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PERFORMANCE OF LABORATORY DESIGNED PERMEABLE ASPHALT MIXTURES

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Abstract. Permeable asphalt pavement is one of the sustainable solutions to remove water from road surfaces. The aim of the research is to analyse the performance of permeable asphalt mixtures depending on the different nominal maximum size and, as a result, to determine the minimum air voids content, which ensures that the asphalt pavement is permeable. To analyse the permeability of asphalt mixtures, ten porous asphalt mixtures with different air voids content and nominal maximum size were designed and tested in terms of air voids content, horizontal and vertical water permeability, water sensitivity, water sensitivity after ultraviolet radiation and mass loss. The results showed that the PA 16 mixture, designed according to the technical requirements TRA ASPHALT 08, was the most porous and permeable mixture, while the modified PA 8 mixture (PA 8_M2) had the lowest air voids content and permeability. Based on the importance of vertical water permeability (0.5%), mass loss (0.3%), water sensitivity (ITSR) (0.2%), the Simple Additive Weighting (SAW) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

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methods showed that PA 11 (0.729 and 0.745) and PA 16 (0.684 and 0.631) had the highest overall weights.

Keywords: asphalt pavement, permeability, permeable pavement, physical properties of asphalt, porous asphalt, sustainable pavement.

Introduction

Since the rapid pace of climate change is having a major negative impact on transport infrastructure around the world, many countries are conducting assessments to determine the impact of climate change on asphalt pavement performance and to develop scenarios to ensure safe traffic conditions and availability of the road network based on the results (Qiao et al., 2022; Barbosa et al., 2023). It is argued that one of the climatic factors that has the greatest impact on the pavement performance is rainfall. Changes in precipitation, such as an increase or decrease in rainfall, and the increasing frequency of short-term heavy rainfall, can alter the moisture balance in pavement structure, which would have an impact on the formation of pavement distresses (Almeida & Picado-Santos, 2022; Vaitkus et al., 2014; Barbosa et al., 2023).

In many countries, the most common way to remove excess water from the surface of roads and streets is by designing a transverse and longitudinal slope and constructing roadside ditches or rainwater harvesting systems. However, in the event of heavy but short-term rainfall, existing rainwater harvesting systems often no longer provide the necessary conveyance, resulting in the accumulation of water on the highway. In addition, in urbanized areas or cities, the construction of new systems is limited by the proximity of existing buildings and the large number of new building constructions, which require significant investment and land, often with insufficient resources. Therefore, it is necessary to look for other solutions to remove the accumulated water from the surface of the pavement. One of the sustainable solutions to remove water from the road surface is the construction of permeable pavements.

A permeable pavement is a sustainable and environmentally friendly pavement that allows rainfall to soak through to the pavement structure layers, preventing the accumulation of water on the pavement surface. The main types of permeable pavements are porous asphalt (PA), pervious concrete (PC), permeable interlocking concrete pavement (PICP) and grid pavement systems (Bruinsma et al., 2017; Eisenberg et al., 2015; Kuruppu et al., 2019; Zhu et al., 2021). Porous asphalt has 18–25% air voids content and depending on the composition of the mixture and environmental conditions, it can drain water between

4318–12700 mm/h. Many studies show that the maximum aggregate size for porous asphalt is 13.2 mm (Eisenberg et al., 2015). It should be noted that few experimental studies have shown that if the nominal maximum aggregate size is greater than 10 mm, it can have a positive effect on water permeability and resistant to cracking (Huang et al., 2020; Liu et al., 2017). According to an experimental study performed by Afonso et al. (2017), there is no significant difference between the tested four designed mixtures (two with cellulose fibre and two without cellulose fibre) in terms of water sensitivity (the difference was only about 8%). It was also observed that the mixtures with fine aggregates were more sensitive to water. To identify the optimal binder content for permeable asphalt mixture, five different amounts of the binder for PG 58-22 were used (3.9%, 4.4%, 4.9%, 5.4% and 5.9%) and performance was evaluated in terms of mass loss by Cantabro test and binder drainage. The results showed that the lowest mass loss of the mixture was with 5.4% and 5.9% of bitumen (12% mass loss and 0.29% binder drainage, and 10% mass loss e and 0.33% binder drainage, respectively). However, considering both parameters it was assumed that the optimal binder content – 4.9%. In this case, mass loss was 15% and binder drainage – 0.25% (Meng et al., 2020a). It is important to mention that only a few researchers have studied both binder drainage and mass loss, and in their works it is mentioned that binder drainage should be less than 0.3% and mass loss should be less than 20% (Meng et al., 2020a; Zhang & Guo, 2015).

One of the most important criteria for designing permeable asphalt pavements is water permeability, which is why Ma et al. (2018) in their research tested water permeability (horizontal and vertical) of porous asphalt mixtures with different binders and additives. In that study, porous asphalt mixture specimens with 20% air void content were designed using the different binders (high viscosity binder, PG 76-22, PG 70-22) and different additives (polyester fibre, mineral fibre, cellulose fibre, hydrated lime and DBS polymer). The results of the study showed that additives had a low effect on water permeability, and the use of a high viscosity binder or PG 76-22 showed better results than PG 70-22. It was also found that using high viscosity binder with polyester fibre water permeability decreased by 20%. However, their research concluded that various admixtures, which could improve hydraulic conductivity and structural behavior, had a major impact on porous asphalt performance (Kuruppu et al., 2019).

The main problem with permeable asphalt pavements is that their surface can get easily clogged. Sañudo-Fontaneda et al. (2018) have shown that in 10 years permeable asphalt pavement without maintenance is completely clogged. Meng et al. (2020b) tried to figure out the main clogging reasons of permeable asphalt pavements. In their study, five permeable asphalt mixtures were designed. The nominal maximum aggregate size was 13.2 mm, optimal binder content – 4.9% and air voids content varied from 16.27 to 22.75%. It was found that vertical clogging happened in four stages and horizontal clogging only in three stages. Therefore, asphalt mixture clogs less in the horizontal direction compared to the vertical direction. Based on this finding, it can be assumed that clogging has a major impact on the permeability and durability of porous asphalt. Therefore, to ensure adequate permeability and long service life, appropriate maintenance activities for permeable pavements must be selected (Bruinsma et al., 2017; Eisenberg et al., 2015; Kuruppu et al., 2019; Weiss et al., 2019; Zhu et al., 2021). In practice, it is observed that the use of mechanical sweepers is not recommended for permeable pavements. Eisenberg et al. (2015) mentioned that preventive sweeping is required 2–4 times a year but regenerative air sweepers should be used only 1–2 times a year.

