DOI: 10.7409/rabdim.025.031

KRZYSZTOF MACIEJEWSKI [1)]
ORCID: 0000-0002-3002-9547

ANNA CHOMICZ-KOWALSKA [3)]
ORCID: 0000-0002-2784-8197

PRZEMYSŁAW ZAPRZALSKI [2)]
ORCID: 0009-0000-1848-0178

WITALIJ ZANKOWICZ [4)]
ORCID: 0000-0002-8115-2342

The effect of fiber-rubber additive compositions on the rheological properties of asphalt mastics

Abstract: The article presents the results of research on the effect of the composition of a fibre-rubber additive, which is currently produced on an industrial scale in Poland and is used as a stabilizer for gap-graded mineral-asphalt mixtures, such as SMA. The study included asphalt mastics composed of paving grade bitumen (unmodified) and limestone filler and additives: a rubber powder obtained by grinding at ambient temperature – partially devulcanized and activated – and synthetic fibers from the textile cords of the end-of-life tires. The tests included dynamic viscosity, rheological characterization for the evaluation of dynamic shear modulus with phase angle in oscillatory shear as well as multiple stress creep recovery tests for the evaluation of non-recoverable creep compliance and elastic recovery at incrementally increasing stress values. The results were related to the asphalt mastic without the additive, consisting only of unmodified bitumen and limestone filler. The results of the research allowed for the assessment of the effect of fibre-rubber additive components on the rheological characteristics of asphalt mastics, which allows for further development of technologies for improving the properties of asphalt mixtures in an environmentally sustainable manner and increasing the functionality of these additives.

Keywords: asphalt mastic, crumb rubber, end-of-life tires, textile cord, tire recycling.

[1)] Kielce University of Technology, Faculty of Civil Engineering and Architecture, 7 Tysiąclecia Państwa Polskiego Av., 25-314 Kielce, Poland; kmaciejewski@tu.kielce.pl (✉)
[2)] Recykl Organizacja Odzysku S.A., 3 Letnia St., 63-100 Śrem, Poland; p.zaprzalski@recykl.pl
[3)] Kielce University of Technology, Faculty of Civil Engineering and Architecture, 7 Tysiąclecia Państwa Polskiego Av., 25-314 Kielce, Poland; akowalska@tu.kielce.pl
[4)] Recykl Organizacja Odzysku S.A., 3 Letnia St., 63-100 Śrem, Poland; w.zankowicz@recykl.pl

1. INTRODUCTION

1.1. THE NEED TO SEARCH FOR NEW MATERIAL SOLUTIONS FOR ROAD PAVEMENTS

With the continuous increase in traffic loads to which road pavements are subjected, significant efforts are being made to ensure the durability, quality and sustainability of their construction and maintenance. Asphalt pavements make up the majority of road surfaces in the world, and asphalt mixtures are well suited for reuse in road construction at the end of their life cycle in the pavement. Currently, more than 95% of asphalt mixtures in Europe are reused, but only about 20-25% of asphalt surfaces are recycled [1]. This means that the road industry has significant prospects for the development of environmentally friendly asphalt technologies, including technologies for the regeneration and effective recycling of reclaimed asphalt (RAP).

Currently, more than 80% of emissions related to the entire life cycle of asphalt pavements are generated before the asphalt mixture leaves the asphalt plant [2], i.e. in the production of raw materials (aggregate, bitumen, additives, etc.) and their transport, as well as in the production process of the asphalt mixtures themselves. That is why the optimization of processes at these stages has great potential to ensure the ecological safety and sustainability of bitumen technologies, in line with the assumptions of the European Green Deal initiative [3], as well as other programs that should lead to achieving carbon neutrality by 2050.

Some of the prospective directions for reducing emissions in the construction of asphalt pavements include, for example, the use of technology for the production of warm mix asphalt [4-8], the wider use of reclaimed asphalt in the production of new asphalt mixtures, the reduction of moisture content of mineral raw materials (aggregate, sand, reclaimed asphalt), the use of bio-binders and low-emission binders of other types, etc. [9-11].

Among solutions aimed at the use of recycled components in the production of asphalt mixtures for reducing dependence on the use of primary natural resources the following can also be listed: modification of asphalt binders with rubber from recycled end-of-life tires (ELTs) and recycled polymers, the use of products from the processing of bituminous membranes, recycled aggregates from construction and demolition waste, use of recycled asphalt pavement, steel slags, etc.

