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SELECTED PROPERTIES OF POLYMER-MODIFIED BITUMENS

WYBRANE WŁAŚCIWOŚCI ASFALTÓW MODYFIKOWANYCH POLIMERAMI

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Abstract

The article presents an analysis of research results on bitumens modified with waste polymers polypropylene (PP) and polyethylene terephthalate (PET). The bitumens were modified under conditions consistent with the Plackett-Burman experimental design by appropriately selecting the mixing process variables. The results of basic tests are presented. The microstructure of bitumens modified with waste polymers was compared with two commercially available bitumens modified with styrene-butadiene-styrene (SBS) copolymer. The analysis of test results revealed certain similarities between laboratory-prepared bitumens and PmB 45/80-55. Modification of road bitumens 20/30 and 70/100 resulted in improvement particularly in the softening point temperature range. Furthermore, modification of certain binder parameters without changing its consistency proved possible. The possibility of polymer particle coagulation at higher homogenizer rotational speeds was also demonstrated.

Keywords: modified bitumen, waste polymer, Plackett-Burman experimental design, bitumen microstructure

Streszczenie

W artykule przedstawiono analizę rezultatów badań asfaltów modyfikowanych odpadowymi polimerami polypropylene (PP) i polyethylene therepthalate (PET). Asfalty zmodyfikowano w warunkach zgodnych z planem eksperymentu Placketta-Burmana, dobierając odpowiednio zmienne procesu mieszania. Przedstawiono wyniki badań podstawowych, takich jak temperatura mięknienia, penetracja, temperatura łamliwości wg Fraassa. Porównano mikrostrukturę asfaltów modyfikowanych odpadowymi polimerami z dwoma asfaltami dostępnymi komercyjnie modyfikowanymi kopolimerem styren-butadien-styren (SBS). Analiza wyników badań ukazała pewne podobieństwa pomiędzy asfaltami przygotowanymi w laboratorium a asfaltem PmB 45/80-55. Modyfikacja asfaltów drogowych 20/30 i 70/100 przyniosła poprawę szczególnie w zakresie temperatury mięknienia. Ponadto możliwa okazała się modyfikacja niektórych parametrów lepiszcza bez zmiany jego konsystencji. Wykazano również możliwość koagulacji cząstek polimeru przy wyższych prędkościach obrotowych homogenizatora.

Słowa kluczowe: asfalt modyfikowany, polimery odpadowe, plan eksperymentu Placketta-Burmana, mikrostruktura asfaltu

1. INTRODUCTION

Polymer-modified bitumens are a commonly used material for road pavement construction. Bitumens modified with SBS elastomer are typically utilized for this purpose. This copolymer allows for obtaining bitumen with very good mechanical properties, which translates into higher fatigue life of mineral-asphalt mixtures compared to traditional road bitumens. Development of work on polymer-modified bitumens (PmB) has led to obtaining binders in which the limits of SBS polymer content have been exceeded, after which the polymer becomes the continuous phase. The properties of bitumen in which so-called phase inversion has occurred depend to a greater extent on

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the properties of the polymer used for modification than on the bitumen [1]. Nevertheless, due to lower availability and higher production costs, these bitumens are used less frequently than PmB with a continuous bitumen matrix.

The properties of bitumens can be modified by agents such as synthetic waxes or styrene-butadiene-styrene copolymer, which have been known in the road industry for many years [2-3]. However, this does not imply stagnation in the field of bitumen modification, and research is ongoing worldwide to improve their properties using various modifiers. Some of these are thermoplastic polymers originally used for entirely different applications, such as the production of plastic bags [4-5]. The results of studies on new binder modifiers are often promising, although certain problems can also be observed. One such issue is the low stability of modified bitumens, which results in phase segregation between the polymer and bitumen [6]. This situation leads to a heterogeneous mixture that cannot be successfully used for the production of mineral-asphalt mixtures. Furthermore, there is a need to use waste and renewable materials in the industry [7]. This situation has led to research focusing on the use of bio-modifiers derived from wood pellets, straw, or vegetable oils [8]. Regardless of the modifier used, the ultimate goal of the research is to improve the properties of mineral-asphalt mixtures.

