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RESISTANCE TO PERMANENT DEFORMATION OF THE TLA-MODIFIED MASTIC ASPHALT MIXTURE BASED ON STATIC AND DYNAMIC INDENTATION

Mastic asphalt mixture (MA) has been particularly popular in recent years for bridge pavements due to many advantages, such as easy application, good waterproofing properties and high durability. However, the drawback of the mastic asphalt mixture in comparison to other asphalt mixtures is its lower resistance to permanent deformation. Additive, such as natural asphalt Trinidad Lake Asphalt (TLA) is often applied to make the mastic asphalt mixture resistant to permanent deformation. Practical experience demonstrates that serious failures may occur if MA pavement design and materials selection is not taken into account sufficiently. Therefore, in this study, the influence of two parameters: the TLA content and bitumen-filler mastic composition described by the filler-binder ratio (f/b), on the rutting resistance of the MA mixture, were evaluated. The rutting resistance of the MA mixtures was evaluated on the basis of static and dynamic indentation tests. Both parameters showed a high correlation with the rutting parameters. The mathematical relationships can be used for the prediction of MA composition in such a way that the final MA mixture meets the relevant requirements of the rutting resistance.

Keywords: dynamic indentation test, filler-binder ratio, mastic asphalt mixture, permanent deformation, static indentation test, TLA-modified binder

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1. Introduction

Mastic asphalt mixture (MA) has been particularly popular in recent years for bridge pavements due to many advantages such as easy application, good waterproofing properties and high durability [3]. Mastic asphalt mixture commonly comprises a blend of penetration grade bitumen and usually a modifier (termed “modified binder”), which is mixed with fine aggregate (termed “filler”) to form “bitumen-filler mastic” [15]. The addition of coarse aggregate completes the composition of the mastic asphalt mixture. Due to its very good fluidity and self-leveling performance when laid down, the mastic asphalt mixture does not require compaction. The application of one or two layers of mastic asphalt mixture in bridge pavement provides very good water and de-icing agent protection of the bridge deck due to the low permeability of the MA mixture with air void content below 1%. Compared to standard asphalt concrete (AC) or stone mastic asphalt (SMA) pavements, MA pavement has a longer service life and a longer fatigue life resulting from the high bitumen content in the mastic asphalt mixture. Since the mastic asphalt mixture is viscoelastic, it does not crack easily [18][24][30][31].

The drawback of the mastic asphalt mixture compared to other asphalt mixtures is its lower resistance to permanent deformation. The main concern with MA bridge pavement courses is the possibility of occurrence of rutting (viscoplastic deformation), resulting from high service loads at high temperatures, as the underlying rigid deck contributes to an increase in stresses in the pavement and, consequently, to its accelerated rutting [17][14][27]. The rutting susceptibility of pavement is mainly influenced by aggregate and mixture properties. However, the characteristics of the binder are also important, especially for modified binders, which are claimed to improve rutting resistance and extend pavement service life. Rutting has been distinguished as a primary distress mechanism and a major design criterion as long as MA pavements have been used.

To make the mastic asphalt mixture resistant to permanent deformation, products that “harden” bitumen are used, such as waxes, polymers and natural asphalts [7]. In the latter case, Trinidad Lake Asphalt (TLA) is often applied. It occurs as a semi-solid emulsion of soluble bitumen, mineral matter, and other minor constituents [26]. TLA is well recognized as an efficient bitumen modifier for its high compatibility, stability, and durability, thus it is often used in mastic asphalt mixture for bridge pavements. The most important advantages of using TLA as a bitumen modifier include optimization of the structural properties of the binder (lower brittleness and greater resistance to ageing), improvement of binder adhesion to mineral material, significant improvement of workability and compaction of the mixture, and ultimately its greater resistance to permanent deformation and fatigue [4][12]. High-quality MA pavement with the TLA-modified binder has been successfully applied for many years on hundreds of bridges around the world [5][6][16][19].

Some of binder properties (eg. ZSV or G*/sinδ) that has been shown to correlate with the rutting performance of the binder. However, within an asphalt mixture, it is probably more appropriate to consider the performance of the bitumen-filler mastic (binder plus filler, i.e. fine mineral material) rather than simply considering the pure bitumen. The main role of the bitumen-filler mastic in the asphalt mixtures is to bind coarser aggregate grains and to prevent their segregation. The most basic parameter that controls the properties of bitumen-filler mastic is its composition, i.e., the correct choice of proportion between binder and filler content [2][8][11]. Binder content in the bitumen-filler mastic cannot be too limited, since it would lead to excessive stiffness and brittleness, which, in effect, renders the pavement susceptible to cracking. However, with a gradual increase in binder content, the effect of sliding or lubricating aggregate particles intensifies, leading to a decrease in resistance to permanent deformation of the pavement. An increase in the filler content leads to a stiffening effect, which increases resistance to permanent deformation. The views on the optimal filler-binder ratio in various asphalt mixtures have changed over the years. Initially, a range of 0.6-1.2 was advised, regardless of the type of mixture. Currently, the recommendations state that the ratio should not exceed 1.6 in coarse-graded mixtures and 1.4 in fine-graded mixtures [21][22]. The composition of the bitumen-filler mastic plays a vital role in terms of the high resistance of mastic asphalt pavements to permanent deformation [17]. Therefore, identification of the optimum binder-filler mastic composition (i.e., filler-binder ratio) may be the basis for the preliminary design of a mastic asphalt mixture [16].

