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The influence of selected additives on improving the properties of mastic asphalt

Abstract: In road construction in Poland, mastic asphalt is not a leading mixture. Traditional mixtures, mainly asphalt concrete (AC) and stone mastic asphalt (SMA) dominate. Nevertheless, mastic asphalt (MA) remains an attractive material due to its specific properties, such as low air void content and the possibility of laying without compaction. This paper reviews selected studies on additives used to improve mastic asphalt performance, focusing on Trinidad Epuré natural asphalt (TE), zeolites, and crumb rubber from waste tires. Experimental research analyzed the effect of TE addition (10% and 20% by binder mass) on the properties of MA 11 mastic asphalt in comparison with a reference mixture. The results showed that TE improved rutting resistance, particularly in mixtures with higher binder content. Tests also covered the use of natural (clinoptilolite) and synthetic (NaP1) zeolites. A 5% addition allowed production temperature to be reduced from 215°C to 180°C, with varied effects on rutting resistance. Furthermore, laboratory tests investigated the influence of crumb rubber on MA 8 mixtures with 35/50 bitumen, applied by wet and dry processes. Rubber addition enhanced stiffness and deformation resistance, especially when incorporated into the binder. The findings confirm that these additives can improve mechanical and technological properties of mastic asphalt and support its broader use in specialized applications.

Keywords: crumb rubber, mastic asphalt, natural asphalt, rut resistance, stiffness modulus, zeolites.

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1. INTRODUCTION

The article presents a review of additives used for modifying mastic asphalt (MA) and their influence on the properties of the mixture. The analysis included mastic asphalt with the addition of natural asphalt, zeolites, and crumb rubber derived from used car tires. Previous literature studies indicate various possibilities for improving the properties of mastic asphalt through the use of additives such as Trinidad Epuré natural asphalt, zeolites, and recycled tire rubber. Trinidad Epuré natural asphalt increases binder stiffness and improves rutting resistance, zeolites enable a reduction in production temperature, and rubber improves rheological properties and fatigue durability of the pavement. The authors propose a comprehensive approach to selecting additives depending on the required performance properties of asphalt mixtures, focusing on the analysis of their mechanical and technological characteristics. In Poland, the most popular mixtures are asphalt concretes or mixed types, whose composition is adapted to the structural layer and expected traffic loads. Another widely used group is stone mastic asphalt (SMA) mixtures, as well as increasingly popular SMA-MA mixtures, which combine the features of mastic asphalt and SMA: high binder and filler content together with a strong aggregate skeleton. It can be observed that the development aimed at improving the properties of mastic asphalt has been less intensive in recent years compared to other mixtures, despite the numerous advantages of this material. Due to its composition, mastic asphalt is an exceptionally tight mixture. It can be produced both in stationary asphalt plants and in mobile cooker. The specific parameters of mastic asphalt make it suitable for application in hard-to-reach areas where proper compaction of traditional mixtures is not possible. Compared to traditional asphalt mixtures, mastic asphalt contains more binder, which positively affects fatigue durability, but at the same time increases susceptibility to plastic deformations [1]. Particular attention should be given to bridge decks, where mastic asphalt serves both as waterproofing and as a protective layer for the deck insulation [2]. Mastic asphalt is widely used on bridge pavements as a protective insulation layer due to its unique properties: low air void content and high durability [1-2] which directly translates into excellent impermeability of the mixture. Mastic asphalt is characterized by a high binder content ranging from 7% to 10%, with filler content between 20% and 40%. The technological temperatures for laying the mixture range from 220°C to 240°C [3]. This is associated with the need to ensure adequate workability of the mixture, even when hard paving bitumens are used.

Mastic asphalt on bridge structures can be applied in the following layers:

- Wearing course – responsible for direct contact with vehicular traffic and serving a similar function as in traditional road pavements. Due to the specific operating conditions, it must exhibit high impermeability and cracking resistance.
- Protective waterproofing layer – protects the insulation against mechanical damage during pavement installation. It should also demonstrate resistance to water and traffic-induced stresses.
- Waterproofing layer – plays a crucial role in protecting the bridge deck slab from water penetration. Additionally, it ensures a durable bond between the concrete deck and the pavement layers.

In many countries, asphalt felt is used as a waterproofing layer on concrete bridge decks, upon which a protective layer of mastic asphalt is then applied [4]. However, exposing the asphalt felt to high temperatures can lead to its degradation, especially if the material has not been designed to withstand temperatures exceeding 180°C [5]. Improper selection of felt for such conditions may result in the formation of gas blisters caused by the thermal decomposition of polymers contained in the felt. This, in turn, can lead to the detachment of the mastic asphalt from the felt or the felt from the concrete surface.

To reduce the risk of overheating, various methods are applied to lower the production temperature of mastic asphalt. Examples include the addition of amide waxes [6-7] or the use of zeolites [8]. However, caution must be exercised to ensure that such modifications do not compromise the quality of mastic asphalt – its durability and workability must remain at an appropriate level in order to prevent premature pavement damage.

The properties of bitominous mixtures (MMA) are significantly influenced by the quality of the binder used. Materials must ensure pavement durability under varying climatic conditions – with high stiffness required during summer and sufficient flexibility in winter. To enhance these properties, asphalts are modified with additives that positively affect their performance in service [9].

According to WT-2 guidelines [10], relatively hard binders such as 35/50, MG 35/50-57/69, or polymer-modified bitumen (PMB 25/55-60) should be used for mastic asphalt. Polymer modification allows for an extended operating temperature range; however, there is a risk of polymer network degradation at the high production and laying temperatures. Adhering to technological regimes and applying viscosity-reducing agents make it possible to preserve the properties of modified asphalts.