Landfilling of end-of-life tires is prohibited in the European Union, so end-of-life tire management models aim to achieve 100% recycling. In 2019, Europe generated 3,555,611 tons of ELT tires, and more than 40% of this amount (over 1.4 million tons) was burned in cement plant furnaces [12], including the waste from production of rubber granulates and powders – rubber-contaminated synthetic fibres from textile cords.

Textile cord accounts for about 5.5% of the weight of passenger car tires, about 3% of light trucks tires, and about 10% of SUV tires [13]. The textile cord is made of high-quality polyester, polyamide, aramid and viscose fibers. These fibers are very durable, resistant to high temperatures and chemicals. Thanks to the activation of the surface, they have increased adhesive properties in relation to rubber and asphalt binders. Therefore, using this component of ELT tires as an energy source is not the most efficient way of their utilization.

1.2. APPLICATION OF ELT TEXTILE CORD FIBRE AS AN ADDITIVE TO ASPHALT MIXTURES: THE CURRENT STATE OF THE ART

A number of studies indicate a high environmental effect of the scenario of using textile cord fibers of ELT tires in asphalt mixtures instead of burning it as an alternative fuel in cement kilns or disposal in landfills [13-15].

The authors [15] indicate the significant impact of synthetic fibers from end-of-life tires in porous asphalt mixtures and SMA mixtures in terms of increasing their fatigue resistance by up to 70% while ensuring the technological properties determined by the binder drainage test as compared to cellulose fibre stabilized mixtures, resulting in a significant (up to 15%) reduction in environmental impact estimated on the basis of CED (Cumulative Energy Demant), GWP (Global Warming Potential) and the ReCiPe model.

It was found that in gap-graded mixtures the textile fibers from ELT tires can perform a similar function as cellulose-based additives, preventing segregation of the compound [16-17], while positively affecting its resistance to water [17]. Due to the limited absorption of the binder by the fibres from ELT tires, it is possible to reduce the

amount of binder in the asphalt mixture without deterioration of its technical parameters [17].

The use of textile fibers from ELT tires in the composition of asphalt mixtures can increase their resistance to cracking [18], and one of the mechanisms of their action is to delay the development of microcracks to macrocracks, as indicated by the results of research [19]. However, it is noted that in mixtures with reduced asphalt film thickness, it is necessary to precisely optimize the bitumen content based on the achievement of the required water resistance indicators [18].

The results of tests of asphalt mixtures with a mixture of textile fibers from ELT tires and rubber powder combined with a bituminous emulsion indicate a significant improvement in the fatigue life of AC and SMA asphalt mixtures [20].

The authors of the study [21] presented the results of research on the rheological properties of an asphalt binder containing textile fibers from used tires, indicating, among other things, an improvement in the rutting parameter $|G^*|/sin\delta$ and recovery in multiple stress creep recovery (MSCR) studies.

Domestically, experimental work was carried out on the use of materials from the processing of car tires to produce asphalt mixtures. These experiments included use of granulated rubber in combination with synthetic fibers from ELT textile cords [22-23].

1.3. CHALLENGES IN THE USE OF TEXTILE CORD FIBRES OF ELT TYRES AS AN ADDITIVE TO ASPHALT MIXTURES

Additives for asphalt mixtures based on textile cord obtained from ELT tires have not yet gained wide use, which can be attributed to the high complexity of cleaning the fibers and difficulty of processing them into a form suitable for simple and effective dosing and homogenization in the production of asphalt mixtures at asphalt plants. Obtaining an additive with constant and well-controlled parameters and a form that allows easy dosing during the production of asphalt mixtures requires attention at the stage of raw material selection of a specialized technological line. ELT textile cord fibers recovered directly from the car tire processing process are in the form of loose braided puffs, characterized by a high degree of heterogeneity and variability of properties [24].

An example of an effective solution to the above-mentioned technical problems is the fiber-rubber additive, which meets the requirements described above and can act as a stabilizing and strengthening additive in asphalt mixtures [25]. The effect on the properties of asphalt mixtures of this additive can be shaped to a wide extent by changing the length of fibers, the content and grain size of the rubber powder contained therein and potentially saturating it with a wide range of substances absent in the primary raw material.