Research on modifying the properties of mineral-asphalt mixtures using plastics has so far been carried out by two methods [9]. The first of these is the so-called wet process. It involves modifying the binder with a polymer and then adding the polymer-modified bitumen to the aggregate. The second method is referred to as the dry method. In this method, plastics are added directly to the mixture without prior contact with the bitumen. Research has also been conducted in which the aggregate is coated with polymer. The plastic coating formed in this way increases the aggregate's resistance to crushing [10] and also reduces the aggregate's water absorption [11]. Studies have also indicated the possibility of using mixtures of various polymer materials [12], such as rubber waste from used car tires and recycled polyethylene terephthalate, for the construction of inexpensive and environmentally friendly roads [13].

The benefits of modifying mineral-asphalt mixtures with polymers are evident in both the dry and wet methods [4-6], [14-15]. The wet method applied in this study allows for determining the properties of the binder after modification and enables the entire added polymer to react in contact with the bitumen, which can be difficult to achieve with the dry method. Furthermore, the wet method allows for a preliminary assessment of the mineral-asphalt mixture's character based on the properties of the binder itself. This significantly reduces the amount of material used to select the optimal solution.

2. MATERIALS

2.1. Road Bitumens and Polymer-Modified Binders (PmB)

Waste polymers were used to modify road bitumens 70/100 and 20/30. The first is a soft bitumen primarily used for the production of bitumen emulsions and cold deep recycling. It can also be used as a binder for the wearing course of road pavements with low traffic intensity in SMA mixtures and bitumen concrete. The second is an bitumen with low penetration and high softening temperature. Due to its high sensitivity to low-temperature cracking, it is used for base and binder layers made of bitumen concrete with a high stiffness modulus. Preferred applications are roads with medium and high traffic volumes.

Polymer-modified bitumens (PmB) can also be used for the production of mineral-asphalt mixtures. They exhibit favorable properties at both low and high service temperatures. For the studies, two bitumens used in surface layers, PmB 45/80-55 and 45/80-65, were selected to compare their properties with bitumens modified with polymer waste materials. They are used on roads regardless of traffic load.

2.2. Waste polymers

Modification of the properties of road bitumens was carried out using two polymers derived from recycling. The first is polyethylene terephthalate (PET), primarily used for beverage packaging production. The second is polypropylene (PP), commonly used for the production of toys and food packaging. Both belong to the group of plastomers with a crystalline structure. An important fact is the relatively high softening temperature of PET compared to PP (approximately 100°C difference).

3. METHODS

3.1. Modification of bitumen with waste polymers

The research was based on the use of two reference bitumens, 20/30 and 70/100, and binders formed from their modification. Recycled waste polymers such as PET and PP were used to modify road bitumens, and selected basic and rheological properties of the resulting binders were then measured.

Laboratory-modified bitumens were produced by dispersing polyethylene terephthalate and polypropylene polymer particles in the matrix of 20/30 and 70/100 road bitumens. Using various values of variable factors affecting the homogenization process, initially eight bitumens modified with plastics used for many years in the production of, among others, food packaging and toys were obtained. Bitumen modification was carried out under conditions specified in Table 1 regarding polymer content, temperature, mixing speed and time, type of polymer, and type of base bitumen. The resulting bitumens were subjected to testing, and the obtained results allowed comparison of the properties of bitumens modified with recycled polymers. The experimental plan variables were selected using the Plackett-Burman elimination design.

Table 1. Plackett-Burman experiment design

Case	Independent variable						
	Mixing speed rpm/min^{-1}	Mixing temperature °C	Mixing time min.	Waste polymer content %	Bitumen type –	Waste polymer type –	Waste polymer granulation –
1	120	160	30	5	70/100	PP	<5.6
2	9500	160	30	2	20/30	PP	>5.6
3	120	180	30	2	70/100	PET	>5.6
4	9500	180	30	5	20/30	PET	<5.6
5	120	160	180	5	20/30	PET	>5.6
6	9500	160	180	2	70/100	PET	<5.6
7	120	180	180	2	20/30	PP	<5.6
8	9500	180	180	5	70/100	PP	>5.6

3.2. Basic properties of bitumens

The prepared bitumens were subjected to tests demonstrating their basic properties. The first of these was the softening point test determined by the ring-and-ball method according to the EN 1427 standard [16]. Two metal rings filled with bitumen are placed in a heated vessel containing water or glycerin with controlled, constant temperature increase and are loaded with steel balls. As the temperature rises, the weight of the balls causes deformation of the bitumen. The temperature at which the sample deformation reaches 25 ±0.4 mm is defined as the softening point.

