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# INFLUENCE OF THE TYPE OF RECYCLED ASPHALT PAVEMENT ON THE PROPERTIES OF THE SMA JENA 16 STONE MASTIC ASPHALT MIXTURE

# WPŁYW RODZAJU DESTRUKTU ASFALTOWEGO NA WŁAŚCIWOŚCI MIESZANKI MASTYKSU GRYSOWEGO SMA JENA 16

**STRESZCZENIE.** Jednowarstwowe nawierzchnie asfaltowe z mastyksem grysowym (SMA JENA) stosowane są w Polsce od 2010 roku. Pomimo licznych zalet, m.in. umożliwiających znaczny postęp robót oraz niższe koszty wykonania w stosunku do tradycyjnych mieszanek mineralno-asfaltowych, technologia ta nie jest szeroko stosowana w Polsce. W pracy dokonano oceny właściwości mieszanki jednowarstwowego mastyksu grysowego JENA 16 z dodatkiem granulatu asfaltowego. W badaniach wykorzystano dwa granulaty asfaltowe uzyskane z frezowania nawierzchni warstwy ścieralnej i wiążącej oraz wiążącej podbudowy. Oba granulaty w znaczy sposób różniły się zastosowanym materiałem mineralnym oraz rodzajem zawartego w nich lepiszcza asfaltowego. Plan badań zakładał dozowanie granulatu w ilości od 10% do 50% względem mieszanki mineralnej, tak aby uzyskana w ten sposób krzywa uziarnienia była jak najbardziej zbliżona do przebiegu analizowanej również mieszanki referencyjnej. Ocenie podlegały podstawowe parametry fizyczne, jak i mechaniczne mieszanki mineralno-asfaltowej JENA 16 oraz obu granulatów. Badania wykazały zróżnicowany wpływ rodzaju, jak również ilości destruktu asfaltowego na właściwości mieszanki SMA JENA 16. Granulat asfaltowy nie wpłynął znacząco na odporność na działanie wody badanych próbek, zanotowano natomiast pozytywny wpływ granulatu na odporność mieszanki mineralno-asfaltowej na deformacje trwałe.

**SŁOWA KLUCZOWE:** destrukt asfaltowy, SMA JENA16, nawierzchnie jednowarstwowe, recykling.

**ABSTRACT.** One-layer asphalt pavements with stone mastic asphalt (SMA JENA) have been used in Poland since 2010. Despite numerous advantages, including facilitating significant progress in work and lower costs compared to traditional asphalt mixtures, this technology is not widely applied in Poland. This paper evaluated the properties of a one-layer JENA 16 stone mastic asphalt mixture with the addition of recycled asphalt pavement. Two asphalt granulates obtained from milling the wearing and binding layers and the binding subbase were used in the research. Both granulates significantly differed in the applied mineral material and the type of asphalt binder contained in them. The research plan involved dosing the granulate in quantities ranging from 10% to 50% relative to the mineral mixture, ensuring that the resulting grain size distribution closely matched the profile of the analyzed reference mixture. Basic physical and mechanical parameters of the JENA 16 asphalt mixture and both granulates were evaluated. The studies showed a varied impact of the type and quantity of recycled asphalt pavement on the properties of SMA JENA 16. The asphalt granulate did not significantly affect the water resistance of the tested samples. However, a positive effect on the resistance of the asphalt mixture to permanent deformations was observed.

**KEYWORDS:** recycled asphalt pavement, SMA JENA16, one-layer pavement, recycling.

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# 1. INTRODUCTION

One-layer asphalt pavements are commonly used during road pavement renovations. By combining the leveling and wearing layers in a single technological process, the construction pace can be significantly accelerated. This is essential as, in the near future, building new roads will constitute only a small part of construction work in road engineering.

In Poland, one can distinguish between two technologies of one-layer asphalt pavements: Asphalt Concrete TD ( in German: *Asphalttragdeckschicht*, the supporting layer of asphalt pavement) [1], and SMA JENA 16 stone mastic asphalt mixtures (also known as AC 16 DTS, in German: *Decktragschicht*) [2]. The aim of these technologies is to create two technological layers, leveling or binding, and wearing, in one process, with the built-in layer thickness typically ranging from 5 to 10 cm. One notable advantage of this approach is the ability to use an asphalt mixture with a larger grain size skeleton, characterized by high resistance to permanent deformations, low free space content in the layer, and good resistance to weathering [3]. The elimination of the connection between the wearing and binding layers positively influences the fatigue durability of the pavement. In traditional asphalt pavements, ensuring a high-quality interlayer connection requires, among other things, the use of a suitable type and quantity of asphalt emulsion in the interlayer spraying of the lower layer, as well as the proper cleanliness of this layer [4]. Poor interlayer connection quality can lead to a significant reduction in road pavement durability [5] and the formation of damage within the asphalt layer package caused by excessive deformations and their independent work [6]. The use of SMA 16 JENA mixture in road pavement construction increases the reliability of the pavement and contributes to extending its service life.

A crucial advantage of one-layer mixtures is that both technologies allow the use of recycled asphalt pavement in the asphalt mixture, which is currently not allowed for wearing layers.