Most of the existing studies focused on the characterization and improvement of the engineering properties of MA mixtures. Little study has researched or provided the detailed design of MA mixtures, such as material selection, TLA content, and filler-binder ratio (f/b). However, practical experience demonstrates that serious failures may occur, if MA pavement design and materials selection are not taken into account sufficiently. The objective of this study is to propose design support for MA mixtures produced from the 35/50 penetration grade bitumen modified with TLA. TLA dosage and filler-binder ratio in the MA mixture were obtained on the basis of static and dynamic indentation tests to predict the rutting performance for MA mixtures. The relationships of TLA content and f/b ratio on the rutting parameters can be used to predict the composition of MA in such a way that the final MA mixture meets the relevant requirements of the resistance of the rutting.

2. Research assumptions

As the study presented here was part of the research project on the development of a typical road bridge surface for the Polish road administration, several assumptions and limitations had to be taken into account before the final research program was established. These restrictions apply to both materials and test methods.

Since 35/50 penetration grade bitumen is the only one recommended for MA bridge pavements by the Polish road administration [28], it had to be chosen as the base bitumen in this study.

To achieve an effective and optimum modification, it is necessary to precisely establish the amount of the modifier dosed into the bitumen. The 35/50 base bitumen was modified with TLA quantities from 0% to 20% (relative to the weight of the base bitumen), with a step of 10%. Such proportions of TLA to base bitumen were assumed based on available studies [7][13][20][29] and the initial research of the authors [1][9] which implied that a 10% step in the quantity of TLA results in a noticeable difference in the properties of the final binder. The addition of more than 20% leads to excessive stiffness of the binder, which can negatively affect the low-temperature performance of the MA mixture. Finally, three combinations of 35/50 penetration grade bitumen and TLA were selected to evaluate the rutting resistance of MA bridge pavement.

The composition of bitumen-filler mastic, i.e. its filler-binder ratio, was determined based on the typical compositions of the mastic asphalt mixtures given in the Polish recommendations [28] which requires the minimum binder content in MA as Bmin = 7.0% and the maximum binder content that still provides the satisfactory durability of the MA mixture. Because in the designed mineral mixture, sieve through a 0.063 mm sieve was 27.8%,(which 25% were grains of lime filler, and 2.7% were aggregate dust), therefore the binder contents in the studied MA mixtures were ranged from 6.9% (the value close to the required minimum content), by 7.7% to the maximum value of 8.7%, which corresponds to the filler-binder ratio of 4.0, 3.6 and 3.2, respectively. The former tests carried out by the authors revealed that the greater binder content than 8.7% led to the production of a very soft mixture with indentations over 15 mm.

The choice of the filler-binder ratio was also based on the definition formulated by Judycki [8], who recommended assuming the filler-binder ratio as the proportion by weight of the particles passing through the 0.063 mm sieve to the total binder content in the mixture. Therefore, the filler-binder ratio was specified by weight. Since the TLA-modified binder is a mixture of bitumen and fine mineral particles, the amount of the added filler was decreased by the number of mineral particles coming from the TLA, following the approach described in the handbook Laborhandbuch für Trinidad Naturasphalt [10].

There are many methods to evaluate the rutting resistance of asphalt mixtures. In this study, the permanent deformation resistance of MA mixtures was evaluated using static and dynamic indentation tests, which simulate stationary and low-speed traffic conditions. Static and dynamic indentation tests were adopted to assess the relative permanent deformation characteristic of different MA mixtures. These tests can be used to better select asphalt mixtures for the type of load and traffic conditions crucial for MA bridge pavements.

3. Materials

Table 1 lists some of basic properties of the 35/50 bitumen in original condition (unaged) and TLA (as Trynidad Epure TE Z 0/8), determined according to the relevant European standards and compared to the European requirements.