According to the WT-2 guidelines [10], mastic asphalt used for the protective waterproofing layer may contain aggregates of 8, 11, or 16 mm, together with binders such as paving grade 35/50, MG 35/50-57/69, or polymer-modified PMB 25/55-60. For wearing courses, the following mixtures are permitted: MA 5 (for kerb zones), MA 8, MA 11, SMA 11, BBTM 11, and, in cases where noise reduction is required, SMA 5, SMA 8, or BBTM 5. A typical system involves two layers with a thickness of about 4 cm each [11]. In 2011, material guidelines for bridge pavements were developed at the Warsaw University of Technology [12], classifying structures according to the type of waterproofing and bridge deck slab. For high traffic categories (KR 5-7), the protective layer is divided into an upper and lower section, with the total thickness of the pavement ranging from 6 to 11 cm. In other countries, including Germany, the Netherlands, and China, similar solutions are applied, but there are also significant differences. In Germany, for example, the construction depends on the deck type: two-layer systems with mastic asphalt as the protective layer are standard, while the wearing course is often made of SMA, asphalt concrete, or porous asphalt.

2. MATERIALS AND METHODS

2.1. SCOPE OF THE STUDY

Three distinct groups of modifiers Trinidad Lake Asphalt, zeolites, and crumb rubber were incorporated into different mastic asphalt mixtures. The individual series of mixtures were developed during separate phases of the research, reflecting the nature and schedule of laboratory work carried out over an extended period. They were of rather practically oriented provided not for one composition of mastic asphalt mixture, which differ with asphalt binder types and granular properties. Consequently, each experimental set was prepared using the materials available at the given stage, based on the currently supplied batches of aggregates, binders, and modifiers.

2.2. MASTIC ASPHALT MIXTURES WITH TRINIDAD LAKE ASPHALT

Trinidad natural asphalt is extracted from the Trinidad Lake Asphalt deposit on the island of Trinidad, off the coast of Venezuela. The refined product (Trinidad Epuré, TE) contains soluble asphalt (53-55%), mineral matter (36-37%), and organic substances insoluble in CS_2 (9-10%) [13]. The soluble asphalt fraction consists of maltenes (63-66%) and asphaltenes (34-37%) [13].

The addition of TE to paving bitumen increases its stiffness, which is reflected in a decrease in penetration values and an increase in softening point [13-16]. The property changes are proportional to the additive content up to about 50%, above which unfavorable effects caused by the high mineral content begin to dominate. With increasing TE content, viscosity also rises, which can hinder the workability of bituminous mixtures and increase the risk of cracking. Likewise, the stiffness modulus G^* increases, while the phase angle δ decreases, meaning that the binder becomes more elastic. The rutting parameter $G^*/sin\delta$ rises progressively with TE concentration – at around 33% the increase is 4.5 times, and at 50% even up to 10 times, which is not recommended. TE also reduces the Penetration Index, increasing the thermal sensitivity of the binder, though this effect may be partially offset by short-term aging [14].

In the study, a single mastic asphalt mixture, MA 11 was tested. Its composition was based on limestone filler supplied by Trzuskawica S.A. (Nowiny, Poland) and granodiorite aggregates, including an all-in aggregate 0/4 fraction and coarse aggregate fractions 4/8 and 8/11, sourced from KSS Bartnica (Braszowice, Poland). The grading curve of the designed mineral mixture is shown in Fig. 1.

Road bitumen 35/50 (PKN Orlen, Płock) was selected as the base binder, consistent with its recommendation for mastic asphalt bridge pavements by the Polish road administration [10]. Its widespread use in both road and bridge surfacings throughout Poland further supports this choice. The modifying agent employed was Trinidad Epuré TE Z 0/8, supplied by CMS Polska (Gdańsk).

In the asphalt mixture design, three levels of binder content were applied to enable a systematic assessment of how variations in binder amount influence the mechanical response and deformation resistance of the MA 11 mixture. These levels were obtained by adopting a variable, weight-defined filler binder ratio of 4.0, 3.6 and 3.2, which assuming a constant filler content in the mineral mixture corresponds to progressively increasing binder contents of 6.9%, 7.7% and 8.7%, respectively. All design assumptions are consistent with national mastic asphalt design practice in Poland.

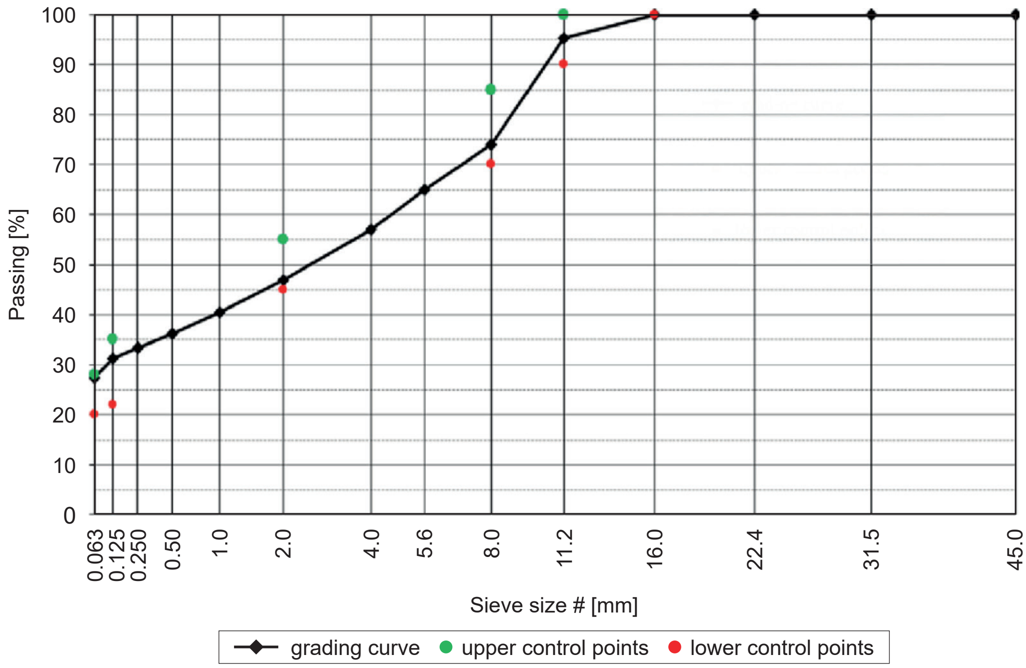

Fig. 1. Grading curve of the tested MA 11 mixture

Own studies were carried out on an MA 11 mixture with two levels of TE addition: 10% and 20% by binder mass, along with a reference mixture without TE, to evaluate the impact of the modifier on mechanical behaviour and resistance to permanent deformation.