Despite numerous benefits, these mixtures are not widely used in national construction, and the awareness of local road management authorities, where the practical application of these technologies could be most effective, is minimal. This might be due to limited access to technical documents, particularly the lack of technical guidelines facilitating the application of these mixtures in practice.

National experience includes the construction of approximately 1200 km of roads only using SMA JENA 16 technology [7]. SMA JENA 16 is a one-layer asphalt pavement [8] based on standard assumptions for SMA mixtures. Like typical SMA mixtures widely known in national practice, it is characterized by a discontinuous grain structure, as shown in Fig. 1, where a comparison of simplified sieves of continuous and discontinuous grain mixtures is presented.

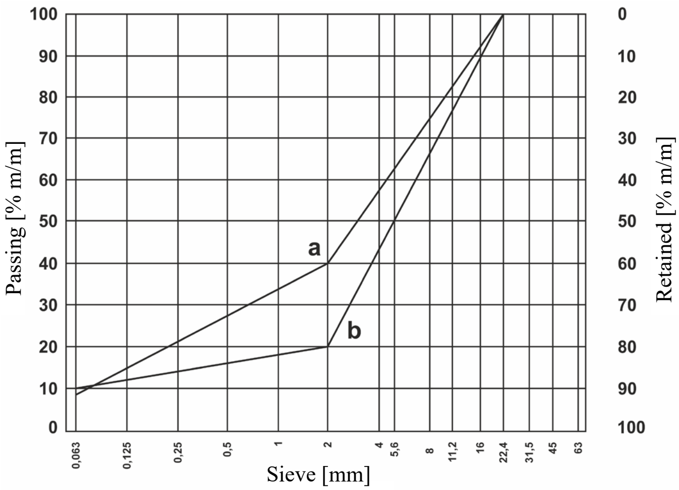


Fig.1. Example of simplified screening of continuous: (a) and discontinuous (b) grain size mixtures [7]

In addition to differences in the composition of the mineral mixture, SMA mixtures have a much higher content of asphalt binder, requiring the use of a stabilizer in their composition to prevent mixture segregation during transport. The application of SMA JENA 16 mixtures in road construction is not a typical material-structural solution – the Catalog of Typical Flexible and Semi-Rigid Pavement Structures [9] does not include the use of this type of technology. The only Polish technical work regarding these materials is „Nawierzchnie jednowarstwowe z SMA 16 JENA" [8], developed by K. Błażejowski and I. Strugała. In this work, the authors provided guidance, recommendations, and discussed elected national experiences with SMA JENA mixtures. It is worth noting that a significant facilitation for investors and designers is attached to the above item in the form of a ready-made document, a model technical specification for construction and acceptance work.

Designing SMA JENA mixtures does not differ from designing typical stone mastic asphalt mixtures, the requirements of which are included in WT-2:2014 [10].

Table 1 contains the requirements for the grain size of the SMA JENA16 mineral mixture.

Table 1. Elevations of grain size control points for SMA 16 mixture [8]

| Mesh size # mm | Pass % m/m |
|---|---|
| | Basic limits required for traffic categories KR1-KR6 |
| 22.4 | 100 |
| 16 | 90–100 |
| 11.2 | 65–80 |
| 8 | 45–58 |
| 4 | 27–37 |
| 2 | 20–30 |
| 0.125 | 7–13 |
| 0.063 | 6–11 |

For the mineral materials used in SMA JENA asphalt mixtures, the current requirements are based on WT-1:2014 [11] for aggregates, as for traditional SMA mixtures, with additional requirements for the content of crushed grains, angularity of fine aggregate, and LA coefficient for coarse aggregate for mixtures intended for traffic categories KR1-2.

As for asphalt binder, the application includes asphalts approved for use according to WT-2:2014 for SMA mixtures, taking into account the traffic load category. Agents enhancing asphalt affinity with aggregates and mastic stabilizer are selected based on the declaration of previous positive use in asphalt mixtures, personal experience, and laboratory research.

The most significant difference in the composition of SMA JENA mixture compared to typical SMA mixture used, based on national requirements, is the possibility of using recycled asphalt pavement. Błażejowski and Strugała describe in [8] that the dosage of the granulate can be done according to general principles as in WT-2:2014, where depending on the granulate dosing method, it ranges from 20% m/m in the cold method to 40% m/m in the hot method when the obtained granulate comes from the SMA layer.

Table 2 presents detailed requirements for the SMA JENA mixture developed by Błażejowski and Strugała [8].

The selection of asphalt quantity is based on general principles according to WT-2 2014, where the minimum asphalt content $B_{min}$ is determined at the level of 5.2% m/m. When using asphalt granulate, it is necessary to consider the addition of old binder, which reduces the amount of new, fresh asphalt. For very hard asphalt present in the asphalt granulate, to achieve the required physical and mechanical parameters, it may be necessary to use an asphalt rejuvenator or apply a softer asphalt. The grain size of recycled material significantly influences the characteristics of the final asphalt mixture. As a rule, coarser recycled material has a lesser impact on the properties of the new asphalt mixture and can be used in larger quantities [12, 13].