In the presently available studies, little attention has been given to the optimization of the composition of this type of additives, which can be associated with the difficulties in controlling their properties. The obvious objective of optimization in this area may be to ensure the homogeneity of the properties of the additive and the predictability of the effect of its use as a component of asphalt mixtures, aimed at improving the properties and durability of asphalt mixtures.

Therefore, in this study, an attempt was made to evaluate the rheological properties of asphalt mastic containing both textile fibers from ELT and fine rubber powder. An attempt was made to investigate this type of asphalt mastic with a composition similar to that found in actual SMA asphalt mixture.

The asphalt mastic was selected for the substrate in the conducted tests (as opposed to plain asphalt binder) due to the introduction of relatively large particles of the additives and significant impact of the properties of asphalt mastic on the properties of the asphalt mixtures [26-28] and the increasingly widely used research methods in this field [29].

Experimental asphalt mastics with synthetic fiber and rubber powder were produced without the use of additional specialized equipment or processes aimed at obtaining a high degree of homogenization – the mastic production process corresponded to the method of "dry" modification in the actual process of preparing asphalt mixtures during the addition of a fibrous additive to the mixer at the asphalt plant, in order to maintain the strengthening effect of the fiber, i.e. without its pulping, dissolving etc. The only additional process not normally used in the asphalt plant was the deagglomeration of additives in order to easily distribute them in mastic on a laboratory scale. Limestone filler, rubber powder and synthetic fibers were added to the asphalt binder at the same time, as required. The

results of the research will allow to determine effective directions for the development of methods for optimizing the composition and production of this type of granular fibrous additives of high quality and efficiency for asphalt mixtures of all types, including those produced using the "hot", "warm" and "cold" methods.

2. TEST METHODS AND MATERIALS

2.1. TEST METHODS

Dynamic viscosity of asphalt mastics was determined using a dynamic shear rheometer with coaxial cylinder geometry at temperatures of 100°C, 125°C, 150°C, 175°C and at a shear rate of 1/s. The tests were carried out in accordance with the PN-EN 13302:2018-06 standard.

The rheological properties of asphalt mastics in oscillatory shearing mode (dynamic shear modulus, phase angle) were determined at temperatures from 10°C to 90°C in steps of 10°C at frequencies from 0.16 Hz to 16 Hz under controlled strain in accordance with PN-EN 14770:2024-01.

Multiple stress creep recovery tests were carried out in accordance with the PN-EN 16659:2016-02 standard at a temperature of 60°C, in sequences of increasing shear stress values of: 0.1 kPa, 1.6 kPa, 3.2 kPa, 6.4 kPa, 12.8 kPa and 25.6 kPa.

The presented results of dynamic viscosity and oscillatory DSR tests represent averages obtained from two samples in the respective tests. Additional samples were tested when the limits for repeatability provided by the testing standards were exceeded. In the MSCR tests, four samples were tested, and 95% confidence intervals were calculated (represented by the error bars in the figures).

2.2. MATERIALS AND SAMPLE PREPARATION

2.2.1. Materials

The basis for the production of asphalt mastics was a 50/70 paving grade bitumen (denoted as A; penetration at 25°C: 64.1 0.1 mm; softening point: 47.8°C) and limestone mineral filler (denoted as MF) meeting the requirements for a filler for the SMA wearing course mixture according to WT-2 [30], which were mixed in the proportion of 1:1.79 (A:MF, m/m). The composition of the base asphalt mastic reflected the proportions of the above-mentioned components in the SMA 11 mixture meeting the national requirements [30].

The study used synthetic fiber (F) from the production of crumb rubber from ELT tires and rubber powder (R) from cleaning of ELT derived synthetic fibers (properties of these components are provided in Table 1). The length of synthetic fibers was determined on the basis of the particle size of the crumb rubber produced throughout the production process. The granulometric composition of crumb rubber and rubber powder was determined in accordance with the requirements of PN-EN 14243-2:2019-04.

The process of preparation of the synthetic fiber used in the study obtained from the processing of textile cord in the production process of rubber granules (Fig. 1a), included: cleaning from impurities (Fig. 1b), activation during agglomeration (Fig. 1c) and pelletizing to obtain hard pellets (Fig. 1d) with a bulk density of about 450 kg/m^3 for their long-term storage in packaging and easy homogenization in a mixer in asphalt plant.