2.3. MASTIC ASPHALT MIXTURES WITH ZEOLITES

The foamed asphalt enable to lower the technological temperatures. This technology is known especially for asphalt concrete mixtures. The foaming process can be realized in two ways: using water or zeolites [17]. Zeolites are aluminosilicates with a framework structure containing voids (chambers and channels) in which zeolitic water can be stored. This water can be removed by heating and then reabsorbed or replaced by other substances. Thanks to this property, zeolites are used in bituminous mixtures to foam the binder and lower technological temperatures [8], [16]. The addition of water-saturated zeolite to a hot mixture causes the release of water vapor, which leads to binder foaming, reduced viscosity, and improved workability and adhesion to the aggregate at lower temperatures. Lowering the production temperature of MMA brings numerous benefits: it reduces the emission of fumes and aerosols, improves working conditions, allows for longer transport times, extends the road construction season, and reduces energy consumption. According to the German Asphalt Association, lowering the temperature by 30°C allows for savings of at least 9 kWh of electricity and 0.9 liters of heating oil per ton of mixture, while reducing asphalt fume emissions by more than 87.5% [18]. To date, the use of zeolites in warm mix asphalt (WMA) technology has mainly concerned asphalt concrete and SMA mixtures [18-20].

In this study, two mastic asphalt mixtures MA 8 and MA 11 were selected for further analysis. These mixtures represent the solutions most frequently applied in bridge pavement systems in Poland, and their composition was therefore prepared in line with the relevant national technical guidelines for such applications [10]. Both mixtures contained limestone filler produced by Trzuskawica S.A. (Nowiny, Poland), while the aggregate structure was based on gabbro fractions 0/2, 2/5, 4/8 and 8/11 supplied by KSS Bartnica (Braszowice, Poland). This material configuration reflects common practice in domestic engineering projects and provides a representative basis for evaluating the behaviour of mastic asphalt under conditions typical for bridge surfaces. The grain size curves of the MA mixtures tested are shown in Figs. 2 and 3, for MA 8 and MA 11 respectively.

Two types of binders were used in the study: road bitumen 35/50 (PKN Orlen, Płock, Poland) and SBS-modified bitumen PMB 25/55-60 (PKN Orlen, Płock, Poland). The binder content in both mixtures was set above the minimum level required by national guidelines [10], adopting a value of 6.5% relative to the total mass of the mastic asphalt. This ensured suitable workability and cohesion of the material during sample preparation and subsequent laboratory testing.