The second test used to determine the basic properties of the binders is the penetration test conducted in accordance with EN 1426 [17]. The result is expressed as the penetration depth of a standardized needle vertically penetrating the bitumen sample at a temperature of 25°C, with the unit being 0.1 mm. The needle load is 100 g, and the loading time is 5 seconds. Bitumens with higher penetration values are classified as "soft," in contrast to binders considered "hard," which have lower penetration. Bitumen penetration is one of the factors enabling the classification of road bitumens according to the applicable European standard nomenclature. The penetration range, along with the minimum declared softening temperature, forms the basis for the designation of modified bitumens.

The next test was the measurement of Fraass cracking temperature performed according to EN 12593 [18]. A thin layer of bitumen placed on a bending metal plate undergoes deformation of a constant value at progressively lower temperatures. The temperature at which the force required to bend the plate with the sample decreases signifies the breaking of the continuity of the applied bitumen layer, i.e., a crack induced by low temperature and constant, standardized deformation. The test result expressed in degrees Celsius provides valuable information about the behavior of bitumen at low temperatures.

3.3. Analysis of the microstructure

The microstructure analysis of modified bitumens was carried out using a Carl Zeiss Axio Scope.A1 epi-fluorescence microscope at 100x magnification. Microstructure observation was performed on a fresh fracture of the sample by analyzing the image in reflected light. The image recorded according to EN 13632 [19] allowed determination of the structure of modified bitumens based on phase continuity (continuous polymer phase, bitumen phase, or continuity of both phases), phase homogeneity (homogeneous, heterogeneous), polymer particle size (small, medium, large), and shape of dispersed particles (round, elongated, other).

4. TEST RESULTS

4.1. Basic properties

The results of the basic properties tests of modified bitumens are presented in Table 2. They included the determination of penetration values, softening temperature, and Fraass cracking temperature. The nomenclature of polymer-modified bitumens was adopted according to Table 1, which defines modification parameters conducted according to the Plackett-Burman experimental design. Furthermore, the obtained values were compared with those for road bitumens before modification. Table 2 also includes data for two bitumens labeled as PMB. Polymer-modified bitumens PMB 45/80-55 and PMB 45/80-65 are commercially available bitumens based on modification technology using the SBS block copolymer (styrene-butadiene-styrene). These binders were developed to reduce the destructive effect of factors acting during the service life on bitumen pavements. The application of SBS elastomer in these bitumens enabled an improvement in the mechanical properties of mineral-asphalt mixtures compared to traditional road bitumens.

The conducted tests revealed the influence of waste polymers on the basic properties of road bitumens. Combinations of the experimental design numbers 1, 3, 6, and 8 containing 70/100 road bitumen demonstrated higher softening point values compared to the base bitumen from which they were derived. Among the modified bitumens, based on 20/30 bitumen, in two cases (combinations 2 and 7), significantly higher softening point values were also obtained. Combinations 4 and 5, despite the relatively high plastomer content (5%), exhibited softening point temperatures similar to the base bitumen, which may suggest lower compatibility between 20/30 bitumen and PET plastomer. It should be noted that some modified bitumens (2, 7, 8) had a higher softening point temperature than the commercially available polymer-modified bitumen PMB 45/80-55, while bitumen no. 8 showed a higher softening point even compared to PMB 45/80-65. Such an effect can be considered beneficial in terms of resistance to permanent deformation under high service temperatures of mineral-asphalt mixtures. Furthermore, modification of bitumen with waste polymers shows a significant influence on the softening temperature of the bitumen.