In the case of developing a type study for SMA JENA 16 mixture, standard physical and mechanical parameters apply, as in the case of a regular SMA mixture. An example of the requirements proposed in [8] is provided in Table 3.

Table 2. Requirements for SMA 16 JENA mixture materials [8]

| No. | Ingredients of the mixture | SMA 16 JENA KR1-KR2 | SMA 16 JENA KR3-KR4 |
|---|---|---|---|
| 1 | Mineral aggregate | Requirements for aggregates according to WT-1 2014 or a newer version, for traffic categories KR1-KR2, as for SMA mixture with additional requirements: content of broken and crushed grains in the coarse aggregate mixture $C_{90/1}$<br>Fine aggregate, angularity category $ECS_{30}$<br>Coarse aggregate $LA_{25}$ | Requirements according to WT-1 2014 or a newer version, for traffic categories Kr3-KR4 and KR5-KR6, as for SMA mixture. |
| 2 | Asphalt granulate | Up to 20% m/m of the mineral mixture for the cold method<br>Up to 30% m/m of the mineral mixture for the hot method<br>Up to 40% m/m of the mineral mixture for the hot method, when the granulate comes from SMA layers. | As per the Purchaser's decision |

Table 3. Requirements for the SMA JENA 16 Mix and the completed layer [2]

| No. | Properties | Compaction conditions according to EN 13108-20 | SMA 16 JENA KR3-KR6 |
|---|---|---|---|
| Requirements for mix design | | | |
| 1 | Void content (Vm) % | Beating 2×50 strokes, | $V_{min}$2.5<br>$V_{max}$4.0<br>$V_{max}$4.5 (for layers with a thickness of ≥ 5 cm) |
| 2 | Asphalt-filled void content, % | Beating 2×50 strokes, | $VFB_{declared}$ |
| 3 | Void content of VMA mineral mix, % | Beating 2×50 strokes, | $VMA_{min}$16 |
| 4 | Water resistance, % | Beating 2×35 strokes | $ITSR_{90}$ |
| 5 | Resistance to permanent deformation | Rolling $P_{98}$ - $P_{100}$ | $WTS_{AIR\ Max}$ 0.15<br>$PRD_{AIR\ Max}$ 7.0 |
| 6 | Binder flow, % | – | $BD_{0.3}$ |
| Requirements for the finished layer | | | |
| 7 | Compaction index of the layer, % | – | ≥98.0 |
| 8 | Void in the layer, % | – | $V_{min}$2.0<br>$V_{max}$6.0 |

## 2. ASPHALT GRANULATE IN THE LIGHT OF APPLICABLE REGULATIONS

Recycled asphalt pavement is “material intended for recycling, in the form of milled asphalt layers, plates torn from an asphalt surface, or rejected asphalt mixture or surplus production” [6]. In everyday language, contractors usually use only this one term, but in technical literature, there are two other different designations:

- qualified recycled asphalt pavement, i.e., “processed recycled asphalt pavement, suitable and ready for use as a constituent material of an asphalt mixture, after testing, assessment, and classification according to the requirements of the PN-EN 13108-20 standard” [14],
- asphalt granulate, i.e., “a certain amount of qualified recycled asphalt pavement, with classified/declared properties, suitable and ready for use as a constituent material in the production of an asphalt mixture” [15].

It should be emphasized that from a legal perspective, recycled asphalt pavement is considered waste, which, in order to become a full-fledged construction material, must undergo a series of rigorous tests, based on which it can be inferred that it loses its waste status, in accordance with the Regulation of the Minister of Climate and Environment of December 23, 2021, on the detailed conditions for the loss of waste status for recycled asphalt pavement [15].

Before proceeding with detailed tests, the waste must be assigned an appropriate code, depending on the tar content in it. The following are distinguished:

- 17 03 01 – bituminous mixtures containing tar,
- 17 03 02 – bituminous mixtures other than those mentioned in 17 03 01.

In hot technology, only waste with the assigned code 17 03 02 is used, to which the status of recycled asphalt pavement will be assigned after testing. The methodology is divided into:

- Simplified for waste for which there is confirmation that it originated from an asphalt mixture produced after December 31, 2000. The indicated material is coated with a preparation whose components react with tar, changing its color [9], as shown in Fig. 2.
- Detailed for other cases where determinations are made, i.e., the total content of aromatic hydrocarbons and the content of benzo(a)pyrene, as well as the maximum permissible concentration of elements in the leakage test from the sample [16].