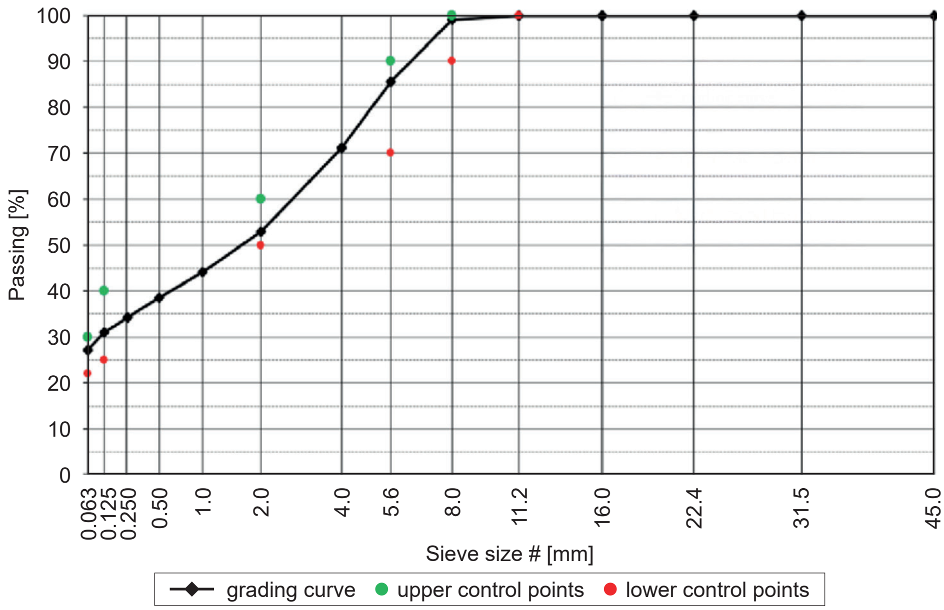

Fig. 2. Grading curve of the tested MA 8 mixture

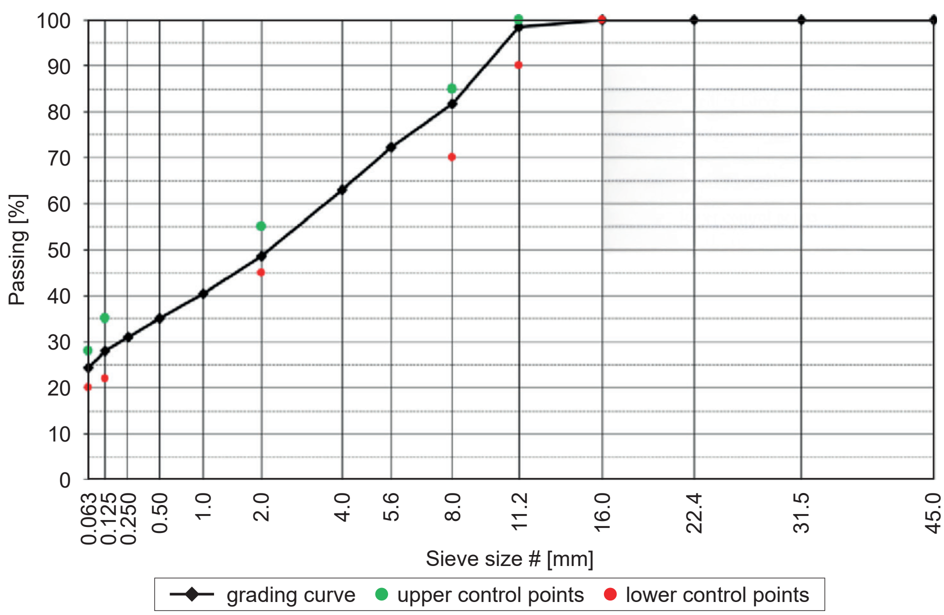

Fig. 3. Grading curve of the tested MA 11 mixture

Based on the materials described earlier, which included two aggregate gradations and two types of bitumen, four variants of mastic asphalt were prepared and subsequently modified with zeolite additives. To evaluate the influence of these mineral activators, each mixture was supplemented with 5% natural zeolite, clinoptilolite sourced from Sokyrnytsya in the Transcarpathian region (designated 5% ZN) and with 5% synthetic zeolite Na-P1 produced at Lublin University of Technology (designated 5% ZS). The unmodified reference mixtures were denoted as 0% Z. Samples of the reference mixtures were molded at 215°C, whereas the mixtures containing zeolites were formed at a reduced temperature of 180°C, reflecting typical procedures for low-temperature mastic asphalt production and enabling assessment of how the zeolite additives influence the forming process and overall material behaviour.

2.4. MASTIC ASPHALT MIXTURES WITH CRUMB RUBBER

Crumb rubber powder obtained from end-of-life tires enhances the deformation resistance of bituminous binders by increasing viscosity and reducing thermal susceptibility, while also improving fatigue performance [21]. Tire shredding is carried out using cryogenic or mechanical methods, which differ in energy demand, fragmentation efficiency, and particle morphology [22-27]. Both techniques produce material suitable for binder modification [28]. According to EN 14243-1 [29], rubber materials range from coarse shreds to fine powder, with the latter being most relevant for bituminous applications [21].

When incorporated into hot binder, crumb rubber undergoes swelling through the absorption of light fractions, partial devulcanisation of sulfur bonds, and subsequent dispersion and homogenisation within the binder matrix [30-31]. Two principal categories of rubber-modified binders are used: asphalt rubber containing at least 15% rubber, and terminal blends produced in refineries with 5-18% fine particles [32]. Their production requires controlled mixing and maturation at elevated temperatures (175-190°C) to achieve a uniform structure [33].

Crumb rubber can be introduced via the wet method with strong physicochemical interaction or the dry method, known domestically as "GUFI" where rubber acts mainly as an additional aggregate fraction [22], [24], [28],[34-35]. Previous studies have shown very good deformation resistance in rubber-modified mastics, with the most favourable balance of stiffness and flexibility observed at moderate rubber contents (12%), whereas higher amounts increased viscosity and led to excessive stiffening [36].

As part of the study, the mastic asphalt mixture MA 8 was employed. This mixture, designed for traffic categories KR3-KR7 and commonly used in Poland as a protective layer in bridge pavement systems, was prepared in accordance with the WT-2 technical guidelines [10]. In the study, a single mastic asphalt mixture MA 8 was used. The mixture contained limestone filler produced by Trzuskawica S.A. (Nowiny, Poland), while the aggregate structure was based on gabbro fractions 0/2, 2/5, 4/8 supplied by KSS Bartnica (Braszowice, Poland).

The grading curve of the designed mineral mixture is shown in Fig. 4.

Road bitumen 35/50 (PKN Orlen, Płock, Poland) served as the binder, reflecting its wide use in domestic engineering practice. The binder content was fixed at 7% by mixture mass.

Three variants of mixtures were developed for the study:

1. Reference mixture M1 – did not contain rubber. Its grading corresponded to the requirements for mastic asphalt MA 8 in accordance with WT-2 guidelines [10].
2. Mixture M2 – contained an addition of crumb rubber powder (fraction 0/0.6 mm), which was added to asphalt 35/50 at 3% of the binder mass (wet process). Based on the literature review, this technology allows rubber additions of up to 15% of the asphalt mass. In this study, however, a low dosage was chosen in order to assess the minimum threshold for effective modification.
3. Mixture M3 – modified with the addition of crumb rubber granulate of the 2/5 mm fraction, which replaced 10% of the gabbro aggregate of the same fraction (equivalent to 1.11% of the total mixture mass). In the dry process, the literature indicates a rubber addition range of 1.5% to 3% of the aggregate mass. In this version, only 1% was used in order to verify whether such a small share of granulate could affect the mixture's properties, particularly considering the possibility of partial melting during mixing.

All three mixtures (M1, M2 and M3) were designed with identical proportions of the mineral components and the asphalt binder. Each mixture consisted of 25% limestone filler, 29% gabbro 0/2 mm, 11% gabbro 2/5 mm, 28% gabbro 4/8 mm and 7% bitumen 35/50. The only distinction between the mixtures was the form and amount of crumb rubber introduced as an additional component. In mixture M2, fine crumb rubber powder was incorporated into the binder using the wet process, corresponding to 3% of the asphalt mass, which translated to 0.21% of the total asphalt mixture mass. In mixture M3, coarse crumb rubber granulate (2/5 mm) was introduced using the dry process by replacing 10% of the gabbro aggregate of the same fraction, equivalent to 1.11% of the total mixture mass.

