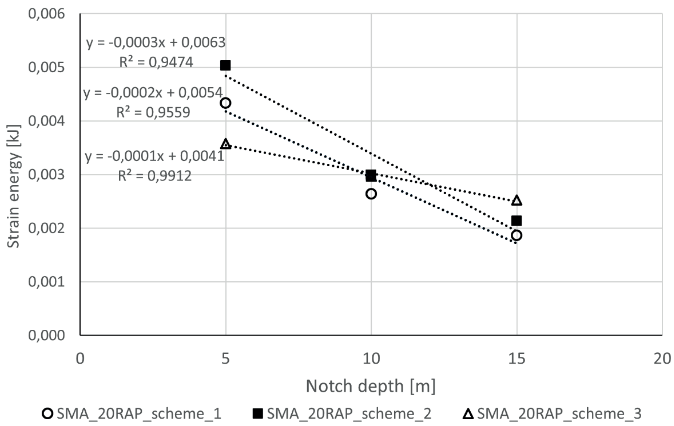

Fig. 21. Strain energy dependence on notch depth for the SMA_20RAP mix

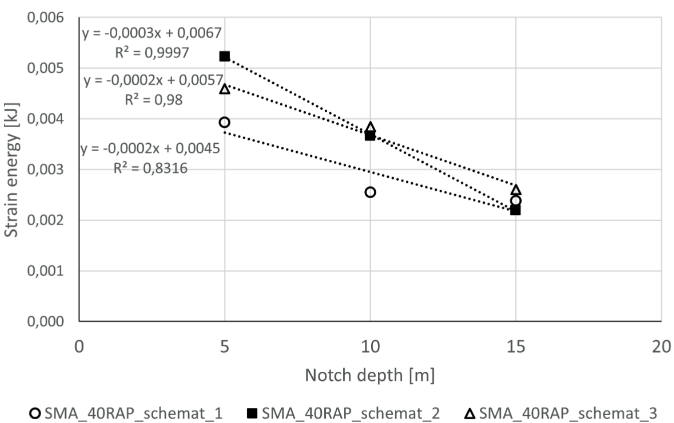

Fig. 22. Strain energy dependence on notch depth for the SMA_40RAP mix

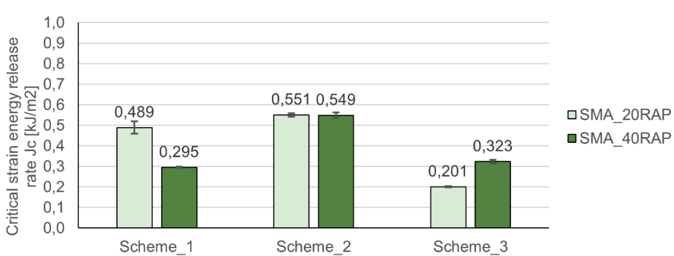

Fig. 23. Comparison of the critical integral Jc values for three mixing schemes in mixtures with 20% and 40% RAP

The last of the analysed parameters was the critical value of the J integral characterizing the rate of energy release during crack propagation. The integral was calculated using the relationship between the strain energy value and the depth of the notch. The determined strain energy values for various notch depths were approximated by a linear function, and its slope was used to calculate the value of the J integral (Jc). The relationships between strain energy and notch depth for SMA_20RAP and SMA_40RAP mixtures are shown in Fig. 21 and 22.

A comparison of the determined values of the J integral (Jc) for SMA_20RAP and SMA_40RAP mixtures produced according to three different dosing and mixing schemes is presented in Fig. 23. Table 7 shows the results of the analysis of variance for the J integral variable.

Analyzing the data presented in Fig. 23, clear differences can be observed in the obtained values of the J integral for each dosing and mixing scheme. Furthermore, in case of schemes 1 and 3, significant differences are also observed between mixtures with different RAP content. It should be noted that the highest J integral values are obtained in scheme 2, both for mixtures with 20% and 40%

Table 7. Results of analysis of variance for critical integral Jc value

Sl. No.	Independent variables	p (probability)	Impact
1	RAP content	0.000000	Very significant
3	Mixing scheme	0.000000	Very significant
5	RAP content * Mixing scheme	0.000000	Very significant

Table 8. Results of Tukey test for critical integral Jc value in mixture with 20% RAP

Sl. No.	Mixing scheme	{1} 4.8734	{2} 5.4889	{3} 1.9768
1	1	–	0.000955	0.000186
2	2	0.000955	–	0.000186
3	3	0.000186	0.000186	–

Table 9. Results of Tukey test for critical integral Jc value in mixture with 40% RAP

Sl. No.	Mixing scheme	{1} 3.0016	{2} 5.5274	{3} 3.1793
1	1	–	0.000198	0.085512
2	2	0.000198	–	0.000198
3	3	0.085512	0.000198	–

RAP content. The lowest J integral value was obtained for the SMA_20RAP mixture produced according to scheme three. On the other hand, the SMA_40RAP mixture produced according to scheme 2 stands out with a significantly higher J integral value compared to mixtures produced according to schemes 1 and 3.

The conducted analysis of variance confirmed a very significant influence of both the dosing and mixing scheme and the RAP content on the obtained J integral values, as well as the interaction between these two variables. Additionally, to determine which schemes had significant differences between them, Tukey's test was conducted. The results of Tukey's statistical test for SMA_20RAP and SMA_40RAP mixtures are presented in Tables 8 and 9.

Based on Tukey test results, it could be mentioned that differences only between number 1 and number 3 scheme are not significant in case of SMA_40RAP mixture. In other cases, the determined values of the J integral differ significantly between mixing schemes.

6. CONLUSIONS

It can be stated that parameters based on the obtained values of force and displacement, such as strain at failure, stress at failure, and crack resistance (K_{ic}) only slightly differentiate the dosing and mixing schemes. An exception is the slope of the force-displacement curve, the values of which clearly differentiate the influence of the mixture production scheme. The parameter significantly differentiating the individual schemes is the critical value of the J integral based on the determined strain energy. Observed influence of the mixing scheme is caused by the variability in the asphalt film on RAP and aggregate grains. It can be concluded that the energy criterion is more sensitive to changes in the asphalt film. Furthermore, based on the results analysis, it can be stated that more significant impact of technological factors is observed in mixtures with higher RAP content.

It has been proven that among the analysed dosing schemes, the most favorable effect in terms of the highest resistance to crack propagation, characterized especially by the critical J integral value, was achieved by scheme 2. In this scheme, the virgin aggregate was coated with a layer of virgin binder in the first step, and in the second the RAP grains were coated by virgin binder redistributed from the virgin aggregate.

Despite the use of RAP containing high-quality binder with a low degree of aging and similar properties to the virgin binder used, the analyses showed a significant influence of RAP content on most analysed parameters characterizing crack resistance. Therefore, it would be reasonable for further research to determine cracking parameters using RAP with a binder that significantly differs from the virgin binder. This should further differentiate crack resistance depending on the applied mixture production scheme.

The conducted studies confirmed the significant influence of the asphalt coating formation on RAP and virgin aggregate grains on the properties of Stone Mastic Asphalt (SMA) mixtures.

The obtained results indicate that further research on modifying the dosing and mixing process in mineral-asphalt mixtures containing recycled materials are needed, especially for production of mixtures with larger amounts of RAP.

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