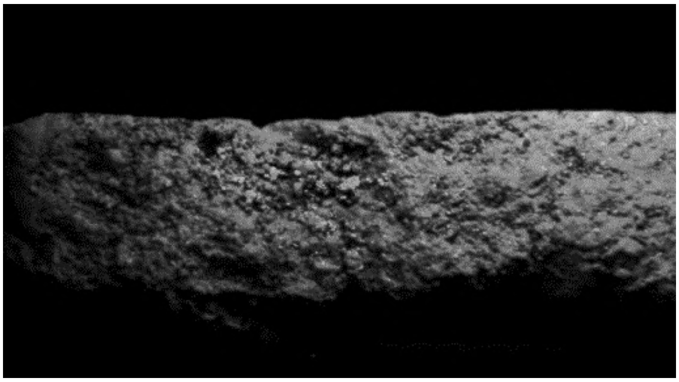

Fig. 2. Sample of recycled asphalt pavement with visible tar inclusions in the cross-section [9]

# 3. STUDY ON THE IMPACT OF RECYCLED ASPHALT PAVEMENT ON THE PROPERTIES OF SMA JENA

## 3.1. RESEARCH PLAN

The main subject of the research was the properties of the mastic asphalt mixture SMA JENA 16 designed for the wearing course in single-layer technology, considering the use of recycled materials from asphalt mixes in its composition. In addition to studying the properties of newly produced asphalt mixtures, the analysis also focused on the properties of recycled materials [17]. These materials included recycled asphalt pavement obtained directly from the milling of the wearing course and binding asphalt surface (designated as D1) and granulated recycled material from the binding layer and subbase (designated as D2). Both recycled materials used in the study were sourced from the dismantling of worn-out asphalt pavements. Therefore, for the purpose of result analysis, they are referred to as D1 and D2 recycled materials. The research aimed to evaluate the properties of selected recycled asphalts and the asphalt binder within them. Furthermore, it assessed the impact of recycled asphalts on the physical and mechanical properties of the single-layer mastic asphalt mixture SMA JENA 16.

The scope of the study included designing a reference mixture and research mixtures using recycled asphalt, dosed at levels of 10%, 25%, and 50%. The asphalt binder in all mixtures was a new asphalt binder 50/70. The research plan for asphalt mixtures is outlined in Table 4.

Table 4. Research plan with designated types of SMA JENA mixtures

| | | Type of recycled asphalt | | |
|---|---|---|---|---|
| | | NONE | D1 | D2 |
| Quantity of recycled asphalt | 0% | X | | |
| | 10% | | X | X |
| | 25% | | X | X |
| | 50% | | X | X |

## 3.2. TESTING OF RECYCLED ASPHALT

The conducted tests for the recycled asphalt pavement included:

- determination of the content of soluble binder according to PN-EN 12697-1:2020-08 [18],
- grain content determination according to PN-EN 12697-2+A1:2019-12 [19],
- density determination of the recycled asphalt pavement according to PN-EN 12697-5:2019-01 [20],
- penetration test according to PN-EN 1426:2015-08 [21],
- softening temperature test according to PN-EN 1427:2015-08 [22],
- high-temperature rheological properties testing of the binder recovered from the recycled asphalt pavement:
  - determination of the complex modulus and phase angle,
  - cyclic creep with recovery (MSCR).

The results of the conducted tests are presented in Table 5 and Fig. 3.

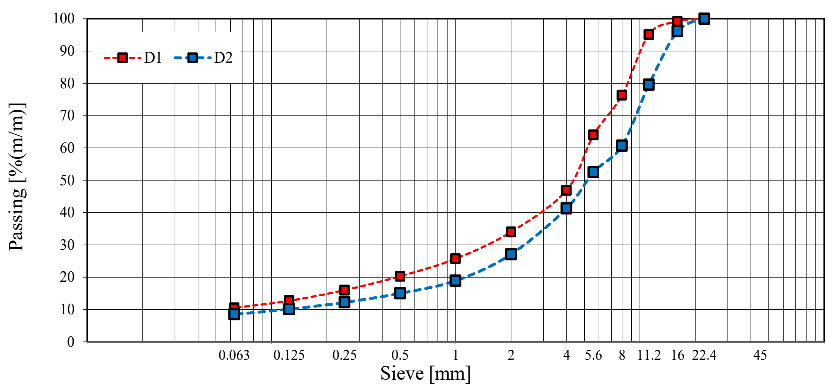


Fig. 3. Grain size curve for recycled asphalt pavement D1 and D2

Table 5. Properties of recycled asphalt pavement and recovered binder

| Property | | Recycled asphalt pavement D1 | Recycled asphalt pavement D2 |
|---|---|---|---|
| Mesh size # [mm] | 22.4 | 0 | 0 |
| | 16 | 0.9 | 3.9 |
| | 11.2 | 4 | 16.5 |
| | 8 | 18.8 | 18.9 |
| | 5.6 | 12.3 | 8.2 |
| | 4 | 17.1 | 11.2 |
| | 2 | 12.9 | 14.2 |
| | 1 | 8.3 | 8.2 |
| | 0.5 | 5.4 | 3.9 |
| | 0.25 | 4.3 | 2.8 |
| | 0.125 | 3.3 | 2.1 |
| | 0.063 | 2.2 | 1.6 |
| | <0.063 | 10.5 | 8.5 |
| Soluble asphalt content [%] | | 4.70 | 3.0 |
| Volumetric density [Mg/m$^3$] | | 2.65 | 2.55 |
| Asphalt penetration [x0.1 mm] | | 25.0 | 17.00 |
| Softening temperature [°C] | | 66.0 | 69.0 |
| High-temperature stiffness at 60°C, G*/sin(δ) [kPa] | | 20.7 | 60.8 |
| Upper critical temperature, G*/sin(δ) = 2.2 kPa [°C] | | 78.1 | 86.0 |
| Irreversible creep susceptibility, $J_{nr\,3.2\,kPa}$[1/kPa] | | 1.61 | 0.37 |
| Elastic recovery, $R_{3.2\,kPa}$ [%] | | 26.5 | 44.3 |