Modification of road bitumens with waste polymers can cause a significant change in the consistency of the base binders. The change in consistency is more noticeable in bitumens characterized by higher penetration. Table 2 shows that with appropriate selection of dependent variables, it is possible to achieve a consistency of polymer-modified bitumen close to that of 20/30 bitumen, regardless of the type of bitumen used for the modification. It can also be observed that in certain cases (combinations 2 and 7) no significant change in penetration compared to the base bitumen was found. Analysis of these cases suggests that it is possible to increase the softening temperature of bitumen by modification with waste polymers without significant change in bitumen consistency.

Table 2. Results of property designation for modified bitumen

Case	Independent variable							Dependent variable		
	A rpm/min^{-1}	B °C	C min	D %	E –	F –	G –	$T_{R\&B}$ °C	Penetration 0.1 mm	Breaking point temperature °C
1	120	160	30	5	70/100	PP	<5.6	46.2 ±0.6	72.6 ±1.2	-12.8 ±3.4
2	9500	160	30	2	20/30	PP	>5.6	65.9 ±3.4	24.1 ±1.3	-9.3 ±1.2
3	120	180	30	2	70/100	PET	>5.6	45.1 ±1.2	86.7 ±2.6	-16.2 ±1.9
4	9500	180	30	5	20/30	PET	<5.6	63.2 ±0.2	22.5 ±1.2	-8.5 ±2.0
5	120	160	180	5	20/30	PET	>5.6	63.4 ±0.5	28.2 ±1.2	-10.8 ±1.0
6	9500	160	180	2	70/100	PET	<5.6	46.5 ±0.3	76.6 ±3.5	-14.0 ±2.1
7	120	180	180	2	20/30	PP	<5.6	67.2 ±0.4	21.3 ±2.5	-8.0 ±1.8
8	9500	180	180	5	70/100	PP	>5.6	75.3 ±11.5	21.7 ±3.8	-12.0 ±1.2
20/30	–	–	–	–	–	–	–	61.3 ±1.2	27.4 ±2.1	-10.4 ±2.2
70/100	–	–	–	–	–	–	–	44.7 ±0.7	91.5 ±3.1	-15.4 ±2.0
PMB 45/80-55	–	–	–	–	–	–	–	63.7 ±2.5	66.6 ±2.8	-17.7 ±1.8
PMB 45/80-65	–	–	–	–	–	–	–	72.0 ±2.1	58 ±2.9	-18.5 ±1.6

Modification of binders with plastomers can also affect the results obtained during Fraass breaking point testing. Studies indicate that commercially used SBS polymer-modified bitumens achieve decidedly better low-temperature properties than laboratory-modified bitumens with waste polymers. However, this does not mean that the properties of PET- and PP-modified binders are at an unacceptable level. It is noteworthy that 20/30 bitumen is less sensitive to changes in low-temperature properties with higher polymer content. The results obtained for bitumen no. 3 indicate that softer bitumens like 70/100 will probably require shorter mixing times and lower polymer content compared to harder bitumens like 20/30 in order to achieve the most favorable low-temperature properties.

4.2. Microstructure of polymer-modified bitumens

To perform microstructure analysis of bitumens modified with PET and PP as well as bitumens modified with PmB 45/80-55 and PmB 45/80-65, digital images of the surfaces of prepared samples were captured using an epi-fluorescence microscope. Example microstructure images of the bitumens are presented in Figure 1. The microstructure images of the binders were processed, which enabled the determination of descriptive statistics and a box and whisker plot for the surface area of the polymer particles dispersed in the bitumen matrix.