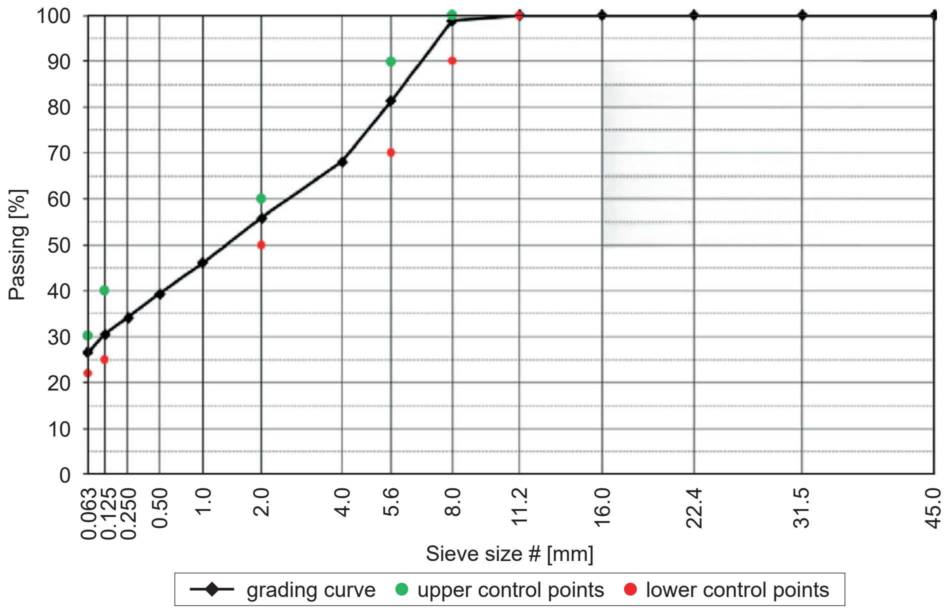

Fig. 4. Grading curve of the tested MA 8 mixture

2.5. PREPARATION OF MASTIC ASPHALT MIXTURE

After preparing the binders, the production of the mineral mixtures was carried out. The corresponding binders and aggregate blends were then heated in a laboratory oven to the required temperatures the binder to 170°C and the aggregates to 230°C, for 1 hour and 3 hours respectively. Once the target temperatures had been reached, the heated components were combined and mixed for 4-5 minutes, until complete coating of the aggregate particles with the binder was achieved. The final mastic asphalt mixture was then returned to the oven and conditioned at 220°C for 1 hour. Subsequently, the heated material was poured into steel moulds, either cubic (70 × 70 × 70 mm) or cylindrical (150 mm in diameter and 70 mm in height), and compacted manually using a wooden rammer (approximately 20 blows) to form the test specimens. After cooling to room temperature, the samples were demoulded and prepared for penetration testing. Cylindrical specimens were trimmed to a height of 60 mm and dried in air for 2 days.

2.6. TESTING METHODS

Bulk density was determined in accordance with PN-EN 12697-6, Method A [37]. This procedure was selected due to the very low air-void content of the mixture, which also resulted in minimal water absorption of the specimens.

In order to assess the resistance of the MA to permanent deformation, static and dynamic indentation tests were used. The static penetration test was conducted in accordance with PN-EN 12697-20 [38], using cubic specimens with dimensions of 70.7 mm. The initial load was 25 N, and after 10 minutes it was increased to a total of 525 N by adding 500 N. The load was applied with a plunger of 500 mm^2 surface area, and the entire test was conducted in a water bath at 40°C. The dynamic penetration test was carried out in accordance with PN-EN 12697-25 [39] and PN-EN 13108-20 [40]. The test was performed on cylindrical specimens with a diameter of 150 mm and a height of 30 mm. Fig. 5 shows the equipment used in the study.

The stiffness modulus test was carried out on cylindrical specimens with dimensions of 60 mm in height and 101.6 mm in diameter, using the indirect tensile test method (IT-CY) in accordance with PN-EN 12697-26 [41].

The specimens were placed between two rigid plates, and a vertical compressive load was applied, causing horizontal deformation of the material. The tests were conducted on three types of mixtures: M1, M2, and M3, at temperatures of 5°C, 10°C, and 15°C, which allowed the relationship between stiffness modulus and test temperature to be determined. In accordance with the procedure described in the standard, a 24 hour interval was maintained between successive measurements of the same specimen.

The test results were subjected to statistical processing, which included assessing whether the data followed a normal distribution, identifying and removing outliers, and determining mean values together with measurement uncertainties based on a type-A evaluation of repeated observations. Outliers were eliminated using the Grubbs test. Differences between result sets arising from the examined factors were verified using Student's *t*-test. A significance level of $\alpha = 0.05$ was adopted, implying that no more than 5% of the results may lie outside the established uncertainty range.

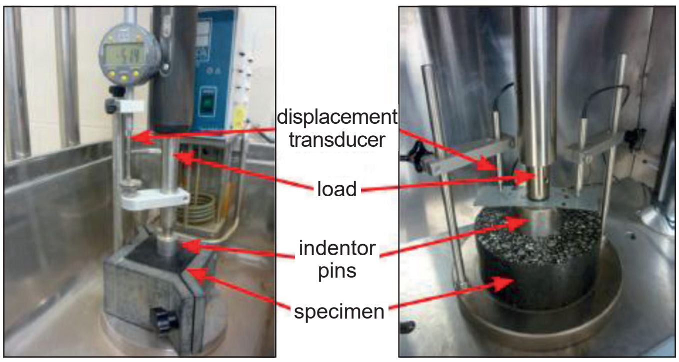

Fig. 5. Equipment used in static and dynamic indentation test

3. RESULTS AND DISCUSSION

3.1. LABORATORY TEST RESULTS FOR MASTIC ASPHALT INCORPORATING TRINIDAD LAKE ASPHALT

Own studies were carried out on an MA 11 mixture with two levels of TE addition: 10% and 20% by binder mass, as well as on a reference mixture without TE. Based on the obtained results, it was found that the addition of natural asphalt improves the rutting resistance of mastic asphalt. With increasing TE content, the penetration values of the tested mixtures decreased (Table 1). The penetration depth was evaluated after 30 minutes (I – penetration [mm]) and the increase in penetration was measured after an additional 30 minutes (I_{nc} – penetration increment). However, the effect of this additive depends on the composition of the mixture. For softer mixtures with higher binder content, the influence of TE was most pronounced. In this case, permanent deformation was reduced by almost 33% (for bitumen content $B = 8.7\%$) compared to 27% for the mixture with lower binder content ($B = 6.9\%$).