Taking all the presented information into account, it can be stated that there are a lot of studies conducted on the topic of permeable asphalt pavements. However, they do not define the minimum air voids content that ensures the adequate permeability and durability of asphalt mixture. Therefore, this paper aims to analyse the performance of permeable asphalt mixtures depending on the different nominal maximum size and, as result, to determine the minimum air voids content, which ensures that asphalt pavement is permeable.

1. Experimental research

To analyse the performance of permeable asphalt mixtures, ten porous asphalt mixtures with different air voids content and nominal maximum size were designed for this experimental study. Three porous asphalt mixtures (PA 16, PA 11, PA 8) were designed according to the normative technical document TRA ASPHALT 08, which provides requirements for asphalt mixtures used in Lithuania and seven porous asphalt mixtures (PA 16_M1, PA 16_M2, PA 16_M3, PA 11_M1, PA 11_M2, PA 8_M1, PA 8_M2) were modified by reducing the air voids content. It

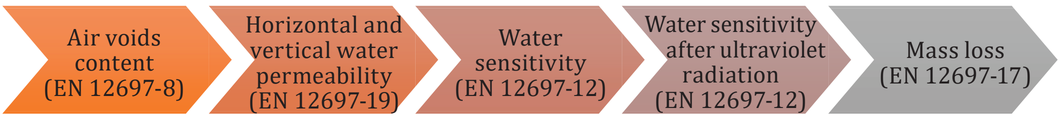

Figure 1. Experimental research plan

should be noted that PA 16, PA 11, and PA 8 mixtures, designed according to TRA ASPHALT 08, had the highest air void content. The experimental research plan is provided in Figure 1.

1.1. Materials

To design porous asphalt mixtures with different air voids content, dolomite fr. 11–16, dolomite fr. 8–11, dolomite fr. 5–8, dolomite fr. 2–5, dolomite fr. 0–2, mineral fillers, cellulose, adhesive additive, and polymer-modified bitumen PMB 45/80-65 were used. The properties of PMB 45/80-65 are provided in Table 1.

Table 1. Properties of PMB 45/80-65

Material	PMB 45/80-65
Penetration, dmm	56.1
Softening point, °C	78.0
Recovery at 0.1 kPa and 60 °C, %	96.1
Recovery at 3.2 kPa and 60 °C, %	89.6
R_{diff}, %	6.7
Non-recoverable creep compliance at 0.1 kPa and 60 °C, %	0.0359
Non-recoverable creep compliance at 3.2 kPa and 60 °C, %	0.0982

1.2. Asphalt mixture design

Table 2 shows the composition of each designed porous asphalt mixture. The actual aggregate particle size distribution of the designed porous asphalt mixtures is provided in Table 3.

Table 2. Compositions of designed porous asphalt mixtures

Component	Asphalt mixture									
	PA 16	PA 16_M1	PA 16_M2	PA 16_M3	PA 11	PA 11_M1	PA 11_M2	PA 8	PA 8_M1	PA 8_M2
Dolomite fr. 11–16, %	90.4	65.84	52.62	76.23	0	0	0	0	0	0
Dolomite fr. 8–11, %	0	6.61	9.45	0	89.82	75.24	63.52	0	0	0
Dolomite fr. 5–8, %	0	8.5	9.45	0	0	4.67	9.4	89.24	79.9	75.23
Dolomite fr. 2–5, %	0	4.72	9.45	0	0	4.67	9.4	0	0	0
Dolomite fr. 0–2, %	0	4.72	9.45	14.17	0	4.67	7.52	0	9.34	14.02
Mineral filler, %	3.78	3.78	3.78	3.78	3.76	3.73	3.76	3.74	3.74	3.74
Cellulose, %	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.5	0.5	0.5
Adhesive additive, %	0.017	0.017	0.017	0.017	0.018	0.02	0.018	0.02	0.02	0.02
Bitumen PMB 45/80-65, %	5.5	5.5	5.5	5.5	6	6.6	6	6.5	6.5	6.5

Table 3. Actual aggregate particle size distribution of designed asphalt mixtures

Sieve size, mm	Passing, %									
	PA 16	PA 16_M1	PA 16_M2	PA 16_M3	PA 11	PA 11_M1	PA 11_M2	PA 8	PA 8_M1	PA 8_M2
31.5	100	100	100	100	100	100	100	100	100	100
22.4	100	100	100	100	100	100	100	100	100	100
16	94.6	97.2	99.1	97.2	100	100	100	100	100	100
11.2	12.4	34.9	45.2	26.6	93.6	94.4	94.6	100	100	100
8	4.1	19	30.8	18.6	17.2	28.6	43	93.7	91.8	94.4
5.6	4	12	22.7	18.6	4	16.3	22.5	20.6	22.6	30.9
2	4	8.1	13.2	18.2	3.6	10.1	11.9	3.8	12.1	19.9
1	4	6.7	10.1	14.1	3.6	8.4	9.2	3.7	9.6	15.1
0.5	4	5.9	8.2	11.1	3.6	7.3	7.7	3.7	7.8	11.6
0.25	3.9	5.4	7.1	9.3	3.5	6.6	6.7	3.7	6.6	9.5
0.125	3.9	5	6.2	7.7	3.5	5.9	5.9	3.6	5.7	7.8
0.063	3.9	4.5	5.1	6	3.3	5	4.9	3.4	4.7	6.1

The optimal bitumen content for porous asphalt mixtures was chosen according to the TRA ASPHALT 08 requirements. For PA 16 and modified PA 16 mixtures the optimal bitumen content was 5.50%. For the PA 11 and modified PA 11 mixtures, except PA_M1, the optimal bitumen content was 6.00% (for PA_M1 – 6.60%). For the PA 8 and modified PA 8 mixtures the optimal bitumen content was 5.50%.