All bitumens modified with waste polymers were characterized by a right-skewed asymmetric distribution of polymer particles. This is indicated by the skewness values given in Table 3. Such a distribution seems to be true for modified bitumens under the assumption

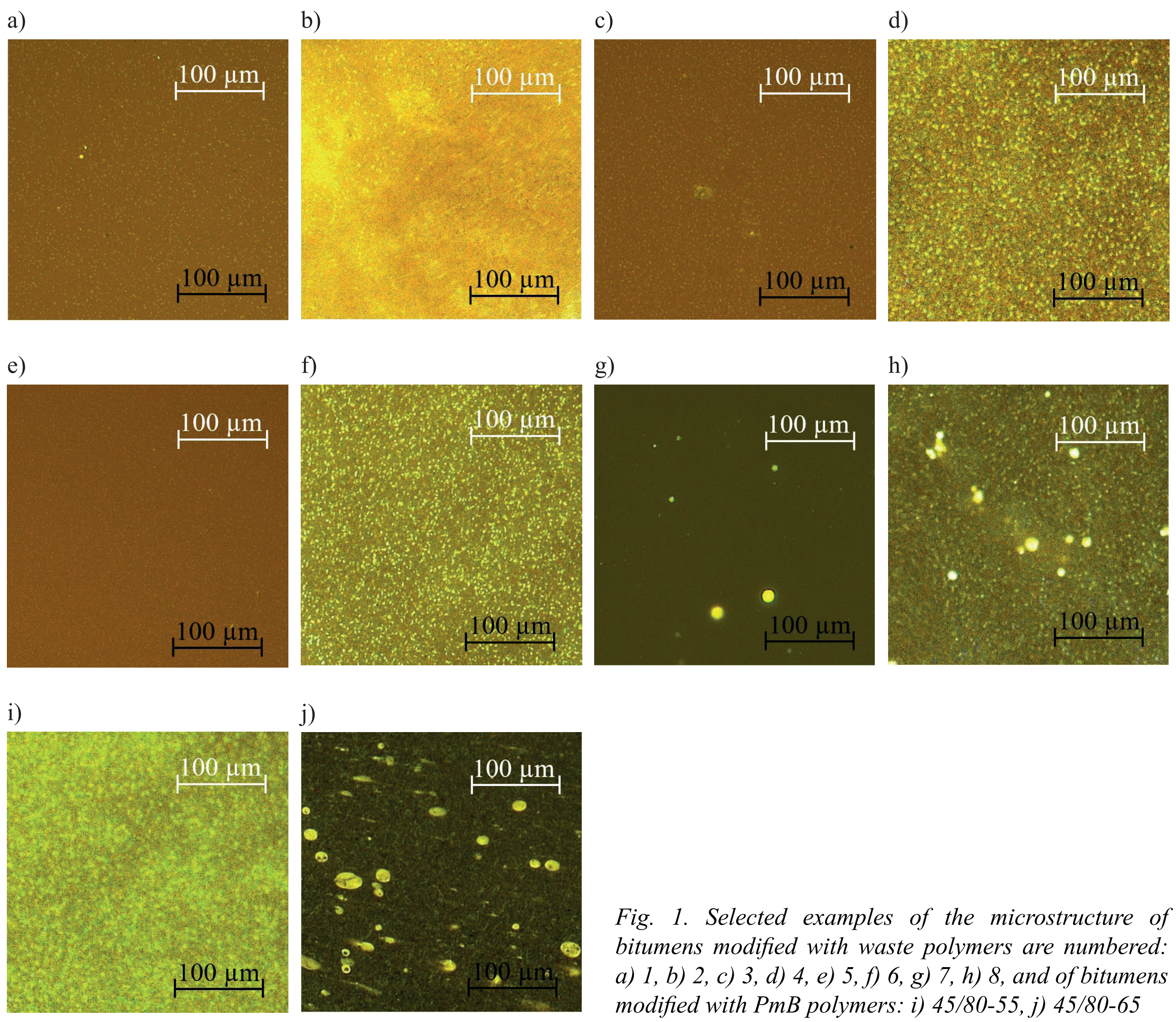

Fig. 1. Selected examples of the microstructure of bitumens modified with waste polymers are numbered: a) 1, b) 2, c) 3, d) 4, e) 5, f) 6, g) 7, h) 8, and of bitumens modified with PmB polymers: i) 45/80-55, j) 45/80-65

Table 3. Descriptive statistics of the surface area of polymer particles dispersed in polymer-modified bitumens