Based on the test results, it can be observed that the recycled asphalt pavements significantly differed from each other. Recycled asphalt pavement D1 had finer grain size and contained more filler compared to recycled asphalt pavement D2. Both recycled asphalt pavements had distinct mineral compositions, assessed based on the visual analysis of aggregates larger than 4 mm after the extraction of the recycled asphalt pavement sample. Recycled asphalt pavement D2 mainly consisted of limestone aggregates, and its density was 2.55 Mg/m$^3$. In recycled asphalt pavement D1, limestone aggregates were observed at approximately 40%, basalt aggregates at around 50%, and likely quartzite at about 10%. The density of recycled asphalt pavement D1 was 2.65 Mg/m$^3$.

Evaluating the properties of the recovered asphalt binder from the recycled asphalt pavements, significant differences were also noted. The binder from recycled asphalt pavement D1 exhibited significantly higher penetration and irreversible creep susceptibility, as well as much lower stiffness and $R_{3,2\,kPa}$ recovery value. However, the softening temperatures of the binders from both recycled asphalt pavements were similar. The high values of elastic recovery in the MSCR test indicated the presence of elastomer modification in both asphalt binders. In summary, the results indicate that the asphalt binder in recycled asphalt pavement D2 had poorer parameters for its application in recycled asphalt mixtures.

## 3.3. DESIGN AND PRODUCTION OF SAMPLES FOR SMA JENA 16

Based on the presented research plan, the work began with the design of the reference mixture (designated as A). The mixture used:

- limestone filler,
- limestone aggregate 0/2,
- gabbro 2/5; 5/8, 8/11, and 11/16,
- road asphalt 50/70,
- adhesive agent,
- cellulose fibers (stabilizer).

The grain size curve of the reference mix is shown in Fig. 4. In the next stage, experimental mixtures were designed, incorporating recycled asphalt pavement at levels of 10%, 25%, and 50%. The percentage of recycled asphalt

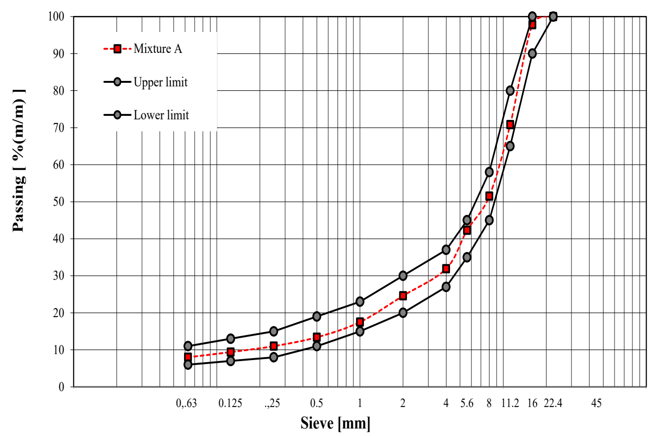


Fig. 4. Grain size curve of mix A

pavement in each mixture is summarized in Table 6. The mixtures were designed to have a particle size distribution similar to the reference mixture. The particle size distribution of the reference mixture (denoted as A) and the other experimental mixtures is presented in Table 7.

Table 6. Percentage of recycled asphalt pavement in each mixture

| Mixture | Recycled asphalt pavement D1 | Recycled asphalt pavement D2 |
|---|---|---|
| B | 10% | – |
| C | 25% | – |
| D | 50% | – |
| E | – | 10% |
| F | – | 25% |
| G | – | 50% |

Table 7. Percentage shares of individual fractions in the research mixtures

| | | Screening of asphalt mixes [%] | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | A | B | C | D | E | F | G |
| Mesh size # [mm] | 22.4 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| | 16 | 97.8 | 97.7 | 97.6 | 97.5 | 97.5 | 97.2 | 96.5 |
| | 11.2 | 70.8 | 69.9 | 69.4 | 70.1 | 70 | 70.3 | 69.9 |
| | 8 | 51.5 | 52.4 | 51.4 | 51.2 | 51.9 | 51.1 | 51.6 |
| | 5.6 | 42.3 | 43.7 | 43 | 43.1 | 43.2 | 42.5 | 43.2 |
| | 4 | 31.9 | 33.1 | 32.2 | 32.4 | 32.7 | 32.4 | 33.2 |
| | 2 | 24.6 | 24.7 | 23.7 | 24.2 | 24.2 | 24.1 | 24.3 |
| | 1 | 17.5 | 17.9 | 17.5 | 18.2 | 17.4 | 17.3 | 17.5 |
| | 0.5 | 13.4 | 14 | 13.9 | 14.4 | 13.6 | 13.5 | 13.9 |
| | 0.25 | 11 | 11.6 | 11.5 | 11.6 | 11.3 | 11.2 | 11.5 |
| | 0.125 | 9.4 | 9.9 | 9.7 | 9.5 | 9.7 | 9.6 | 9.8 |
| | 0.063 | 8 | 8.5 | 8.3 | 8 | 8.3 | 8.2 | 8.4 |