1.3. Methods

The following physical and mechanical properties were determined in the laboratory. Three samples were tested for each porous asphalt mixture and different test conditions (for example, three dry samples and three wet samples for indirect tensile strength (ITSR)).

1.3.1. Air voids content

The air void content was determined according to the standard EN 12697-8. The air voids content was calculated based on the maximum and bulk density of the mixture. The maximum density was determined by standard EN 12697-5 and the bulk density – by standard EN 12697-6.

1.3.2. Horizontal and vertical water permeability

Water permeability in the vertical and horizontal direction was determined by standard EN 12697-19. In the vertical water permeability test, the sample was placed in the test equipment and the water flow in the container was allowed to reach 300±1 mm high. To prevent horizontal leaks, the specimen was covered with a rubber membrane and a pressure of 50 kPa was applied to firm press on the specimen walls. Then, the jet was allowed to flow for 10 min until the sample was saturated with water and there were no air bubbles. After the prescribed period of time, the sample was placed in an empty vessel and the mass of the empty vessel was determined beforehand, allowing the water to flow for 1 min. At the end of the flow cycle, the amount of water entering the vessel was determined and the vertical water permeability was calculated.

For horizontal water permeability tests, test samples were placed on the test device and water flowed into a container that reached 300±1 mm high. To prevent the water from flowing vertically, the bottom of the sample was protected by paraffin and the aluminium ring was placed on the top of the sample, which was sealed with silicone.

1.3.3. Water sensitivity

The water sensitivity test was carried out by standard EN 12697-12. In this study, six specimens were formed according to the standard EN 12697-30 and subjected to 50 blows on each side. The specimens were divided into two groups of three specimens each. One group of specimens was kept dry at a constant temperature of 20 °C for 72 h and the other group of specimens was placed in a water bath for 72 h at a constant temperature of 40 °C. After 72 h, all the specimens were kept in a climate chamber for 4 h at a constant temperature of 20 °C. When the temperature of the specimens was kept constant at 20 °C in the climatic chamber, an indirect tensile strength test was carried out with a compression testing machine according to standard EN 12697-23. After that indirect tensile strength ratio (ITSR) was calculated by standard EN 12697-12.

1.3.4. Water sensitivity after ultraviolet radiation

At first, specimens were aged under ultraviolet radiation and after that the water sensitivity was determined as described in Section 1.3.3. To simulate the realistic ultraviolet radiation, an ultraviolet radiation, which reaches the Earth's surface, was analysed. Lithuanian hydrometeorological station collects and manages these data. It was determined that an average annual ultraviolet radiation of 7630 mW/m^2 reached the Earth's surface in Lithuania. Since pavements were designed for 20 years, the average ultraviolet radiation reaching the Earth's surface over the lifetime of the pavement structure was 156.600 mW/m^2. The samples were aged five hours with specific device. The water sensitivity test was then performed according to the procedure set out in Section 1.3.3.

1.3.5. Mass loss

The mass loss was determined by the standard EN 12697-17. The samples were formed according to the EN 12697-30 standard. The sample was stored for 4 h at a constant temperature of 15 °C to 25 °C. The test was carried out on the Los Angeles machine drum according to the EN 1097-2 standard.

1.3.6. Simple Additive Weighting (SAW)

Following an analysis of the literature and expert opinions, three indicators have been chosen to evaluate desired asphalt mixtures: vertical water permeability, mass loss, and water sensitivity (ITSR). Each indicator was weighted (assigned significance) according to expert opinions: vertical water permeability – 0.5%, mass loss – 0.3%, and water sensitivity (ITSR) – 0.2%. A decision table (matrix) was then constructed to evaluate the alternatives (designed asphalt mixtures) and a normalised matrix was obtained. In a normalised matrix, the members of the same alternative were multiplied by significance and added to the members of the other alternative (row). The resulting estimates were used to assign ranks and select the higher priority of the asphalt mixtures designed.

1.3.7. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

The identical indicators and weights (significance) to those used in the previously discussed multicriteria decision-making approach were employed. A decision matrix was constructed and normalised. The weights of the indicators were used to create a weighted normalised matrix from the normalised matrix. Using the calculation formulae of the TOPSIS method, the weighted, normalised matrices were used to form both "ideal" and "nonideal" alternatives. Once these alternatives were generated, the difference between the compared alternative and the "ideal" or "nonideal" alternative was calculated. The next stage was to evaluate the discrepancy between the ratios of the alternatives and the "nonideal" option. These values were then used to establish a priority queue.

2. Results and discussion

2.1. Air voids content

Figure 2 shows that the content of air voids changes from 11.5% to 27.4%. The mixture PA 8_M2 had the lowest air void content (11.5%) and PA 16 had the highest air void content (27.4%). PA 11 (27.0%) and PA 8 (23.3%) also had the highest values of air void content. Compared to the threshold values of air voids content (18–22%) set in the Eisenberg et al. (2015) guidelines and the results obtained in the experiment, only two of the ten permeable asphalt mixtures tested were compliant with the specified values PA 16_M1 (19.9%) and PA 11_M1 (19.1%).

The bulk and maximum density of the designed ten permeable asphalt mixtures are shown in Figure 3. The bulk density ranged from 1.867 Mg/m^3 (PA 16) to 2.205 Mg/m^3 (PA 8_M2), while the maximum density ranged from 2.493 Mg/m^3 (PA 8_M2) to 2.589 Mg/m^3 (PA 11).