Table 1. Results of static indentation test

Asphalt content [%]	TE content [%]		
	Mean indentation test I [mm]		
	0	10	20
6.9	3.07 ± 0.32	2.54 ± 0.21	2.23 ± 0.24
7.7	4.40 ± 0.27	4.18 ± 0.35	3.86 ± 0.38
8.7	7.44 ± 0.91	6.39 ± 0.74	5.02 ± 0.56

In the case of penetration growth between the 30th and 60th minute of testing, for mixtures without the addition of TE, a reduction in asphalt content results in more than a threefold decrease in deformation growth, compared to the mixture with 20% TE addition, where the decrease is only 2.5-fold (Table 2). It can also be observed that the use of natural asphalt is most effective in the case of softer mixtures, i.e., those with higher asphalt content. In this case, increasing the TE content leads to a significant reduction (by more than 50%) in deformation growth compared to the mixture with lower binder content, where the decrease is only half as large. Based on the above results, it can be concluded that the addition of TE has a positive effect on the rutting resistance of mastic asphalt mixtures. In some cases, particularly for mixtures with lower binder content, the use of 10% and 20% TE led to very similar increases in static indentation. This suggests that, beyond a certain dosage threshold, the additional stiffening effect of TE compensates mainly for the higher binder content, rather than further improving rutting resistance.

Table 2. Results of increase in static indentation test

Asphalt content [%]	TE content [%]		
	Mean increase in static indentation test I_{nc} [mm]		
	0	10	20
6.9	0.43 ± 0.13	0.31 ± 0.04	0.30 ± 0.05
7.7	0.64 ± 0.11	0.61 ± 0.11	0.64 ± 0.14
8.7	1.42 ± 0.58	1.26 ± 0.23	0.73 ± 0.16

3.2. LABORATORY TEST RESULTS FOR MASTIC ASPHALT WITH ZEOLITE

The results of own research on the rutting resistance of mastic asphalt mixtures with the addition of zeolites are presented in Table 3. The tests were carried out using the static indentation test. The letter "N" denotes the addition of natural zeolite (clinoptilolite), while the letter "S" denotes the addition of synthetic zeolite (Na-P1). For both mixtures, the penetration results fell within the range specified by WT-2 [10], between 1 and 3 mm. Only for the MA8 mixture with polymer-modified asphalt was a result obtained slightly below the lower penetration limit. In both mixtures, the change of binder from road asphalt 35/50 to polymer-modified PMB 25/55-60 had a significant effect on the measured penetration values. The addition of 5% zeolite and the simultaneous reduction of the production temperature from 215°C to 180°C influenced the obtained penetration results. In the tested mixtures except for the MA8 35/50 mixture a deterioration in rutting resistance was observed. For this mixture, a decrease in penetration values of 0.44 mm was observed when using natural zeolite, and 0.40 mm when using synthetic zeolite. When relating the obtained static penetration results to the WT-2 requirements, it can be concluded that despite the increase in penetration values, the tested mixtures still meet the requirements specified in the guidelines. Overall, the results indicate that zeolite modification is more favourable for mixtures with finer aggregate structure and harder paving grade bitumen, whereas in coarser mixtures or when polymer-modified binder is used, the reduction in production temperature tends to outweigh the potential beneficial effect of zeolite on rutting resistance.

Table 3. Static indentation results after 30 min loading and corresponding increase between 30 and 60 minutes for mastic asphalt mixtures with zeolite additives

Mixture	Zeolite content [%]	Results [mm]			
		35/50 Binder		PMB 25/55-60 Binder	
		Indentation	Increase	Indentation	Increase
MA 8	0 Z	1.59 ± 0.22	0.16 ± 0.03	0.94 ± 0.10	0.11 ± 0.03
	5 N	1.15 ± 0.12	0.12 ± 0.03	1.04 ± 0.08	0.10 ± 0.03
	5 S	1.19 ± 0.14	0.12 ± 0.01	1.09 ± 0.06	0.13 ± 0.05
MA 11	0 Z	1.62 ± 0.23	0.17 ± 0.03	1.12 ± 0.17	0.16 ± 0.04
	5 N	1.82 ± 0.22	0.20 ± 0.04	1.38 ± 0.04	0.15 ± 0.04
	5 S	1.87 ± 0.22	0.18 ± 0.02	1.24 ± 0.15	0.13 ± 0.02

The obtained penetration growth falls within the permissible range specified in WT-2 [10], it is less than 0.60 mm (Table 3). It can be observed that the addition of zeolite affects the penetration growth value differently. For MA8 35/50 and MA11 PMB 25/55-60 mixtures, the addition of both natural and synthetic zeolite allowed for a slight reduction in penetration growth. For the MA8 PMB 25/55-60 mixture, the addition of natural zeolite caused a slight decrease in the penetration growth rate, while the addition of synthetic zeolite caused a slight increase. For the MA11 35/50 mixture, the addition of both natural and synthetic zeolite resulted in an increase in penetration growth; however, in the case of the latter, the increase was minimal.

3.3. LABORATORY TEST RESULTS FOR MASTIC ASPHALT WITH CRUMB RUBBER

The results of the bulk density determination of the mastic asphalt samples are presented in Table 4. For each series (M1, M2, M3), the mean value was calculated based on six independent measurements.