Table 1. Characteristics of components from the processing of textile cord from ELT tires

Synthetic fiber (F)				Rubber powder (R)		
Fiber length [mm]	Fiber content [%]	Average fiber length [mm]	Rubber powder content [% fiber mass]	Sieve [mm]	Passing [%]	Content of fibers shorter than 1 mm [% of rubber powder mass]
11-13	1.1-5.2	2.9	22.1-26.7	1.4	100	13.2-17.3
7-11	5.7-6.7			1.2	99.9	
5-7	8.1-9.4			0.8	99.1	
3-5	14.3-18.5			0.6	93.2	
1-3	28.4-35.3			0.3	40.5	
<1	29.2-38.2			0.15	1.1	

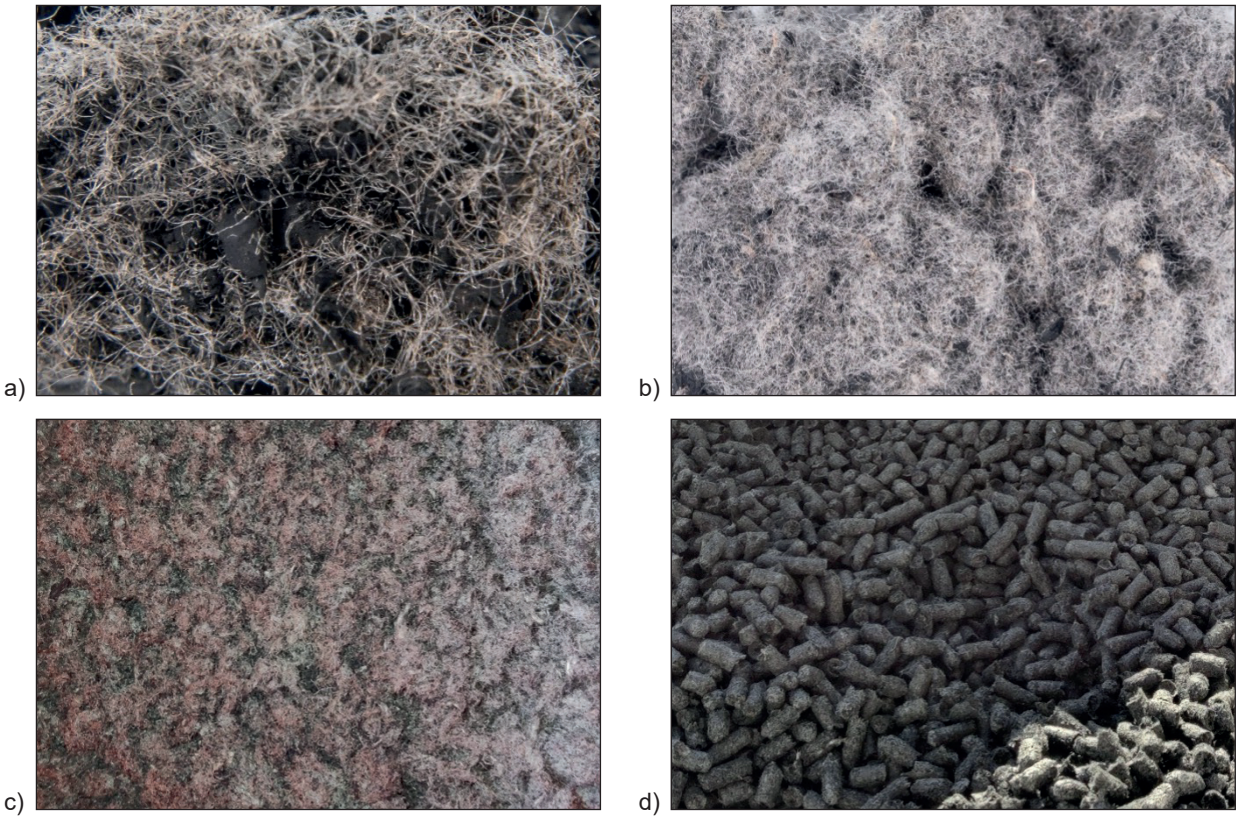

Fig. 1. Processing steps of synthetic fiber from ELT textile cord

Synthetic fibre in the form of pellets was deagglomerated with the use of a knife shredder before commencing the production of asphalt mastics in the laboratory. The rubber powder obtained during the purification of synthetic fibres also underwent the agglomeration, activation and granulating stages, after which it was deagglomerated to a homogeneous bulk state.