Feature	Case									
	1	2	3	4	5	6	7	8	45/80-55	45/80-65
Mean	2.1	3.3	1.9	10.3	3.2	9.7	7.3	9.2	12.4	119.1
Standard error	0.0	0.1	0.0	0.1	0.1	0.2	1.9	0.3	0.2	19.1
Median	1.9	2.1	1.4	8.3	2.3	7.4	1.4	6.5	9.3	37.4
Standard deviation	2.0	3.6	2.7	8.7	3.9	8.8	26.9	12.3	11.0	183.4
Variance	4.1	12.8	7.4	75.7	15.3	76.8	722.4	150.4	120.5	33640.7
Kurtosis	374.4	4.3	4782.5	4.5	146.7	4.6	50.9	59.1	3.8	5.5
Skewness	11.0	1.9	58.6	1.7	7.8	1.8	6.8	6.2	1.6	2.3
Range	88.9	22.0	236.0	72.2	108.8	69.0	257.3	184.2	79.6	946.6
Minimum	0.5	0.1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.1
Maximum	89.3	22.1	236.5	72.7	109.2	69.4	257.8	184.6	80.1	946.7

of a polymer dispersion scheme in the bitumen matrix involving primarily the dispersion of small particles, which at higher polymer content can agglomerate into larger clusters. This assumption is also confirmed by the frequency distribution of the commercially available PMB 45/80-55. Produced by a Polish refinery, this modified bitumen also exhibits a right-skewed asymmetric distribution of particle size frequency. Comparing the microstructure images of PMB 45/80-65 and PMB 45/80-55 modified bitumens also reveals larger polymer particle sizes in the former binder. This indicates a tendency for the polymer to group into larger clusters at higher bitumen modification levels. The increase in polymer particle size observed under the microscope with increasing polymer dosage is also confirmed by image analyses conducted by other researchers [20].

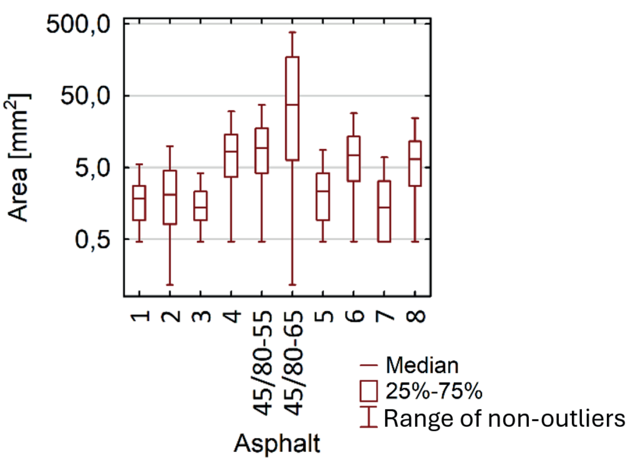

Fig. 2. A box and whisker plot of polimer particle surface area

A box and whisker plot presented in Figure 2 shows the size range of polymer particles dispersed in the bitumens. It should be noted that PmB 45/80-65 bitumen has significantly larger dispersed particle sizes than the other modified bitumens. The other commercially available bitumen, PmB 45/80-55, was characterized by much smaller particle sizes most similar to the polymer-modified bitumens numbered 2, 6, and 8. These were PP and PET modified bitumens produced at higher homogenizer rotational speed. It can therefore be hypothesized that a higher rotational speed influenced the coagulation of the dispersed particles, thus increasing their size. The first and third quartiles of bitumens numbered 1, 3, 5, and 7 fall within the (0;5 μm) range. These were bitumens modified at low rotational speed. The median surface area of these bitumen particles seems to confirm the rule that low rotational speed is a factor influencing the achievement of smaller dispersed polymer particle sizes. An exception to this rule is bitumen no. 2. Its production according to the experimental plan required high rotational speed, but the obtained polymer particle sizes were similar to those obtained under low rotational speed conditions. Explaining this anomaly requires further examination of other independent experimental variables. Bitumen no. 2 was produced at lower temperature and shorter mixing time. Therefore, despite high rotational speed during the modification process, the polymer particles did not have time to coagulate and thus form larger surface area particles. The bitumen with the largest polymer particle surface area was PmB 45/80-65.