Table 1. Basic properties of the 35/50 penetration grade bitumen and TLA

Properties	Unit	Test methods	35/50 bitumen		TLA	
			Test results	Requirements according to EN 12591	Test results	Requirements according to EN 13108-4
Penetration	[×0.1 mm]	EN 1426	42.8 ± 0.6	35.0 – 50.0	4.0 ± 0.5	0.0 - 4.0
Softening point	[^{o}C]	EN 1427	55.1 ± 0.6	50.0 – 58.0	101.2 ± 1.0	93.0 - 99.0
Fraass breaking point	[^{o}C]	EN 12593	-13 ± 1.5	≤ -5	--	--
Density at 25 ^{o}C	[kg/m^3]	EN 15326	1020 ± 6	no requirements	1380 ± 8	1390 - 1420
Solubility	[% (m/m)]	EN 12592	--	--	57.6 ± 1.0	52.0 – 55.0

As shown in the relevant table, the base bitumen used in this study fulfilled the respective European requirements. However, in the case of TLA small deviations from the requirements were revealed. It is due to the fact that the natural asphalt supplied by the manufacturer was covered with diatomite (an agent preventing asphalt pieces from sticking together) and was added to the mixer in this form. In this study, it was assumed that the tests would be conducted on the binder delivered in the form available to the manufacturer. This agent could stiffen the TLA resulting in revealed deviations.

Limestone powder, granodiorite all-in aggregate of fraction 0/4 and coarse aggregate of fractions 4/8 and 8/11, produced following the European standard EN 13043, was used to complete a final mastic asphalt mixture with filler-binder ratios of 3.2, 3.6 and 4.0.

The rutting tests were performed on the MA 11 mixture, required for the higher traffic categories by the Polish Road Administration and most often applied on bridge pavements in Poland. The grading curve of the MA 11 mixture is presented in Fig. 1.

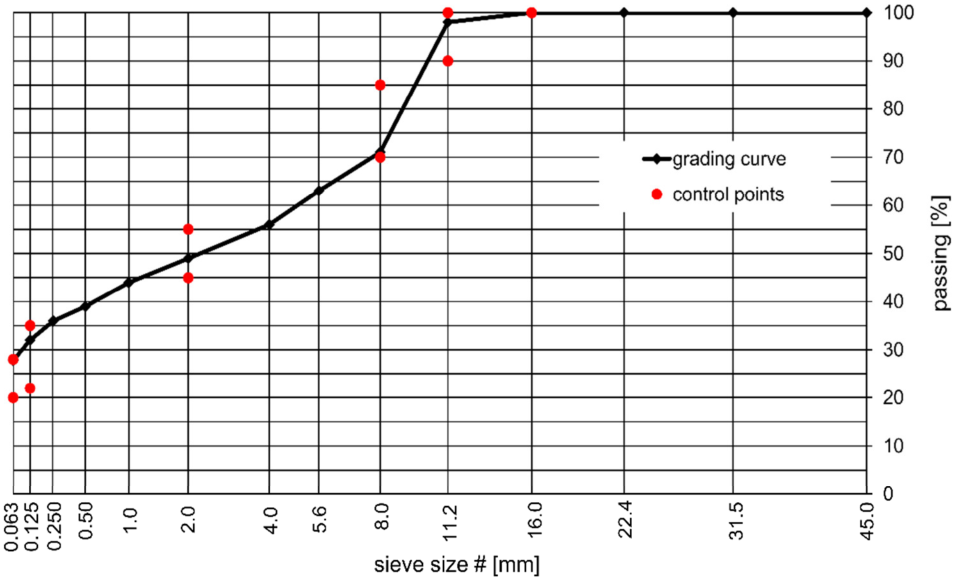

Fig. 1. Grading curve of the MA 11 mixture used in the study

4. Methods

4.1. Preparation of TLA-Modified Binders

To obtain a homogeneous TLA-modified binder, the laboratory blender was used to ensure a constant mixing speed, and thus no voids were created in the mixture. The base bitumen and TLA were heated until they became fluid before mixing. The base bitumen was preheated at 160°C in an oven for 0.5 hour to make it ready for mixing. The modifier, a specified amount of TLA, was added to the liquid base bitumen with the external addition method. The temperature of the modified binders was kept at 160°C for 1 hour, as recommended by the 35/50 bitumen manufacturer. After this time, the mixture was stirred at 3000 rpm for 5 min according to EN 12594, so that the TLA was homogeneously dispersed in the base bitumen. Immediately after preparation, the ready mixture was poured into short-term ageing containers or used to prepare the mastic asphalt mixture.

4.2. Preparation of Mastic Asphalt Mixture

The preparation of the binders was followed by the preparation of the aggregate mixtures, which comprised 45% coarse aggregate, 27% fine aggregate and 28% filler. The relevant binders and aggregate mixtures were then heated in an oven at the respective temperature (binder: 170°C, aggregate: 230°C) for 1 and 3 h, respectively. After this time, the heated components were mixed for 4-5 minutes, until all aggregate particles were coated by the binder. The final mastic asphalt mixture was then placed in an oven again and stored at a constant temperature of 220 °C for 1 hour. Finally, the warmed MA mixture was poured into a steel cubic mould (dimensions: 70x70x70 mm) or cylindrical mould (diameter 150 mm, 70mm height) and compacted by hand with wood rammer (ca. 20 blows) to form test specimens. After being cooled to room temperature, the samples were demoulded and prepared for indentation tests. The cylindrical specimen was cut to 60 mm height and dried in air for 2 days.