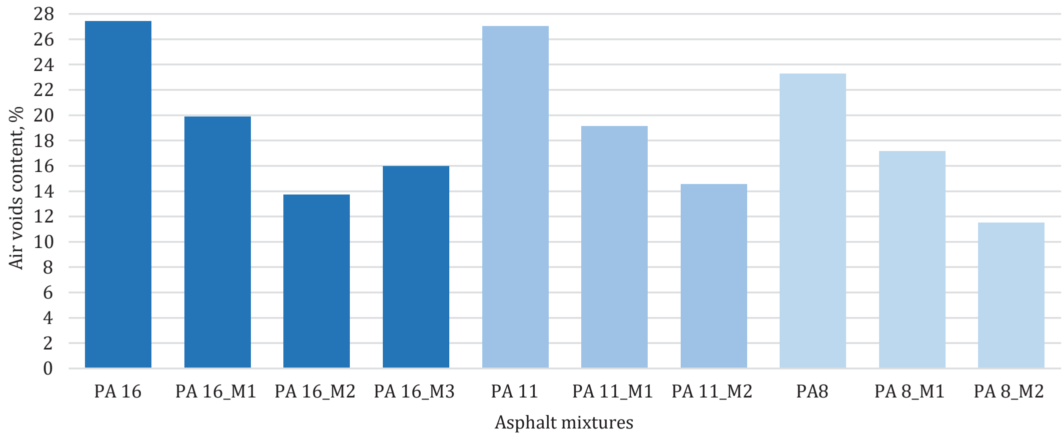

Figure 2. Results of air voids content

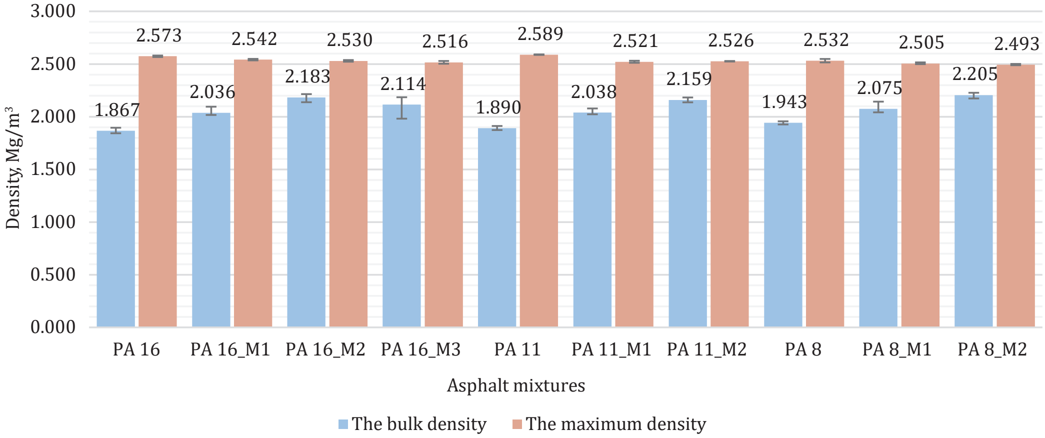

Figure 3. Results of the bulk and maximum density

2.2. Horizontal and vertical water permeability

Figure 4 represents the results of vertical and horizontal water permeability. The average vertical water permeability of the mixtures tested was in the range $0.1 \cdot 10^{-3} \sim 1.8 \cdot 10^{-3}$ m/s. The highest values of the average vertical permeability were obtained for the mixtures PA 11 – $1.8 \cdot 10^{-3}$ m/s, PA 16 – $1.6 \cdot 10^{-3}$ m/s, PA 8 and PA 16_M1, which had identical values of $0.6 \cdot 10^{-3}$ m/s, and the lowest values of the average vertical permeability were obtained during the test for the mixtures: PA 16_M2 – $0.1 \cdot 10^{-3}$ m/s, PA 16_M3, PA 11_M1, PA 11_M2 and PA 8_M2 with identical values being $0.2 \cdot 10^{-3}$ m/s, and PA 8_M1 with value of $0.3 \cdot 10^{-3}$ m/s. The highest variation of the samples was found for the PA 16 mixture, which varied from $1.02 \cdot 10^{-3}$ m/s to $2.28 \cdot 10^{-3}$ m/s, while the lowest variation of the samples was observed for the PA 11_M1 mixture, which varied from $0.14 \cdot 10^{-3}$ m/s to $0.24 \cdot 10^{-3}$ m/s.

The average horizontal water permeability of the mixtures tested was in the range of $0.2 \cdot 10^{-3} \sim 3.9 \cdot 10^{-3}$ m/s, shown in Figure 4. The highest values of the average horizontal water permeability were given for the mixtures: PA 11 – $3.9 \cdot 10^{-3}$ m/s, PA 16 – $2.3 \cdot 10^{-3}$ m/s, PA 8 – $1.4 \cdot 10^{-3}$ m/s and the lowest values were given for the mixtures: PA 8_M2 – $0.2 \cdot 10^{-3}$ m/s, PA 8_M1 – $0.5 \cdot 10^{-3}$ m/s, PA 16_M2 and PA 11_M2 with identical values of $0.6 \cdot 10^{-3}$ m/s. Moreover, it was identified that the highest variation of the samples was found for PA 16, this mixture varied from $3.10\ 10^{-3}$ m/s to $5.21\ 10^{-3}$ m/s, while the lowest variation of the samples was noticed for the PA 16_M2 mixture, which varied from $0.60 \cdot 10^{-3}$ m/s to $0.63 \cdot 10^{-3}$ m/s. In the article by Aboufoul & Garcia (2017) it is mentioned that the minimal water permeability should be more than $1.0 \cdot 10^{-3}$ m/s as opposed to the guide book by Eisenberg et al. (2015), where it is revealed that the minimal water permeability is $0.5 \cdot 10^{-3}$ m/s. Therefore, the minimal water permeability value written in the Eisenberg et al. (2015) guide book was compliant with four of the ten designed asphalt mixtures – PA 16 ($1.6 \cdot 10^{-3}$ m/s and $3.9 \cdot 10^{-3}$ m/s), PA 16_M1 ($0.6 \cdot 10^{-3}$ m/s and $0.8 \cdot 10^{-3}$ m/s), PA 11 ($1.8 \cdot 10^{-3}$ m/s and $2.3 \cdot 10^{-3}$ m/s) and PA 8 ($0.6 \cdot 10^{-3}$ m/s and $1.4 \cdot 10^{-3}$ m/s), but compared with the article by Aboufoul & Garcia (2017) only two designed mixtures were compliant with minimal water permeability value – PA 16 ($1.6 \cdot 10^{-3}$ m/s and $3.9 \cdot 10^{-3}$ m/s) and PA 11 ($1.8 \cdot 10^{-3}$ m/s and $2.3 \cdot 10^{-3}$ m/s). It should be noted that for the PA 8_M1 ($0.3 \cdot 10^{-3}$ m/s and $0.5 \cdot 10^{-3}$ m/s) mixture, only $0.2 \cdot 10^{-3}$ m/s is needed to reach for the minimal water permeability value as written by Eisenberg et al. (2015).