The arithmetic mean was found not to be an adequate measure of central tendency for the obtained frequency distributions, as illustrated by descriptive statistics in Table 3. Both analysis of variance and the sample standard deviation revealed a large dispersion of polymer particle surface areas from the arithmetic mean. The results showed a wide range of particle surface areas dispersed in the bitumen matrix. Furthermore, the frequency distribution was leptokurtic for all investigated cases. Notably, bitumens numbered 2, 4, and 6 were the most similar to PMB bitumens in this respect. For the remaining bitumens, it can be inferred that there is a greater number of outlier observations.

The analysis of the microstructure images of polymer-modified binders provided information about the morphology of the bitumens (Table 4). According to EN 13632 [20], the structure of modified bitumens is described using a set of letter codes. The code set characterizes the bitumen with the following letter notations:

1. For describing phase continuity:
   a. Continuous polymer phase – „P",
   b. Continuous bitumen phase – „B",
   c. Continuity of both phases – „X".
2. For describing phase homogeneity:
   a. Homogeneous – „H",
   b. Heterogeneous – „I".
3. For describing polymer particle size:
   a. Small (<10 μm) – „S",
   b. Medium (10 – 100 μm) – „M",
   c. Large (>100 μm) – „L".
4. For describing the shape of dispersed particles:
   a. Round – „r",
   b. Elongated – „s",
   c. Other – „o".

Table 4. Mikrostructure of polimer-modified bitumens according to EN 13632 [20]

Feature	Case									
	1	2	3	4	5	6	7	8	45/80-55	45/80-65
Phase continuity	B	B	B	B	B	B	B	B	B	B
Homogeneity	H	H/I	H	H	H/I	H	H	H/I	H	H
Size	S	S	S/M	S	S	S	S/M	S/M	S	S/M
Shape	r	r/s	r	r	r	r	r	r/o	r	r/s

Mixed notations were also used when polymer particles with different shapes, such as round and elongated, were observed in samples of a given bitumen. It is worth noting that all polymer-modified bitumens had a continuous bitumen phase. Presumably, a significantly higher polymer content would be required to reverse the phases, where the polymer would form the continuous phase and bitumen would be dispersed within it, acting as a plasticizer. Bitumens modified with PET and PP, similar to PMB, exhibited similar shapes of dispersed particles. Bitumens numbered 1, 3, 4, 5, 6, and 7, like PMB 45/80-55, had microstructures characterized by round, smooth-shaped particles. Meanwhile, PMB 45/80-65, in addition to round particles, also had elongated particles, similar to bitumen number 2. It should be noted that not all modified bitumens were classified as homogeneous. This may indicate the need to improve polymer-bitumen compatibility in some cases. Bitumens 2, 5, and 8, depending on the observed sample, had either homogeneous or heterogeneous phases, with their common feature being the use of polymer particles larger than 5.6 mm, suggesting the influence of polymer particle size on bitumen homogeneity.

5. CONCLUSIONS

The article focuses on the evaluation of selected properties of bitumens modified with waste polymers: polyethylene terephthalate and polypropylene. Based on the conducted studies, the following conclusions were drawn:

- It is possible to select mixing process parameters to change selected bitumen properties without significant change in binder consistency.
- Modified bitumens exhibited a right-skewed asymmetric distribution of dispersed polymer particle surface areas.
- The morphology of bitumens modified with waste polymers was more similar to PMB 45/80-55 bitumen than to PMB 45/80-65, which contains polymer particles with larger surface area.
- Higher rotational speed in the bitumen modification process may result in coagulation of polymer particles.
- Modification with waste polymers can cause significant change in bitumen consistency.
- Modification with waste polymers can lead to a significant increase in softening temperature, suggesting a beneficial effect of waste polymers on resistance to permanent deformation of mineral-asphalt mixtures at high service temperatures.
- Appropriately selected process parameters for modification of bitumen with waste polymers allow maintaining favorable low-temperature properties compared to base bitumen.
- Modification of 70/100 bitumen using waste polypropylene allowed obtaining a consistency corresponding to 20/30 bitumen with a beneficially higher softening temperature and better low-temperature properties compared to 20/30 bitumen properties. This indicates the potential for practical use of waste polymer-modified bitumens in constructing durable road pavements.