4.3. Static and Dynamic Indentation Tests of the Mastic Asphalt Mixture

Indentation tests were performed on nine mastic asphalt mixtures, prepared with three different binders having different TLA quantities from 0% by 10% to 20% and three different mastics having filler-binder ratios of 3.2, 3.6 and 4.0.

Static indentation was tested using 70.7 mm cubic specimens formed at a temperature of 220°C according to EN 12697-20. The load was transferred to the samples using an indentor pin with a circular base (a cylindrical piston with a contact surface area of 500 mm2) and the penetration of the indentor into the sample (indentation) was measured. The load was applied for some time, starting with the initial loading of 25 N and then, after 10 minutes of preloading, increasing the load by 500 N, thus giving the total test load of 525 N. During the test, the specimen remained submerged in water at a constant temperature of 40°C. The values registered as the results of the test included indentation of the piston after 30 minutes and increase in indentation after additional 30 minutes of constant loading.

Dynamic indentation tests were performed on cylindrical specimens with a diameter of 150 mm and height of 60 mm formed at a temperature of 220°C according to EN 12697-25 and EN 13108-20. Before testing, the specimens were conditioned for 4 hours at a constant test temperature of 50°C and then preloaded with a static load of 10 kPa. The load was transferred to the samples using a cylindrical piston with a contact surface area of 2500 mm^2 and a flat-ended base diameter of 56.4 mm. The parameters of a cyclic load were as follows:

- maximum load: 0.875 kN (corresponding to the stress of the specimen of 0.35 N/mm^2),
- minimum load: 0.2 kN (corresponding to the stress of the specimen of 0.08 N/mm^2),
- load time: 0.2 s,
- rest time: 1.5 s,
- duration of the cycle: 1.7 s,
- the shape of the loading curve: half-sine.

The results were recorded after 2500 and 5000 cycles of dynamic loading. The indentation of the piston into the specimen was determined as the average of three displacement values: two from linear variable differential transformer (LVDT) transducers placed on a plate mounted on the piston and one from the displacement sensor of the piston itself. The values registered as the results of the test included piston indentation after 2500 cycles and increase in indentation after additional 5000 cycles of dynamic loading. The device used to investigate of rutting performance shown in Fig. 2.

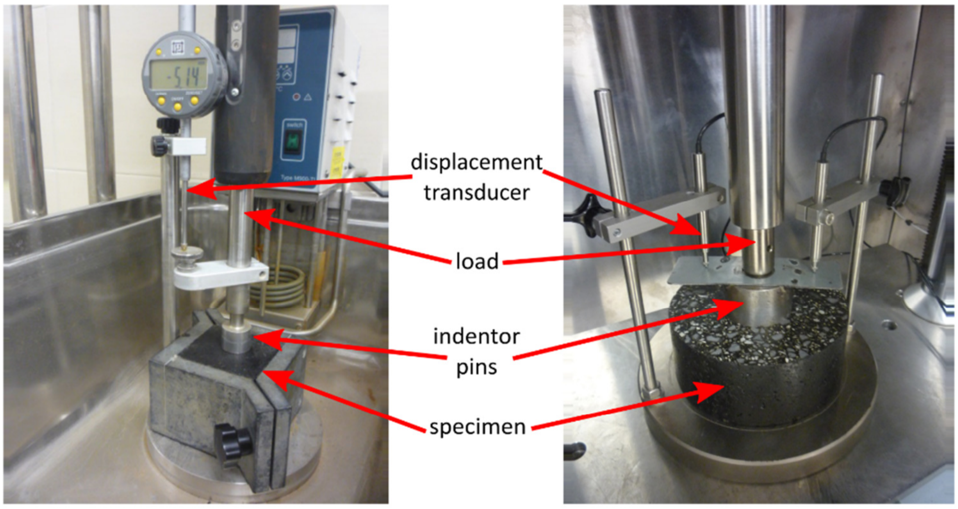

Fig. 2. Static (left) and dynamic (right) test device

In both static and dynamic indentation tests, six measurements were performed for each of the nine MA mixtures. As in the case of binder test results, before their further processing, outliers were excluded using the Grubbs test and measurement uncertainties were evaluated using the A method, based on a statistical analysis of a series of repeated measurements.