2.2.2. Sample preparation

The methodology of preparing samples for testing has been developed taking into account the conditions during the production of SMA mixtures in accordance with the guidelines described in WT-2 [30] and the conditions for conducting the binder drainage test in accordance with the PN-EN 12697-18:2017-07 standard. The mixing and conditioning temperature of asphalt mastic samples was set at the level of 175°C, which is equal to the temperature of binder drainage testing for a 50/70 SMA mix. Five different compositions of asphalt mastics were analyzed in this paper, differing in the amount of synthetic fiber (F) and rubber powder (R) ranging from a reference asphalt mastic (no fiber and powder additives included) up to 12% of total additive content. Compositions of the analyzed asphalt mastics are provided in the results section. For each of the mixtures, three batches were prepared for testing: immediately after mixing and one and two hours of conditioning.

The mixtures were produced by adding hot mineral filler and unheated synthetic fibres and rubber powder to the previously weighed hot asphalt binder in glass containers. The temperature of the hot components of the mixture was adjusted so that immediately after mixing, the temperature of each batch was not lower than 165°C and could be quickly brought to 175°C without overheating the asphalt binder.

After mixing, the batches subjected to further conditioning were placed in a laboratory oven and their temperature was controlled. Eventually, the mastics were poured into separated silicone molds into blocks with dimensions of 100 × 20 × 20 mm in horizontal orientation, which limited the possibility of segregation of the mixture. Samples for testing using in a dynamic shear rheometer were prepared by trimming them off with a heated blade.

3. RESULTS

3.1. DYNAMIC VISCOSITY

The results of the tests presented in Table 2 indicate that the addition of both synthetic fibers and rubber powder caused a significant increase in the dynamic viscosity of asphalt mastics at all test temperatures. This effect, in each case, was greater the higher the temperature of the test. It was observed that the addition of synthetic fiber had a smaller effect on the dynamic viscosity at lower temperatures, while significantly increasing its value at high temperatures (see experiments 3 and 4), which could be attributed to larger surface area of the introduced additives (fine synthetic fibers with fine rubber powder). It can be speculated that at higher temperatures the flow of the mastic is more affected by the particles suspended within it (filler, fibers, rubber powder), while at lower temperatures the properties of the asphalt binder have higher significance in this scope. In the case of the highest content of the analyzed additives in experiment 5, the potential occurrence of a strong interaction of their joint use was observed, manifested by a significant increase in the tested parameter at 175°C. This increase goes beyond the additive nature of the isolated effects of both additives, which could be expected when comparing the results of experiments 2 and 4.

When analyzing the results of the dynamic viscosity of asphalt mastics from the point of view of the production technology of asphalt mixtures, the results observed in experiments 3 and 4 can be considered as beneficial, showing an approx. 16-18-fold increase in dynamic viscosity at 175°C and decreasing to 8-12 times for temperatures corresponding to the paving and compaction of the asphalt mixture. This relates to increased resistance to binder drainage, possibly without excessive negative effects on compaction.

3.2. RESULTS OF OSCILLATORY TESTS

The relationships between the values of the dynamic stiffness modulus and the phase angle presented in Fig. 2 allow to assess the effect of the additives on the viscoelastic properties of the evaluated asphalt mastics in a wide range of temperatures and loading times corresponding to pavement operation.

Based on the results obtained for experiment 2, it can be stated that the asphalt binder contained in the mastic interacted with the rubber powder shortly after mixing the components, and during the next hour the modification with the rubber particles caused further slight changes in the properties of the mastic. This statement can be based on the change in the Black curve in the middle range of dynamic shear moduli values (approx. 102 kPa) not observed in the reference mastic (see experiments 1 and 2). At this stage of the modification, no significant increase in the values of the dynamic stiffness modulus was observed at the highest temperatures and low loading frequencies.

The increase in the amount of additives used in experiments 3, 4 and 5 has significant changes in the rheological character of the mastics analyzed. A significant reduction in the maximum values of the phase angle and an increase in mastic stiffness were observed at the highest test temperatures. It is worth noting that the shape of the Black curves in the range of low temperatures and high frequencies did not change equally in these cases – the biggest difference is a slight decrease in the values of the phase angles, but the maximum values of the dynamic shear moduli observed in all experiments were comparable.