A simple linear regression model was built to identify the dependence of vertical water permeability and air voids content shown in Figure 5. The dependence of the vertical water permeability and air voids content in designed asphalt mixtures is written by linear regression formula $\hat{y}(x) = 0.0994x - 1.2977$. The coefficient of determination, which is equal to the square of the empirical correlation coefficient is $R^2 = 0.697$ (see Figure 5). The square of empirical correlation coefficient shows that mathematical model explains 69.7% of vertical water permeability of the designed asphalt samples variations in relation to the variation of air voids content of the designed asphalt samples.

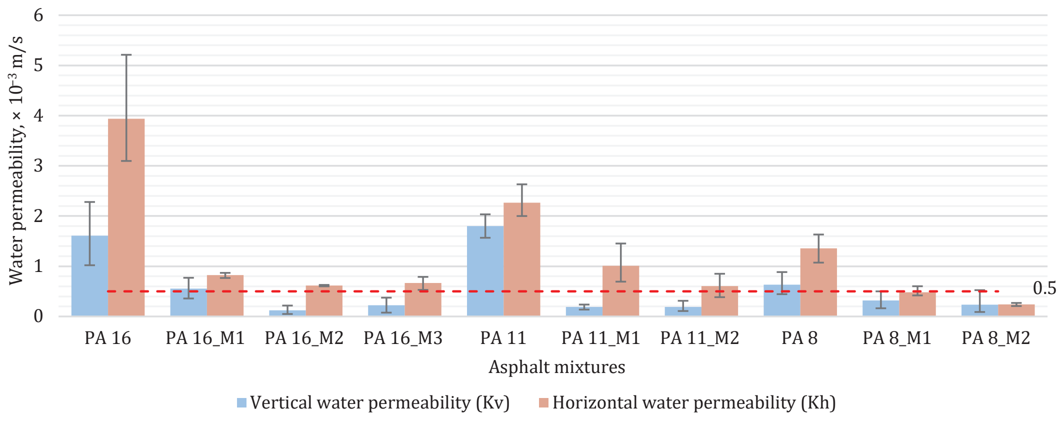

Figure 4. Results of horizontal and vertical water permeability

A simple linear regression model was built to identify the dependence of horizontal water permeability and air voids content shown in Figure 6. The dependence of the horizontal water permeability and air voids content is designed asphalt mixtures is written by linear regression formula $\hat{y}(x) = 0.1766x - 2.1475$. The coefficient of determination, which is equal to the square of the empirical correlation coefficient is $R^2 = 0.6816$ (see Figure 6). The square of empirical correlation coefficient shows that mathematical model explains 68.16% of horizontal water permeability of the designed asphalt samples variations in relation to the variation of air voids content of the designed asphalt samples.

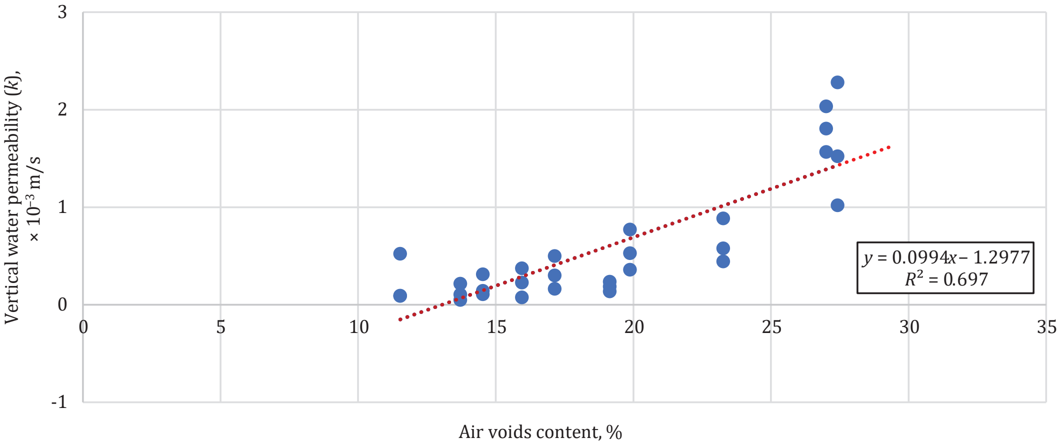

Figure 5. Dependence of the vertical water permeability of asphalt samples on the air voids content

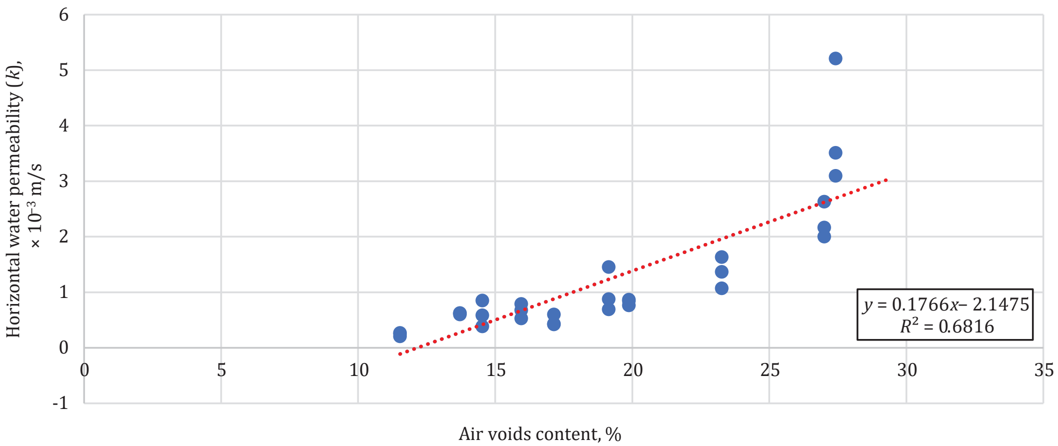

Figure 6. Dependence of the horizontal water permeability of asphalt samples on the air voids content