REFERENCES

[1] *Poradnik asfaltowy* 2023.
[2] Mazurek G.: *Ocena reologicznych zmian w strukturze asfaltu spowodowanych dodatkiem wosku syntetycznego F-T*, Drogownictwo, nr 6, 2015.
[3] Pakholak R., Plewa A., Hatalski R.: *Evaluation of selected technical properties of bitumen binders modified with SBS copolymer and crumb rubber*, Structure and Environment, Vol. 12 (1), 2020, doi: 10.30540/sae-2020-002.
[4] Rajput P.S., Yadav R.K.: *Use of Plastic Waste in Bituminous Road Construction*, International Journal for Science Technology and Engineering, 2016.
[5] Swami V., Jirge A.: *Use of waste plastic in construction of bituminous road*, International Journal of Engineering Science and Technology (IJEST), 2012.
[6] Becker Y., Méndez M.P., Rodríguez Y.: *Polymer modified asphalt*, 2001.
[7] Domínguez F.J.N., García-Morales M.: *The use of waste polymers to modify bitumen*, Polymer Modified Bitumen, Elsevier, 2011, 98-135. doi: 10.1533/9780857093721.1.98.
[8] Mousavi M., Kabir S.F., Fini E.H.: *Polyphosphoric Acid's synergy with bio-modified bituminous composites*, Resources, Conservation and Recycling, 168, 2021, 105310, doi: 10.1016/j.resconrec.2020.105310.
[9] Kalantar Z.N., Karim M.R., Mahrez A.: *A review of using waste and virgin polymer in pavement*, Constr. Build. Mater., 33, 2012, 55-62, doi: 10.1016/j.conbuildmat.2012.01.009.
[10] Anand R.M., Sathya S.: *Use of Plastic Waste in Bituminous Pavement*, International Journal of ChemTech Research, 10, (2017), 804-811.
[11] Chavan A.J.: *Use of plastic waste in flexible pavements*, International Journal of Application or Innovation in Engineering & Management (IJAIEM), 2013.
[12] Joohari I.B., Giustozzi F.: *Chemical and high-temperature rheological properties of recycled plastics-polymer modified hybrid bitumen*, Journal of Cleaner Production, 276, 2020, 123064, doi: 10.1016/j.jclepro.2020.123064.
[13] Karahrodi M.H., Jazani O.M., Paran S.M.R., Formela K., Saeb M.R.: *Modification of thermal and rheological characteristics of bitumen by waste PET/GTR blends*, Construction and Building Materials, 134, 2017, 157-166, doi: 10.1016/j.conbuildmat.2016.12.134.
[14] Ahmadinia E., Zargar M., Karim M.R., Abdelaziz M., Ahmadinia E.: *Performance evaluation of utilization of waste Polyethylene Terephthalate (PET) in stone mastic asphalt*, Construction and Building Materials, 36, 2012, 984-989, doi: 10.1016/j.conbuildmat.2012.06.015.
[15] Appiah J.K., Berko-Boateng V.N., Tagbor T.A.: *Use of waste plastic materials for road construction in Ghana*, Case Studies in Construction Materials, 6, 2017, 1-7, doi: 10.1016/j.cscm.2016.11.001.
[16] EN 1427: Bitumen and bituminous binders – Determination of the softening point – Ring and Ball method, 2015.
[17] EN 1426: Bitumen and bituminous binders – Determination of needle penetration, 2015.
[18] EN 12593: Bitumen and bituminous binders – determination of the Fraass breaking point, 2015.
[19] EN 13632: Bitumen and bituminous binders – Visualisation of polymer dispersion in polymer modified bitumen.
[20] Brzozowska T., Makomaski G., Zieliński J., Legocka I.: *Struktura asfaltu modyfikowanego kopolimerem styren-butadien-styren (SBS) i woskiem syntetycznym*, Elastomery, 21 (1), 2017.