The next step in designing the asphalt mix was to determine the amount of added asphalt and soluble asphalt according to the principles outlined in WT-2:2014. The initial value of $B_{min}$ was set at 5.2%, as per [8]. Further work was conducted with the assumption that the total amount of soluble binder in the research mixtures should be similar to the reference mixture. Table 8 presents a comparison of asphalt binders in each mixture.

Table 8. Contents of recycled asphalt pavement and asphalt in the analyzed SMA JENA 16 mixtures

| | Amount of recycled asphalt pavement in the mineral mixture [%] | | Added asphalt [%] | Asphalt from recycled asphalt pavement [%] | Asphalt replacement index [%] |
|---|---|---|---|---|---|
| | D1 | D2 | | | |
| Recipe A | 0 | 0 | 4.8 | – | – |
| Recipe B | 10 | 0 | 4.3 | 0.47 | 10.2 |
| Recipe C | 25 | 0 | 3.7 | 1.18 | 25.1 |
| Recipe D | 50 | 0 | 2.7 | 2.35 | 49.0 |
| Recipe E | 0 | 10 | 4.5 | 0.30 | 6.5 |
| Recipe F | 0 | 25 | 4.2 | 0.75 | 16.0 |
| Recipe G | 0 | 50 | 3.6 | 1.50 | 30.6 |

Based on the above table, it can be observed that in the case of recycled asphalt pavement D1, a higher asphalt replacement index was achieved for each percentage content in the mineral mixture compared to recycled asphalt pavement D2. For the maximum recycled asphalt pavement content of 50%, the asphalt replacement index was 49% for recycled asphalt pavement D1 and 30.6% for recycled asphalt pavement D2.

In each mixture, an adhesive agent was applied at a rate of 0.3% relative to the amount of asphalt in the mixture, and cellulose fibers were used at a rate of 0.3% in the asphalt mixture.

During the production of SMA JENA 16 mixture, the recycled asphalt pavement was preheated to a temperature of 60°C, and the temperature of the new aggregate was gradually increased from 140°C for the mixture without recycled asphalt pavement to 220°C for the mixture with 50% recycled asphalt pavement. The total temperature of the materials during mixing was 140°C. The samples were compacted at a temperature of 135°C, using a Marshall compactor and a gyratory compactor.

## 3.4. ANALYSIS OF THE RESEARCH RESULTS

The impact of recycled asphalt pavement on the properties of SMA JENA 16 mixture, depending on the type used, was assessed based on the physical and mechanical parameters presented in Table 4. The obtained results are shown in the following graphs, and the average values represented by the height of the bars are supplemented with corresponding standard deviation values from the sample (in the form of whiskers).