2.3. Water sensitivity

Figure 7 shows water sensitivity test results of the minimum and maximum samples with error bars. Since the ratio of indirect tensile strength is determined by wet and dry samples, the results of the test are first evaluated for wet and dry samples. The average indirect tensile strength of dry samples ranges from 437 to 1071 kPa, and the average indirect tensile strength of wet samples ranges from 333 to 957 kPa. The highest values of the average indirect tensile strength of the dry samples are 1071 kPa (PA 16_M2), 962 kPa (PA 8_M2) and 822 kPa (PA 11_M2), while the lowest values are obtained for the following test mixtures: PA 11 – 437 kPa, PA 16 – 450 kPa, and PA 8 – 511 kPa. The highest variation in the indirect tensile strength of dry samples is found in PA 16_M3 mixtures between 571 and 884 kPa, while the lowest variation in dry samples between 501 and 530 kPa is found in PA 8 mixtures. The highest indirect tensile strength values of wet samples are obtained on average of the test mixtures: 957 kPa (PA 16_M2), 790 kPa (PA 16_M3) and 746 kPa (PA 8_M2), while the lowest test results for the following mixture samples are PA 11 – 333 kPa, PA 16 – 411 kPa, PA 11_M1 and PA 8, which obtained the same values of 487 kPa. It should be noted that the highest variation in the sample was found for PA 16_M3, which varied from 631 to 888 kPa and the lowest variation was for the PA 11 mixture, which varied from 309 to 353 kPa. Afonso et al. (2017) provided the results of the indirect tensile strength test, which assumed that dry samples should have an indirect tensile strength of at least 780 kPa and wet samples should not have an indirect tensile strength

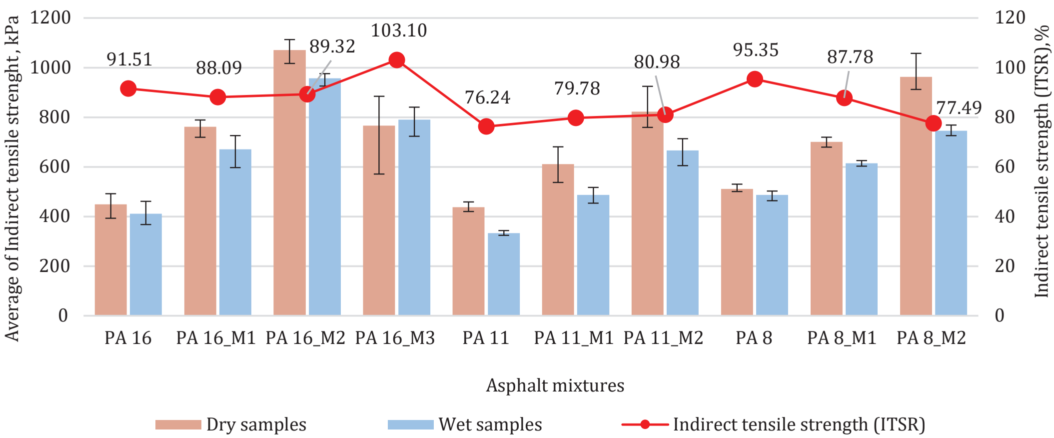

Figure 7. Results of water sensitivity

of less than 480 kPa. Consequently, according to the experimental results presented in Figure 7, the following mixtures meet the value of the indirect tensile strength of the dry samples according to Afonso et al. (2017): PA 16_M2 has 1071 kPa, PA 11_M2 has 822 kPa, and PA 8_M2 has 962 kPa. It should be noted that PA 16_M3 had a deficiency of 14 kPa and PA 16_M1 had a deficiency of 19 kPa compared to the minimum value given by Afonso et al. (2017). According to Afonso et al. (2017), the indirect tensile strength of wet samples was not achieved in two of the ten designed mixtures: PA 16 – 411 kPa and PA 11 – 333 kPa.

The percentage of indirect tensile strength ranges from 76.69 to 101.12%. The lowest values of the indirect tensile strength ratio for the observed mixtures: PA 11 – 76.24%, PA 8_M2 – 77.49% and PA 11_M1 – 79.78%, and the highest values of the indirect tensile strength ratio were determined for the following designed permeable asphalt mixtures: PA 16_M3 – 103.10%, PA 8 – 95.35% and PA 16 – 91.51%. The difference between the highest and lowest determined values of the indirect tensile strength ratio is 26.86%. ITSR higher than 100% was determined only for PA 16_M3. This mixture had high fineness and rather high binder content compared to other mixtures. It resulted in almost the same or slightly higher indirect tensile strength of wet specimens compared to dry specimens. According to AASHTO T283 and Šernas et al. (2021), the indirect tensile strength ratio (ITSR) has to be ≥ 80% for the determination of water sensitivity, but in agreement of the Swiss standard SN 640, the ITSR has to be ≥ 70%. In view of the results obtained from the SN 640 standard and the designed mixtures (see Figure 7), it was found that all mixtures complied with the minimum threshold, but according to the AASHTO T283, three of the ten tested mixtures did not reach the minimum value: PA 11 – 76.24%, PA 11_M1 – 79.78% and PA 8_M2 – 77.49%.

2.4. Water sensitivity after ultraviolet radiation

Figure 8 shows water sensitivity after ultraviolet radiation test results of the minimum and maximum samples with error bars. The average indirect tensile strength of dry samples ranges from 473 to 1100 kPa, and the average indirect tensile strength of wet samples ranges from 422 to 969 kPa. The highest values of the average indirect tensile strength of the dry samples are 1100 kPa (PA 16_M2), 989 kPa (PA 8_M2) and 878 kPa (PA 11_M2), while the lowest values are obtained for the following test mixtures: PA 11 – 473 kPa, PA 16 – 495 kPa and PA 8 – 538 kPa. The highest variation in the indirect tensile strength of dry samples is found in PA 16_M1 mixtures between 647 kPa and 909 kPa, while the lowest variation in dry samples between 1084 kPa and 1125 kPa is found in PA 16_M2 mixtures. The highest indirect tensile strength values of wet samples are obtained on average of the test mixtures: 969 kPa (PA 16_M2), 852 kPa (PA 16_M3) and 758 kPa (PA 8_M2), while the lowest test results for the following mixture samples are PA 11 – 422 kPa, PA 16 – 446 kPa, PA 8 – 504 kPa. It should be noted that the highest variation in the sample was found for PA 16_M1, which varied from 637 to 766 kPa and the lowest variation was for the PA 11 mixture, which varied from 412 to 432 kPa. The percentage of indirect tensile strength ranges from 76.69 to 101.12%. The lowest values of the indirect tensile strength ratio for the observed mixtures: PA 8_M2 – 76.69%, PA 8_M1 – 85.08% and PA 11 – 89.16%, and the highest values of the indirect tensile strength ratio were determined for the following designed permeable asphalt mixtures: PA 16_M3 – 101.12%, PA 8 – 93.66% and PA 11_M1 – 92.80%. The difference between the highest and lowest determined values of the indirect tensile strength ratio is 24.43%.