5. Results and Discussion

5.1. Static indentation results

As mentioned above, the rutting resistance of the MA mixture is determined by static (I) and dynamic (ET) indentations. The static indentation dependence on the TLA content and the filler-binder ratio (f/b) is shown in Fig. 3. On the graph shown also predicted value of penetration computed by Eq. (5.1) (mesh graph). This 3-D plot revealed that the static indentation can be credibly estimated using these two parameters (%TLA, f/b). It can be seen that the higher influence on the static indentation of a MA mixture has the bitumen-filler mastic composition (f/b) than the TLA addition. Since static indentation can be used as a measure of the rutting resistance of the MA mixture, choosing the specific TLA content and/or the relevant bitumen-filler mastic composition, the permanent deformation resistance of MA can be optimized.

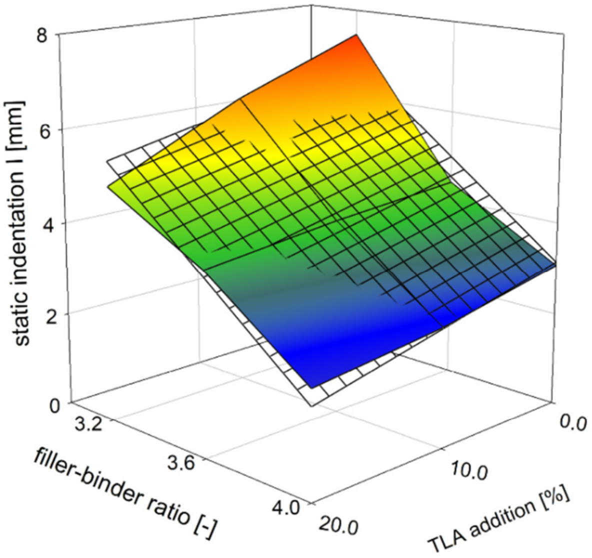

Fig. 3. The dependence of MA static indentation on the TLA addition and filler-binder ratio

The bitumen-filler mastic composition has a big impact on the static indentation of the MA mixture. Rutting resistance directly depends on the stiffness of the bitumen filler mastic, as the coarse aggregate grains are suspended in the bitumen filler mastic and do not have direct contact with each other. Increasing the filler-binder from 3.2 to 4.0 results in a decrease in static indentation by about half. On the other hand, with a constant value of the filler-binder ratio, the binder change by the increase of TLA content no longer causes such large changes in static indentation values, particularly for higher f/b ratios (3.2 or 4.0). The decrease in static indentation at the constant TLA content in the binder, which represents the modification of the MA mixture without the change of the binder, is similar for each level of the TLA addition.

The increase of the rutting resistance as the effect of the TLA content is most pronounced in a soft mixture, i.e. with a lower filler-binder ratio. To compare with softer mixture (f/b=3,2 and TLA addition 0%) increase f/b for 4,0 results decrease static indentation of 4,37 mm. Increase TLA addition from 0 to 20% for f/b ratio equal 0 is 2,42 mm. The static indentation decrease on the TLA content and the filler-binder ratio (f/b) is shown in Fig. 4.

A parameter that can also be used to evaluate MA rutting resistance is the increment of the static indentation (Inc) between 30 and 60 minutes of the test. The static indentation shows the rutting resistance of the MA mixture at only one point, i.e. after a certain time, whereas the static indentation increment illustrates these changes over time. Mixtures with a smaller increment will be more resistant to rutting, as the rut will develop more slowly than those with mixtures with larger increments. The dependence of the MA static indentation increment on the TLA content and the filler-binder ratio is shown in Fig. 5.

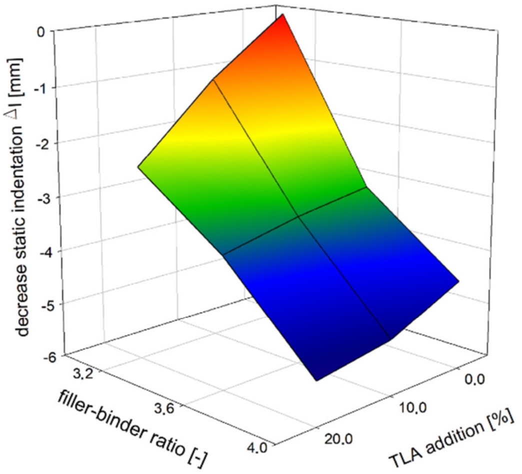

Fig. 4. The static indentation decrease on the TLA addition and the filler-binder ratio (f/b)

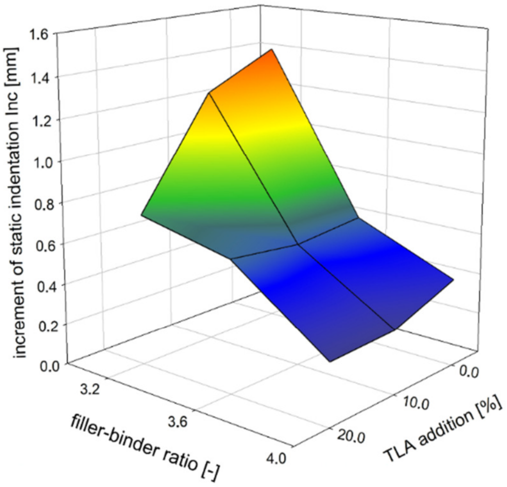

Fig. 5. The dependence of MA static indentation increment on TLA content and filler-binder ratio