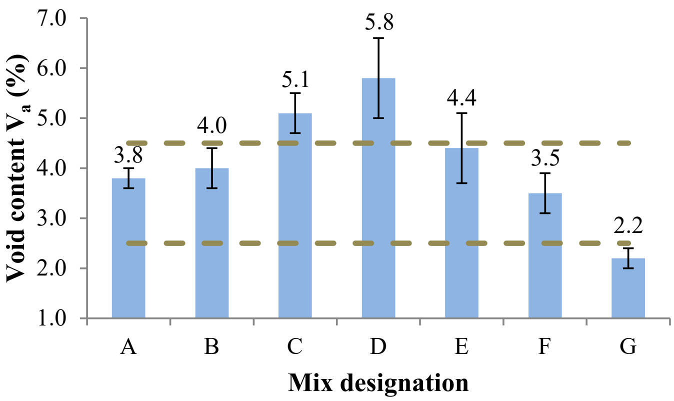


Fig. 5. Void content $V_a$

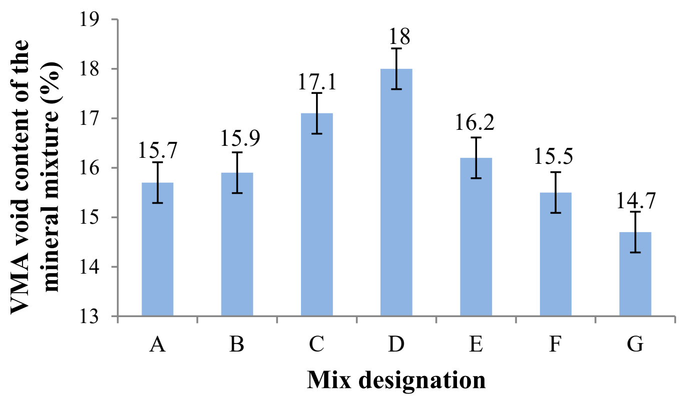


Fig. 6. Void content of the VMA mixture

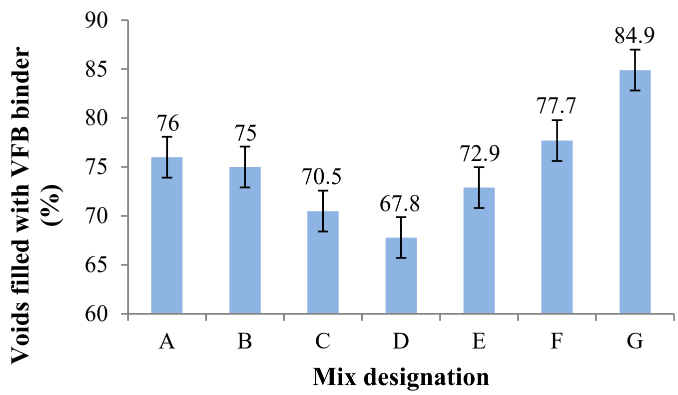


Fig. 7. Voids filled with VFB binder

The first of the presented parameters is the void content which is shown in Fig. 5.

Analyzing the obtained results, it can be concluded that only four mixtures, including the reference mixture, achieved the void content requirements in the samples. Mixtures with recycled asphalt pavement D1 labeled as "C" and "D" did not reach the required void content (>4.5%), while the mixture "G" containing recycled asphalt pavement D2 had too low void content. In the case of using recycled asphalt pavement D1, the void content in the samples increased with its higher content in the mineral mixture. In mixtures with recycled asphalt pavement D2, the opposite relationship was observed. This was influenced by the different origin of both recycled asphalt pavements and their processing methods – recycled asphalt pavement D1 was material directly obtained from milling, while recycled asphalt pavement D2 was granulated. Additionally, the asphalt replacement index indicates that in mixtures with recycled asphalt pavement D1, significantly more old asphalt was introduced compared to the same amount of recycled asphalt pavement D2.

The next analyzed parameters were the void content in the mineral mixture and the void content filled with asphalt. The results of both determinations are presented in Fig. 6 and 7.

For the VMA and VFB parameters, the results were considered as not having a specific evaluation criterion. However, concerning the requirements for void content in the mineral mixture, the literature often recommends a minimum value of 16% [8]. According to these requirements, the condition was met for mixtures C, D, and E. The obtained results are clearly strongly correlated with the void content in the samples, and similar dependencies can be observed as in the case of this parameter.

Figure 8 presents the results of the water and freeze resistance determination for the tested mixtures. The obtained results indicate that each of the mixtures achieved a minimum ITSR value higher than the required value for this type of material (90%).

Based on the conducted research, it can be observed that the addition of recycled asphalt pavement did not significantly affect the resistance of the mixtures to water and freeze. In the case of recycled asphalt pavement D1, a greater decrease in the ITSR parameter was observed compared to the use of recycled asphalt pavement D2. Furthermore, the quantity of applied recycled asphalt pavement D2 had a minimal impact on the value of this parameter.

Figure 9 presents the results of the asphalt binder flow determination in the analyzed mixtures. In the conducted research, none of the mineral-asphalt mixtures exceeded the value of 0.3% for the binder flow.

It should be noted that the mixture with recycled asphalt pavement D1 from the wearing course achieved better asphalt binder runoff parameters. The fact that this recycled asphalt pavement originated from the wearing course, which was an SMA mixture containing a stabilizer

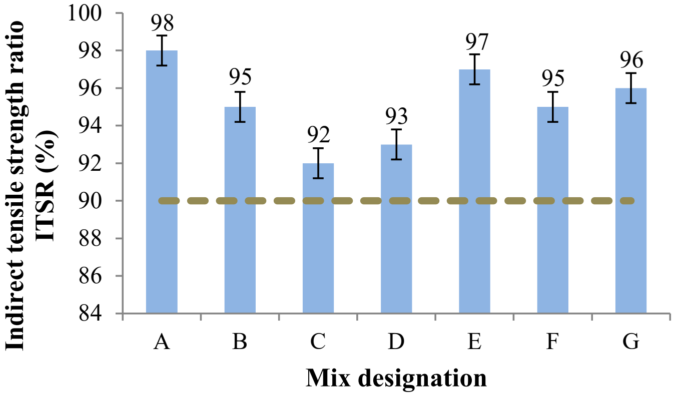


Fig. 8. Indirect tensile strength ratio (ITSR)