Fig. 3 presents the results of oscillatory tests in a dynamic shear rheometer performed at a temperature of 60°C and a frequency of 1.59 Hz. The effects of sample age (heating time at 175°C) and the amount of additives used on the

Table 2. Results of tests on the dynamic viscosity of asphalt mastics

Mastic composition				Dynamic viscosity [Pa·s]				Change in dynamic viscosity [%]			
#	A + MF	F	R	100°C	125°C	150°C	175°C	100°C	125°C	150°C	175°C
1	1	0	0	165	28	7.7	2.7	–	–	–	–
2	0.960	0	0.04	305	57	19.2	8.9	85	104	149	230
3	0.925	0.05	0.025	1061	262	88.6	46.5	543	836	1,051	1,622
4	0.920	0.08	0	1015	272	102.9	52.6	515	871	1,236	1,848
5	0.880	0.08	0.04	1542	836	279.3	195.2	835	2,886	3,527	7,130

previously mentioned rheological parameters was evaluated in detail. In the case of both the dynamic shear modulus and the phase angle, a significant effect of the time of high temperature exposure in the asphalt mastic – additive system can be noticed. While in the case of the reference mastic a relatively small increase in stiffness and a decrease in the phase angle were observed in the analyzed time of 2 hours, the changes in these values in the experiments with the addition of rubber powder and synthetic fiber were significantly greater and depended on the mastic composition. In experiments 2 and 3, an initial increase followed by a small decrease in the value of the dynamic shear modulus was observed. In the case of experiments 4 and 5, where the amounts of additives used were higher, the greatest increase in the stiffness of the material occurred after the first hour of heating, and after 2 hours a further slight increase in the dynamic shear modulus was observed. Based on the values of the phase angle, it can be stated that in most cases the largest changes were observed after the first hour, while after 2 hours there was a further slight decrease or stabilization of this parameter.

By analyzing the relationships presented in Fig. 4 showing the changes in $|G^*|$ and δ values measured at 1.59 Hz but at different temperatures, it is possible to confirm the observations based on the Black curves. All the analyzed asphalt mastics were characterized by similar values of the dynamic shear modulus at the lowest temperatures considered, while at high temperatures an increase was observed with the increase of rubber powder and synthetic fibers content. In the evaluation of phase angles, a significant effect of the additives on the reduction of this parameter at high temperatures (80°C and 90°C) was again noted in the case of experiments 3, 4 and 5. Tables 3 and 4 present the values of dynamic shear modulus and phase angles of analyzed asphalt mastics determined at the frequency of 1.59 Hz after 1 h of heating.