It can be observed that for a mixture without TLA the change in the filler-binder ratio from 3.2 to 4.0 results in a more than 3 times decrease in the static indentation increment than for a mixture with 20% TLA addition, where this decrease is only 2,5 times. It can also be noted that the use of the TLA modifier makes the most sense in the case of soft mixtures, i.e. where the filler-binder ratio is the smallest. In this case, the increase in the TLA content results in a significant decrease (more than 50%) in rut growth compared to the mixture with a filler-binder ratio of 4.0, where this decrease is half as small. The addition of TLA limits rut growth well.

The relationship between the MA static indentation (i.e. rutting resistance), the TLA content and the mastic composition can be described by a linear equation in the form of:

$$\mathrm{I} = \mathrm{a_1 TLA} + \mathrm{a_2 (f/b)} + \mathrm{I_0} \tag{1}$$

where: I – static indentation [mm];

$\mathrm{a_1, a_2}$ – constants determined based on regression analysis;

TLA – TLA content [%];

$\mathrm{(f/b)}$ – filler-binder ratio [-];

$\mathrm{I_0}$ – free constant.

For the assumed test conditions, the following values of the coefficients of linear Eq. (1) were obtained: $a_1 = -0.063$, $a_2 = -4.587$, $I_0 = 21.496$.

Analysis of the correlation between rutting resistance parameters and TLA content indicates a high level of agreement. The result of fitting TLA content and filler-binder ratio to the static indentation is equal R^2=0.948. Equation (1) with the above coefficients can be used to estimate the static indentation of the MA mixture and thus to predict the rutting resistance of the MA pavement, starting from the choice of TLA content for binder modification and following by determination of the relevant filler-binder ratio.

5.2. Dynamic indentation test

The differences between dynamic indentation values for the tested MA mixtures are greater than for static indentation values (Fig. 6). A much larger range of dynamic indentation test results may be noticed than for static indentation. It follows that the composition of the MA mixture has a greater impact on the dynamic indentation values than the static indentation values. This is evident in both the case of the influence of the amount of TLA and the influence of the bitumen-filler mastic composition. In the first case, this effect is more pronounced for soft mixtures with a low filler-binder ratio. The absolute terms, to compare with softer mixture is shown on Fig. 7.

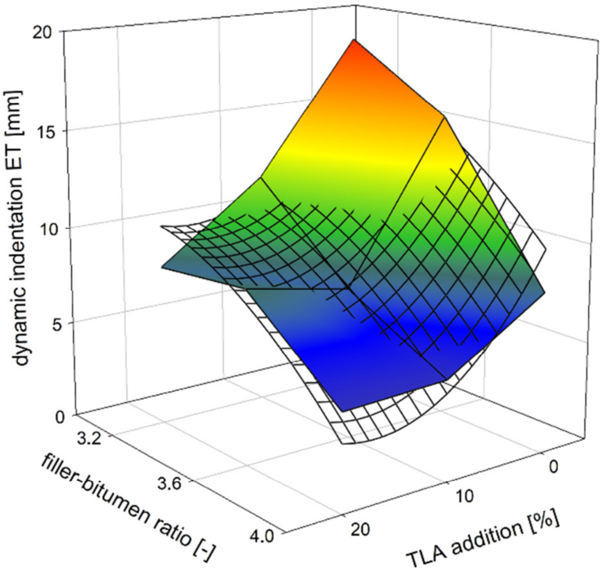

Fig. 6. The dependence of the MA dynamic indentation on the TLA content and the filler-binder ratio

In general, the dependence of the MA dynamic indentation shown in Fig. 6 is similar to the static indentation tests (Fig. 3). Only in the case of a mixture with 20% TLA content and the filler-binder ratio of 3.6, the MA mixture behaved differently from expectations, as a dynamic indentation result of 8.76 mm was achieved. In this test, both increasing the filler-binder ratio, as well as increasing the addition of TLA caused the mixture to harden, which is seen in the decrease in dynamic indentation value. A difference of almost 14 mm was obtained between the extreme results compared to just over 5 mm in the static indentation tests, which confirms a much larger range of the results of the dynamic indentation test.