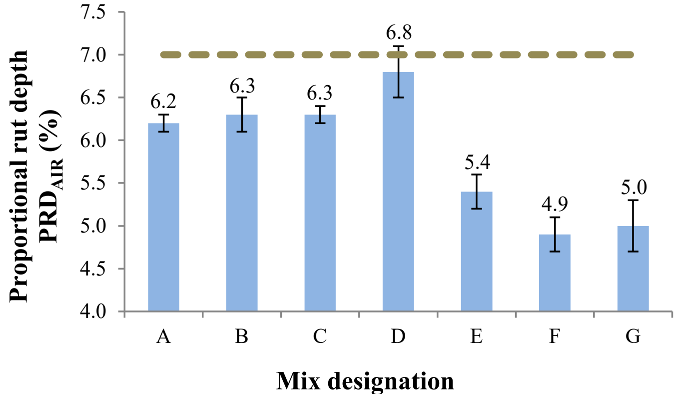


Fig. 10. Proportional rut depth $PRD_{AIR}$

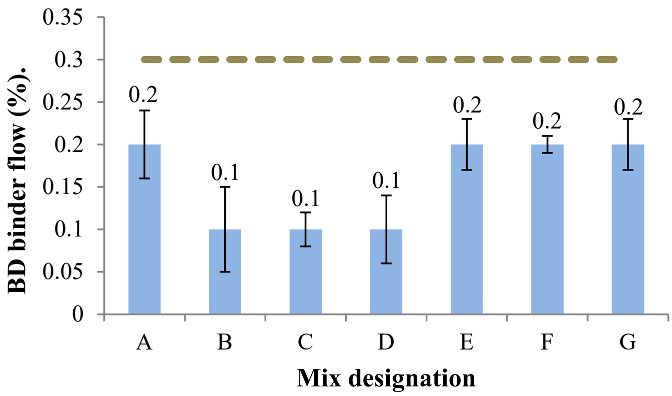


Fig. 9. BD binder flow

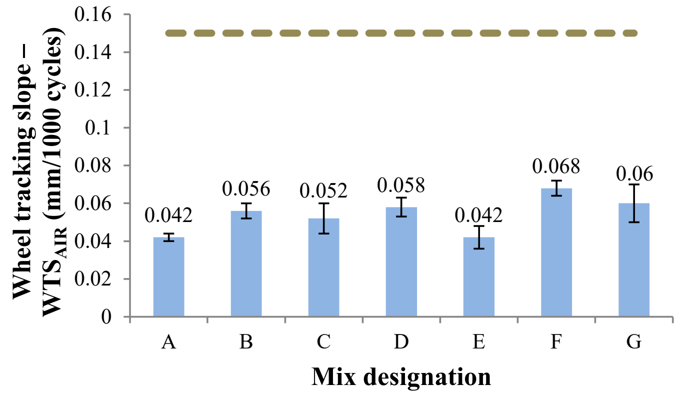


Fig. 11. Wheel tracking slope $WTS_{AIR}$

additive, may have influenced these results. For both parameters, the addition of recycled asphalt pavement did not significantly impact the values.

Figures 10 and 11 depict the results of the proportional rut depth after initial rutting ($PRD_{AIR}$) and wheel tracking slope after initial rutting ($WTS_{AIR}$) for the analyzed mineral-asphalt mixtures, respectively.

For both parameters, Proportional Depth Rutting After Initial Rutting (PRDAIR) and Wheel Tracking Slope After Initial Rutting (WTSAIR), the addition of up to 50% recycled asphalt pavement allowed achieving results that meet the specified requirements. The type of recycled asphalt pavement had a greater impact on the rut depth determined by the $PRD_{AIR}$ parameter. In the case of recycled asphalt pavement D1, increasing the content of recycled material did not lead to an increase in resistance to rutting in the SMA JENA mixture. This could be attributed to the simultaneous increase in the content of voids in the mixture. For mineral-asphalt mixtures with recycled asphalt pavement D2, a significant improvement in the rut depth parameter was observed with an increase in the content of recycled asphalt pavement. This could be attributed to a higher proportion of aged binder and a lower content of voids. Regarding the wheel tracking slope after initial rutting parameter, it can be observed that the use of recycled asphalt pavement in the composition of SMA JENA 16 mixtures led to a slight deterioration.

## 4. CONCLUSIONS

Based on the analysis of the obtained research results, the following conclusions can be formulated:

- The asphalt recyclables used in the study significantly differed in the type of aggregate, particle size, asphalt binder content, and its parameters. This resulted in a diverse impact of the applied asphalt recyclables on the physical and mechanical parameters of the designed SMA JENA 16 mixtures.
- Designing mixtures in such a way that their curves overlap demonstrated that the type and quantity of asphalt recyclable significantly affect the change in the void content in the SMA JENA 16 mixture. However, this impact was not as significant for other parameters.
- The determination of void content showed that concerning the average void content in the samples, only mixtures C, D, and G did not meet the specified requirements.

- Both the results of the water resistance index (ITSR) and the asphalt binder drainage (D) met the criteria for each mixture. Mixtures with the addition of asphalt recyclables from the wearing course and binding layer (recycled asphalt pavement D1) achieved better results.
- The results of the resistance to permanent deformation for all analyzed asphalt mixtures, in terms of the proportional rut depth ($PRD_{AIR}$) and the wheel tracking slope after initial rutting ($WTS_{AIR}$), met the set requirements. Unlike other parameters, better results were obtained for mixtures with the addition of asphalt recyclables from the subbase and binding layer (recycled asphalt pavement D2).

The conducted research demonstrated that it is possible to use recycled asphalt in the SMA JENA 16 mixture in a way that meets the required physical and mechanical parameters. However, in the analyzed case, the maximum amount of recycled asphalt is 25%.

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