Table 4. Bulk density test results

Mixture	Mean bulk density [kg/m^3]
M1	2,542 ± 6
M2	2,536 ± 3
M3	2,503 ± 5

In the case of bulk density (Table 4), mixture M1 exhibits the highest density value, which is typical for unmodified mixtures. At the same time, it showed the greatest scatter of results, which may indicate a higher sensitivity to slight variations in compaction or to microstructural non-uniformities within the specimen. Mixture M2, in which the modification was carried out using the wet process, was characterised by the smallest measurement variability, suggesting a more homogeneous internal structure resulting from the uniform dispersion of fine crumb rubber particles within the binder. In turn, the lowest density was observed for mixture M3, where crumb rubber replaced part of the 2/5 mm aggregate fraction. The reduction in density is consistent with expectations, as rubber has a lower density than gabbro and does not disperse within the binder, creating locally less compacted zones in the mixture structure.

The results of the static penetrometer test for the mastic asphalt samples are presented in Table 5.

Table 5. Static indenation test results

Mixture	Mean indentation test I [mm]	Mean increase in static indentation test I_{nc} [mm]
M1	2.01 ± 0.13	0.29 ± 0.02
M2	1.79 ± 0.14	0.26 ± 0.03
M3	1.78 ± 0.20	0.27 ± 0.03

For each mixture (M1, M2, M3), the mean penetration value and the mean penetration growth were calculated based on the results obtained from six specimens.

According to the requirements specified in the WT-2 [10], all tested specimens met the criteria for static penetration - the permissible penetration depth ranged from 1 to 3 mm, while the maximum increment did not exceed 0.60 mm. The analysis of static indentation (Table 5) shows that the reference mixture M1 exhibits the greatest indentation depth, confirming its higher susceptibility to permanent deformation. The modified mixtures M2 and M3 reach similar, lower values, indicating improved rutting resistance, although the mechanisms responsible for this effect differ: for M2 it results from binder stiffening associated with the wet process, whereas in M3 it is related to the presence of rubber granules acting as elastic inclusions without actual modification of the asphalt binder. The effect of addition of crumb rubber parts was the same. But, regarding the capacity of each additive for both methods (respectively 0.21% and 1.11% of MMA weight), the wet process was more effective.

The results of the dynamic penetrometer test are presented in Table 6. For each mixture (M1, M2, M3), three specimens were analyzed, based on which the mean penetration depth after 2500 cycles (*ET* – dynamic indentation [mm] and the mean penetration increment between the 2500th and 5000th test cycle (D_{ET} – penetration increment [mm]) were determined.

Table 6. Results of dynamic indentation test

Mixture	Mean dynamic indentation test *ET* [mm]	Mean increase in dynamic indentation test D_{ET} [mm]
M1	4.27 ± 0.34	1.70 ± 0.30
M2	3.31 ± 1.23	1.53 ± 0.60
M3	4.10 ± 0.33	1.86 ± 0.08

In the dynamic indentation test (Table 6), mixture M2 achieved the most favourable parameters, confirming the effectiveness of the wet process in reducing deformations under cyclic loading. Mixture M1 shows the highest indentation, while M3 performs intermediately, which again highlights the limited efficiency of the dry process. The increase in deformation between 2500 and 5000 cycles also indicates that M2 undergoes the slowest degradation, whereas M1 and M3 present comparable levels of fatigue susceptibility. Those results do not confirm results obtained for static indentation tests. It can be the effect of better sensitivity of the dynamic test method. The results confirm better influence of rubber addition on the mastic asphalt mixture rutting resistance in the wet method and of course its effectiveness.

The results of the stiffness modulus tests for the analyzed mixtures are presented in Table 8.

Table 8. Results of stiffness modulus test

Mixture	Mean stiffness modulus E^* [MPa]		
	Temperature 5°C	Temperature 10°C	Temperature 15°C
M1	7,578 ± 472	5,529 ± 419	3,587 ± 271
M2	7,849 ± 171	5,617 ± 274	3,781 ± 228
M3	7,473 ± 520	4,990 ± 251	3,354 ± 235

The stiffness modulus results (Table 8) constitute an essential part of the analysis, as stiffness at low temperatures is closely associated with resistance to permanent and fatigue deformation. Mixture M2 consistently achieved the highest modulus values at all tested temperatures (5°C, 10°C, 15°C), demonstrating that the incorporation of crumb rubber into the binder significantly increases the rigidity of the mastic asphalt. The reference mixture M1 exhibits intermediate stiffness, whereas mixture M3 shows the lowest modulus and the strongest temperature dependence, reflecting its modification mechanism, in which rubber granulate replaces a portion of the aggregate rather than modifying the binder itself. These findings clearly indicate that the wet modification method (M2) provides a far stronger structural enhancement than the dry method (M3), where the rubber acts only as an elastic aggregate component and does not contribute to binder stiffening. The stiffness modulus results clearly confirm that the wet modification method provides distinctly superior performance, leading to the highest stiffness values across the entire temperature range studied.

6. CONCLUSIONS

Mastic asphalt is a mixture with unique properties. Its composition includes a high content of filler and binder, which results in low air voids and excellent impermeability. For this reason, it is widely used in bridge pavements as a protective insulation layer. This mixture is not free from drawbacks, but it has many advantages that make it valuable in specific applications. Some of its limitations can be mitigated through the selection of appropriate materials or careful mixture design. Similarly to compacted asphalt mixtures, mastic asphalt can also be effectively modified depending on the intended design objective. The article presents two principal enhancement approaches: the first focuses on reducing the technological temperature and limiting environmental impact through the use of zeolites, while the second aims at increasing the mixture's resistance to permanent deformation by incorporating Trinidad Epuré natural asphalt or crumb rubber obtained from recycled tires. Owing to the wide availability of waste rubber and the possibility of its efficient utilisation through the wet process, this method appears to be the most advantageous both economically and environmentally, while simultaneously providing a measurable improvement in the rheological properties of mastic asphalt.