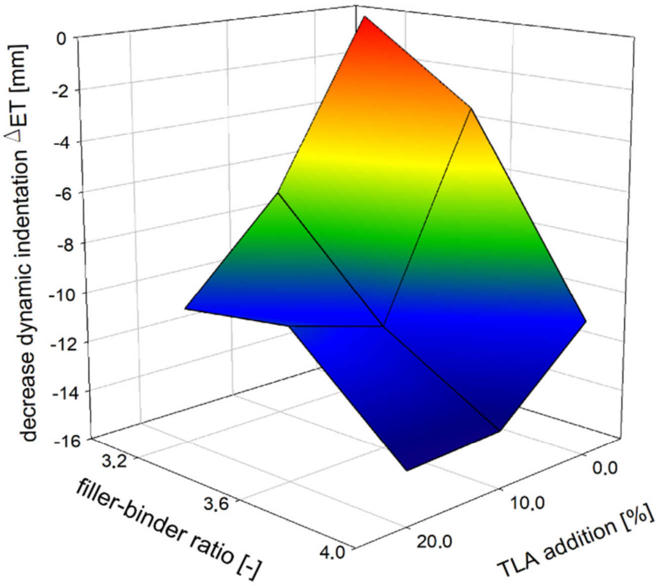

Fig. 7. The dynamic indentation decrease on the TLA addition and the filler-binder ratio (f/b)

Similar observations can be made from the evaluation of the dynamic indentation increment (Fig. 8). The addition of TLA reduces the increase of dynamic indentation (i.e. deformation over time) regardless of the filler-binder ratio. The reduction in the dynamic indentation increment is almost 50% for

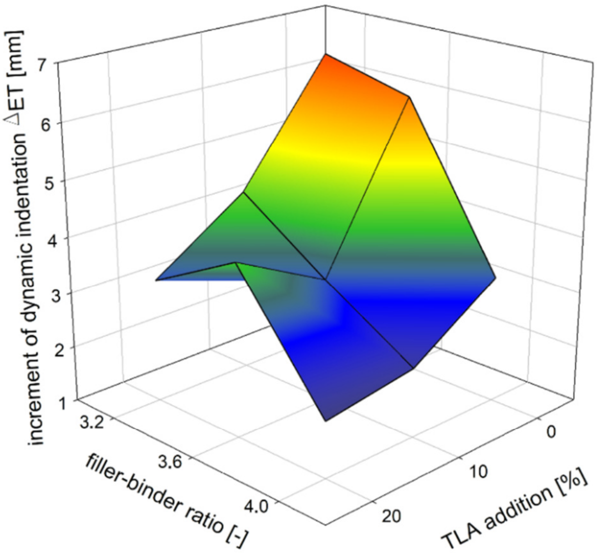

Fig. 8. The dependence of MA dynamic indentation increment on TLA addition and filler-binder ratio

the filler-binder ratio of 3.2 and less than 40% for the filler-binder ratio of 4.0. This is a significant difference compared to the static indentation test, in which for the ratio of 3.2 the addition of TLA reduced the static indentation increment at a level similar to the dynamic test (approximately 48%), while for the ratio of 4.0 the reduction of the static indentation increment gained 30%.

The relationship between the MA dynamic indentation, the TLA content and the bitumen-filler mastic composition can be described by a quadratic equation in the form of:

$$\mathrm{ET} = \mathrm{a_1 TLA^2} + \mathrm{a_2 TLA} + \mathrm{a_3 (f/b)^2} + \mathrm{a_4 (f/b)} + \mathrm{ET_0} \tag{2}$$

where: ET – dynamic indentation [mm];
$\mathrm{a_1, a_2, a_3, a_4}$ – constants determined based on regression analysis;
TLA – TLA content [%];
(f/b) – filler-binder ratio [-];
$\mathrm{ET_0}$ – free constant.

For the assumed test conditions, the following values of the coefficients of a quadratic Eq. (2) were obtained:

$$a_1 = 0.025,\ a_2 = -0.838,\ a_3 = -7.479,\ a_4 = 45.083,\ ET_0 = -50.422.$$

Analysis of the correlation between the rutting resistance parameters and the TLA content indicates a high level of agreement. The result of fitting the TLA content and the filler-binder ratio to the dynamic indentation is equal R^2=0.902, it is the slightly worse relationship which can be observed for the static indentation. Similarly, as in the case of static indentation, Eq. (2) with the above coefficients can be used to estimate the dynamic indentation of the MA mixture and thus the rutting resistance of the MA pavement, starting from the choice of TLA content for the modification of the binder and followed by the determination of the relevant filler-binder ratio. Predicted value of penetration computed by Eq. (2) (mesh graph) are presented on Fig. 6.

5.3. Discussion

All four tested parameters (static and dynamic indentations and static and dynamic indentation increases) were adopted to evaluate the rutting resistance of different MA mixtures basis of the TLA-modified binders. These parameters can be used to predict the rutting resistance, crucial for MA bridge pavements, basis of the quantity of the binder modifier and the composition of bitumen-filler mastic, i.e. its filler-binder ratio. The lower the static and dynamic indentations, the better the rutting resistance of the MA mixtures. If static and dynamic indentations are too high, the MA mixture is too soft and easy to rut. Similarly, the lower the static and dynamic indentation increases, the better the rutting resistance of MA mixtures. In this case, it also means that the lower indentation increases, and the permanent deformation of the MA pavement will develop slower.