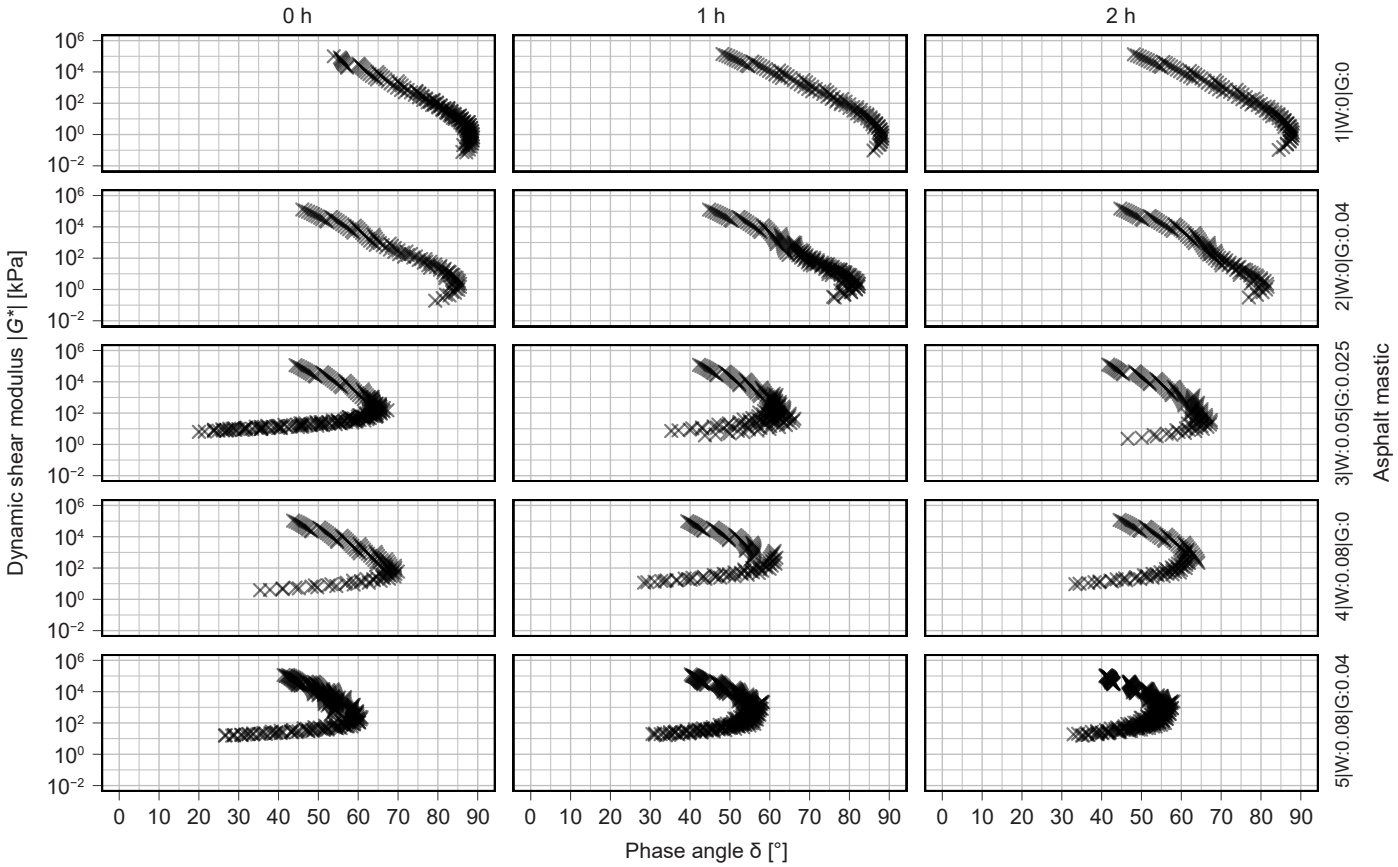

Fig. 2. Black curves for the analysed asphalt mastics

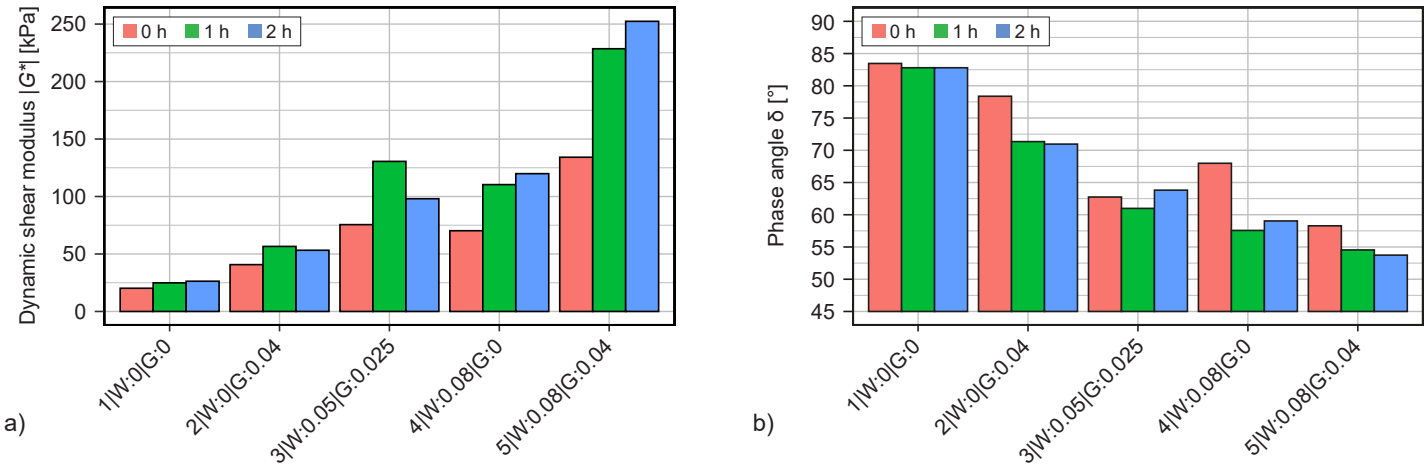

Fig. 3. Results of DSR rheometer oscillation tests at 60°C and 1.59 Hz: a) dynamic shear modulus |*G**|, b) phase angle δ