2.5. Mass loss

Figure 9 presents the mass loss results in the error bars with the minimum and maximum sample results. The average mass loss of Los Angeles after 300 revolutions ranges from 19.6% to 97.9%. The highest average mass loss was 97.9% (PA 16), 72.8% (PA 11), and 39.1% (PA 8), the lowest average mass loss was 19.6% (PA 16_M2), 21.1% (PA 8_M2), and 25.9%, which was found in the PA 8_M1 mixture. It should also be noted that the most significant variation in the sample was found in the error bar of PA 11, from 58.8% to 80.4%, while the least significant

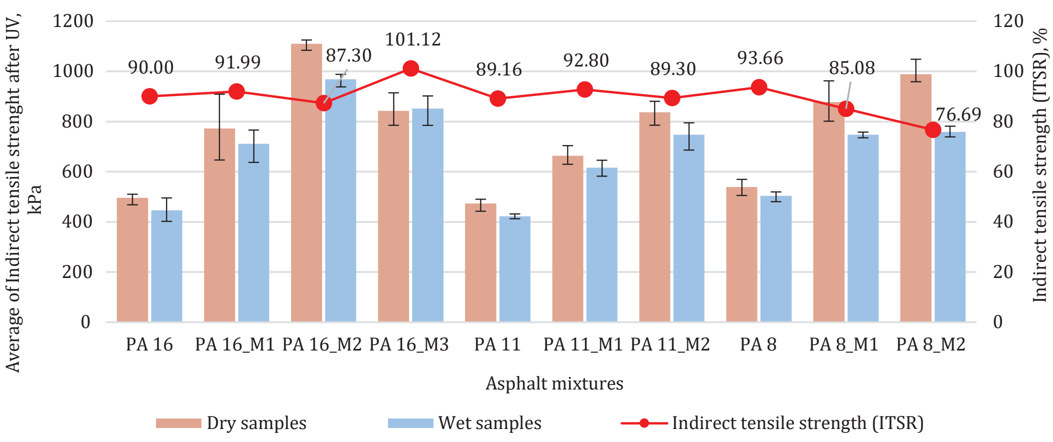

Figure 8. Results of water sensitivity after ultraviolet radiation

variation in the error bar of PA 8_M2 was observed in the error bars of PA 8, from 19.1% to 22.4%. The research work of Eisenberg et al. (2015) declared that the mass loss of a mixture must not exceed 20%. Only one design mixture, PA 8_M2, meets the minimum mass loss of 19.6%. All other permeable asphalt mixtures designed have values greater than the thresholds set in the articles mentioned above, between 1.1% and 77.9%.

A simple linear regression model was built to identify the dependence of mass loss after 300 revolutions of the Los Angeles drum and air voids content shown in Figure 10. The dependence between the mass loss of designed asphalt mixtures after 300 revolutions of the Los Angeles drum and the air voids is expressed by the linear regression formula

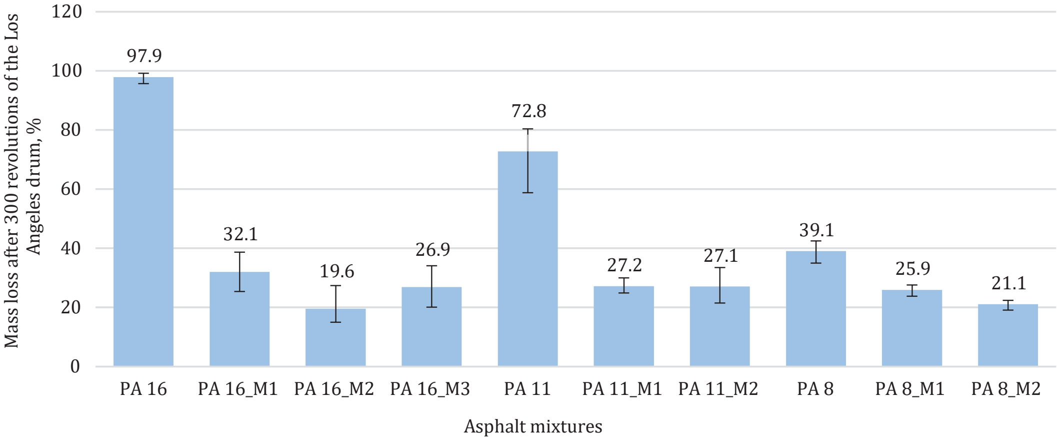

Figure 9. Results of mass loss

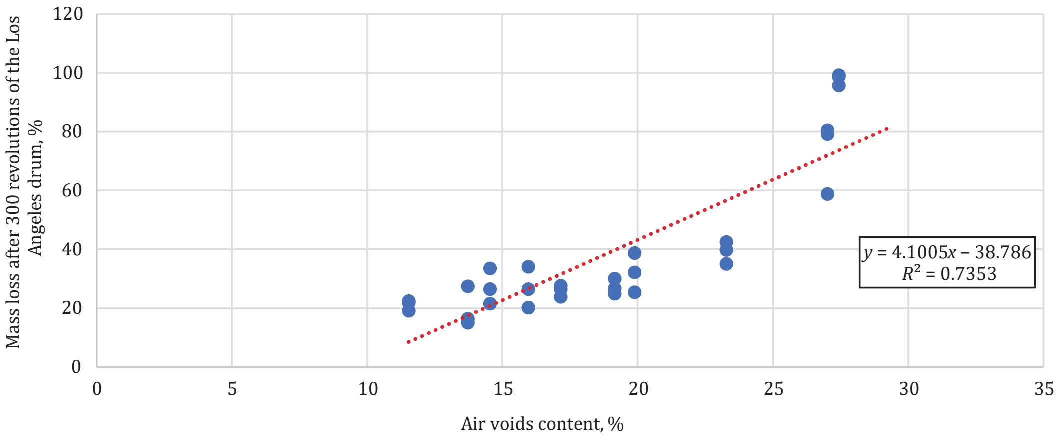

Figure 10. Dependence of the mass loss after 300 revolutions of the Los Angeles drum of asphalt samples on the air voids content

$\hat{y}(x) = 4.1005x - 38.786$. The coefficient of determination is represented by the square of the empirical correlation coefficient, which is $R^2 = 0.7353$ (see Figure 10). The square of the empirical correlation coefficient shows that the mathematical model explains 73.53% of mass loss after 300 revolutions of the Los Angeles drum of the designed asphalt samples variations in relation to the variation of air voids content of the designed asphalt samples.