The test results revealed that the quantity of the binder modifier and the composition of bitumen-filler mastic is a very good measure for predicting the rutting resistance of MA mixtures based on the TLA-modified binders. The high coefficients of determination R^2 for both relationships (1) and (2) showed the high influence of the content of TLA and the filler-binder ratio on the static and dynamic indentation. Increasing the addition of the TLA modifier positively affects the permanent deformation resistance of the MA mixture. The improvement in rutting resistance is visible in both the direct deformation value and the increase in deformation over time. The positive effect of higher TLA content is most visible in a mixture with a low filler-binder ratio, where the binder has a more impact on rutting resistance. When the f/b ratio increases with increasing filler content and thus the MA mixture is stiff enough, the influence of the TLA content on rutting resistance is not visible as much. Regardless of the bitumen-filler mastic composition, the positive effect of the TLA-modified binder is revealed and the increase in the addition of viscosity of the binders by the TLA addition improves the deformation properties of the MA mixture. However, the degree of improvement depends on the composition of MA.

When comparing the two test methods, it can be concluded that the dynamic method shows greater differences in permanent deformation resistance testing compared to the static method. In the static indentation test, the total relative difference for MA mixtures with the extreme values of the TLA additions is only 32% and 27% for the mastic composition f/b of 3.2 and 4.0, respectively. In the dynamic indentation test, the respective differences are 56% and 40%. The greater sensitivity of the dynamic method to changes in the composition of the MA mixture was revealed, particularly in terms of binder type and proportions between components.

In the case of both static and dynamic indentation tests, the minimum TLA content can be indicated, below which there is a significant change in the rutting resistance of the MA mixture. In the case of the static indentation test, it is visible in the increase in static indentation (particularly when the f/b ratio equals 3.2) and less visible in the static indentation itself. In the case of the dynamic indentation test, the improvement of permanent deformation resistance is visible in both the dynamic indentations itself and the dynamic indentation increase.

In many countries, the rutting resistance of MA mixtures to be applied for bridge pavements is crucial for proper material selection. Therefore, many restrictions are set in various guidelines or recommendations to ensure the appropriate rutting behavior of MA pavement. For example, the Polish recommendations WT-2 2014 [28] imposes the limit values of static indentation and its increase over time for MA mixtures designed as bridge pavement layers. The static indentation should be in the range of 1 to 3 mm, while its maximum increases should be no more than 0.6 mm, regardless of the type of loading and traffic conditions.

On the basis of the tests performed, it can be concluded that the MA mixture with the filler-binder ratio = 4.0 meets the guidelines requirements, regardless of the amount of TLA addition. For mixes with a lower filler-binder ratio, meeting the requirements may require a large addition of TLA, which may result in overstiffening of the binder and the low-temperature cracks. It is also visible that the mastic composition has a greater influence on the resistance to permanent deformation than that of the TLA additivee.

Proposed Eq. (1) and (2) apply to the tested mix only. The authors regard that similar relationships will be observed for other mixtures. Based on literature studies, it can be concluded that the penetration of the mastic asphalt mixture will be influenced much more by the type of asphalt, its amount and the amount of filler than its grain size [23][24]. In order to define a universal equation, more mixtures should be tested.

6. Conclusions

A comprehensive laboratory investigation on the influence of the content of TLA-modifiers and the composition of the bitumen-filler mastic on the static and dynamic indentations of the mastic asphalt mixture was carried out and presented in the paper. Knowing this relationship, presented in the form of mathematical equations, the optimal composition of MA can be predicted with respect to the rutting resistance of the MA bridge pavement. On the basis of the test results of this study, the following conclusions can be drawn:

1. Where MA mixtures are modified with TLA, the TLA content and filler-binder ratio can be used as parameters describing permanent deformation of mastic asphalt mixtures in the rutting test.
2. The TLA content and filler-binder ratio show high correlation with the parameters of permanent deformation, i.e. static and dynamic indentations of MA mixtures, for the assumed test conditions.
3. Equations (5.1), (5.2) can be used for the prediction of MA composition based on two parameters: TLA content and filler-binder ratio in such a way that the final MA mixture meets the relevant requirements of the rutting resistance.
4. Using Eq. (1), (2) the minimum TLA content can be indicated for a given filler-binder ratio, for which the required rutting resistance of the MA mixture can be obtained in terms of both static and dynamic indentations and their increases.
5. The dynamic indentation method (as compared to the static method) is more sensitive to changes in the composition of the MA mixture and the binder type.

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