As a result of the conducted research, it can be concluded that:

1. All the methods described lead in various ways to an improvement in the properties of mastic asphalt mixtures. Depending on the desired effects, one of the presented modification methods can be applied.
2. The use of Trinidad Epuré natural asphalt increases the rutting resistance of mastic asphalt. With higher additive content, a decrease in penetration values measured with the penetrometer was observed, with this effect being more pronounced in mixtures with higher binder content.
3. The use of zeolites makes it possible to reduce the production and laying temperature of mastic asphalt by 35°C (from 215°C to 180°C) without significantly impairing its rutting resistance. The increase in penetration values is minor or remains at the same level as for the reference mixture.
4. The addition of crumb rubber to the binder (wet method) resulted in a stiffening of the mixture by approximately 5% compared to the reference mixture, which corresponded with the results of the static and dynamic penetration tests. This indicates that rubber in the binder can reduce the risk of premature rutting of mastic asphalt pavements, especially on bridge decks. In the case of rubber added directly to the aggregate (dry method), such an effect was not achieved, and the mixture showed higher susceptibility to deformation.
5. In the bulk density tests, it was found that the control mixture M1 achieved the highest bulk density value, while also showing the greatest scatter of results. For the mixture modified with crumb rubber (M2), the smallest scatter of results was recorded, although its bulk density was lower than that of M1. The mixture in which rubber was added directly to the aggregate (M3) was characterized by the lowest bulk density and a moderate level of result scatter. Statistical analysis revealed significant differences in bulk density between mixtures M2 and M3, as well as between M1 and M3. However, the differences between the control mixture M1 and mixture M2 were not statistically significant.
6. In the static penetration tests, the highest value – 2.01 mm – was obtained for the reference mixture M1. In contrast, the modified mixtures, both with rubber added to the binder (M2) and with rubber introduced into the aggregate (M3), achieved lower but very similar penetration values of 1.79 mm and 1.78 mm, respectively. Statistical analysis did not reveal significant differences between the results for the individual mixtures. Additionally, the relationship between bulk density and static penetration was evaluated. It was found that for mixture M1 the correlation was weak, for M2 moderate, and for M3 very strong. The results indicate that in the case of M3, an increase in bulk density clearly leads to a decrease in penetration values. All tested specimens met the penetration requirements specified in the WT-2 guidelines [10].
7. In the dynamic penetration tests, the highest value was recorded for the control mixture M1, which reached 4.27 mm. Mixture M3, in which rubber was introduced into the aggregate, achieved 4.10 mm. The lowest penetration level, 3.31 mm, was observed in mixture M2, modified with rubber-added binder. Statistical analysis of the obtained results did not reveal significant differences between the tested mixtures, indicating that the method of modification did not have a significant effect on the properties related to dynamic penetration.
8. The stiffness modulus tests showed the greatest variation in results at 15°C, while the smallest differences were observed at 10°C. Mixture M2, containing binder modified with crumb rubber, achieved the highest stiffness modulus values regardless of the test temperature. The lowest values of this parameter were recorded for mixture M3, in which rubber was introduced directly into the aggregate.

The wet modification method proved to be the most effective, as it provides higher stiffness at the same additive volume due to the use of finer crumb rubber and its full integration with the binder, which translates into better technical and economic efficiency. Both TE and crumb rubber clearly reduce the rutting susceptibility of mastic asphalt. Zeolites, in turn, allow for a reduction in production temperature, although they require raw material extraction or laboratory processing. Considering the wide availability of waste rubber, the wet method offers the most environmentally and technically advantageous solution. From an application perspective, the choice of an appropriate additive should take into account the specific operational requirements of the pavement: rutting resistance, service temperature range, and technological conditions.

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Wpływ wybranych dodatków na poprawę właściwości asfaltu lanego

Streszczenie: W budownictwie drogowym w Polsce asfalt lany nie jest mieszanką wiodącą. Prym wiodą tradycyjne mieszanki, głównie betonu asfaltowego oraz mieszanki mastyksowo-grysowe SMA. Ze względu na niską zawartość wolnych przestrzeni oraz możliwość rozkładania bez zagęszczania, asfalt lany wciąż pozostaje atrakcyjnym materiałem, szczególnie w nawierzchniach mostowych. W artykule przedstawiono wyniki badań nad zastosowaniem wybranych dodatków: asfaltu naturalnego Trinidad Epuré (TE), zeolitów oraz gumy pochodzącej ze zużytych opon samochodowych. Analizowano wpływ dodatku asfaltu naturalnego (10 i 20% masy lepiszcza) na właściwości mieszanki MA 11 w porównaniu z mieszanką referencyjną. Wyniki wykazały poprawę odporności na koleinowanie, zwłaszcza przy wyższej zawartości lepiszcza. Badania obejmowały również zastosowanie zeolitów naturalnych (klinoptylolit) i syntetycznych (NaP1). Dodatek 5% pozwolił obniżyć temperaturę wytwarzania z 215°C do 180°C, przy zróżnicowanym wpływie na odporność na deformacje. Ponadto przeanalizowano działanie gumy w mieszance MA 8 z asfaltem 35/50, wprowadzanej metodą „na mokro" oraz „na sucho". Dodatek gumy zwiększał sztywność i odporność na deformacje, szczególnie w przypadku modyfikacji lepiszcza. Wyniki badań potwierdzają, że zastosowanie opisanych dodatków może poprawić właściwości mechaniczne i technologiczne asfaltu lanego, poszerzając zakres jego praktycznego zastosowania.

Słowa kluczowe: asfalt lany, asfalt naturalny, miał gumowy, moduł sztywności, odporność na koleinowanie, zeolity.