2.6. Simple Additive Weighting (SAW)

The results of SAW are provided in Figure 11. As can be seen in Figure 11, the following porous asphalt mixtures are recommended for use to construct permeable asphalt pavements: PA 11 (0.729), PA 16 (0.684), PA 8 (0.512) and PA 16_M2 (0.508). The priority order of permeable porous asphalt mixtures based on the alternative classification is: PA 11 > PA 16 >> PA 8 > PA 16_M2 > PA 16_M1 > PA 8_M2 > PA 8_M1 > PA 16_M3 > PA 11_M3 > PA 11_M1.

2.7. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

The results of TOPSIS are presented in Figure 11. As can be seen in Figure 11, the following porous asphalt mixtures are recommended to be used to construct permeable asphalt pavements: PA 11 (0.745), PA 16 (0.631), PA 8 (0.408) and PA 16_M1 (0.398). The priority order of permeable porous asphalt mixtures based on the alternative classification is: PA 16 > PA 11 > PA 8 > PA 16_M1 > PA 8_M1 > PA 8_M2 > PA 16_M2 > PA 11_M3 > PA 11_M2 > PA 16_M1.

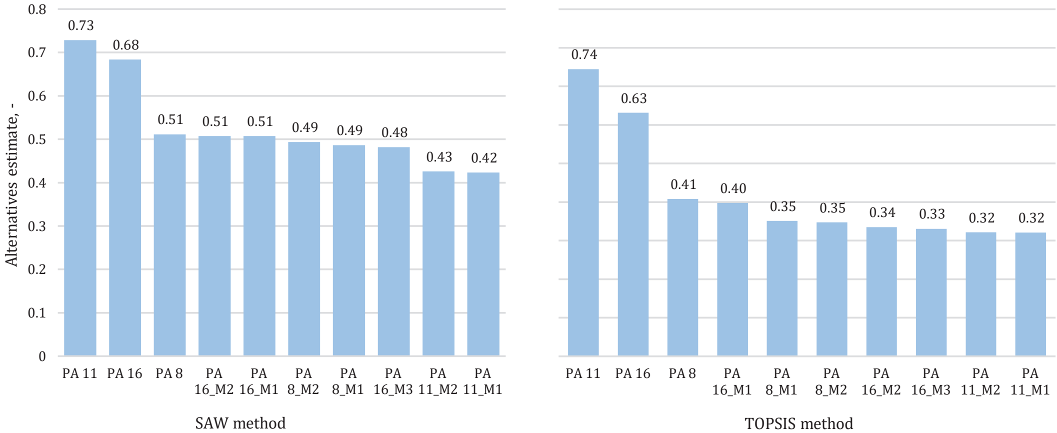

Figure 11. Results of SAW and TOPSIS methods

Conclusions

This article has described the performance of permeable asphalt mixtures depending on the different nominal maximum size (16 mm, 11 mm and 8 mm) and air voids content. Overall, 10 porous asphalt mixtures have been designed and tested in terms of air voids content, water permeability, water sensitivity and mass loss. In addition, the effect of ultraviolet radiation has been analysed. Porous asphalt pavements have higher porosity compared to asphalt concrete and, as a result, are more sensitive to aging. The main conclusions of this paper are as follows:

1. From all analysed asphalt mixtures, the PA 16 mixture, designed according to the technical requirements TRA ASPHALT 08, had the highest air voids content (27.4%), while the modified PA 8 mixture (PA 8_M2) had the lowest air void content (11.5%). It should be noted that all porous asphalt mixtures designed according to the technical requirements TRA ASPHALT 08, had 3.4–7.5% more air voids than other tested asphalt mixtures.
2. After applying simple linear regression models to analyse the vertical and horizontal water permeability of asphalt samples in relation to air void content, the determination coefficient (R^2) was 0.697 and 0.6816, respectively, for vertical and horizontal water permeability. As expected, the higher air void content results in higher permeability.
3. Indirect tensile strength increased due to ultraviolet radiation up to 27% depending on the mixture. This increase can be explained by the fact that bitumen aged and became harder (stiffer) during the expose to ultraviolet. However, there was no relationship between the increase in indirect tensile strength and air voids content. Therefore, a wider analysis is required to answer how the ultraviolet radiation affects the performance of porous asphalt.
4. Mass loss strongly depends on the air void content (R^2 – 0.7353). The higher the air void content, the higher amount of asphalt mixture are lost. During the test, the mixtures with air void content below 15% lost from 20% to 30%, while asphalt mixture PA 16 with the highest amount of air void (27.4%) practically broke down.
5. This study has revealed that asphalt pavements can be assumed as permeable asphalt pavements irrespective of nominal aggregate size without compromising their performance when:
   - The amount of air voids is 19–28%;
   - Vertical and horizontal permeability is not less than $0.5 \cdot 10^{-3}$ m/s;

- Water sensitivity of PA 8 and PA 11 mixtures is at least 90%, and for the PA 16 mixture – at least 80%.

6. Considering that the most important criteria for permeable asphalt mixtures are vertical water permeability (0.5), mass loss (0.3), and water sensitivity (ITSR) (0.2), SAW and TOPSIS prioritization methods have revealed that PA 11 and PA 16 from all tested asphalt mixtures have the highest overall weight (0.73 and 0.68 based on SAW method and 0.74 and 0.63 based on TOPSIS method). Since mixtures with such high air void content (about 27%) have lower durability, further research should be undertaken to determine how to improve it.

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