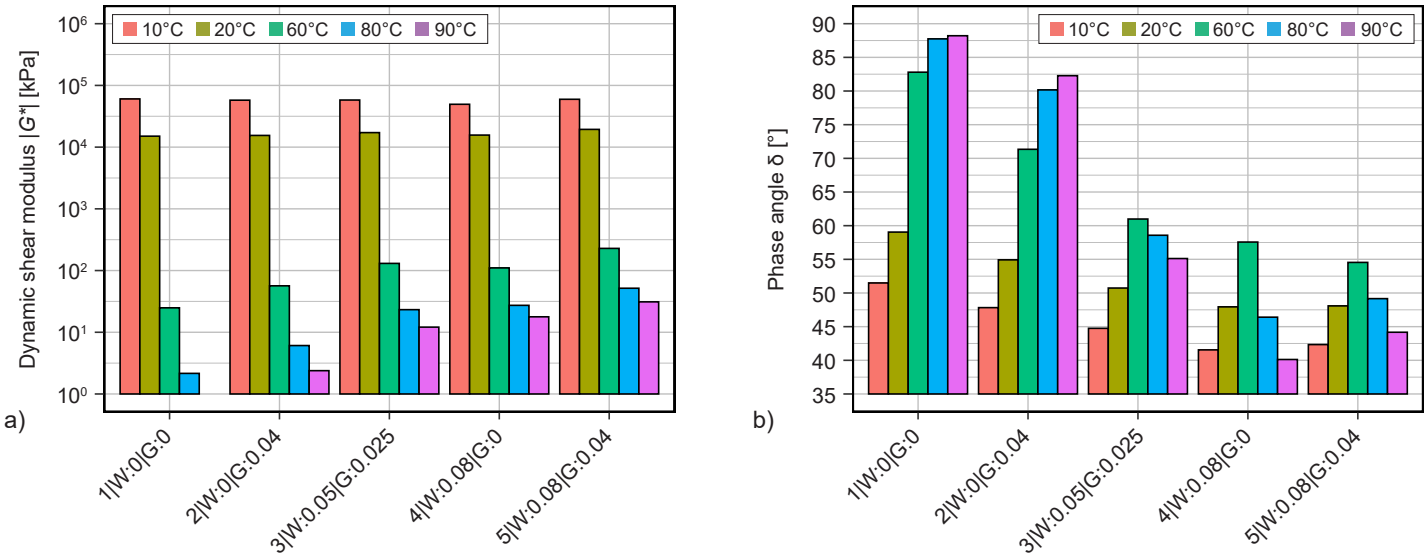

Fig. 4. Results of DSR rheometer oscillation tests performed at 1.59 Hz after 1 h of heating: a) dynamic shear modulus |*G**|, b) phase angle δ

Table 3. Dynamic shear modulus determined at 1.59 Hz after 1 h of heating.

Mastic composition				Dynamic shear modulus |*G**| [kPa]								
#	A + MF	F	R	10°C	20°C	30°C	40°C	50°C	60°C	70°C	80°C	90°C
1	1.00	0.00	0.000	60,384	15,047	2,990	566	113	25	6.6	2.2	0.84
2	0.96	0.00	0.040	57,653	15,469	3,406	768	198	57	17.6	6.1	2.39
3	0.93	0.05	0.025	57,969	17,190	4,373	1,122	391	131	51.5	23.2	12.12
4	0.92	0.08	0.000	49,453	15,671	4,264	1,178	302	110	49.9	27.3	17.80
5	0.88	0.08	0.040	59,610	19,382	5,717	1,705	621	229	99.6	51.7	31.09

Table 4. Values of phase angles determined at 1.59 Hz after 1 h of heating.

Mastic composition				Phase angle δ [°]								
#	A + MF	F	R	10°C	20°C	30°C	40°C	50°C	60°C	70°C	80°C	90°C
1	1.00	0.00	0.000	51.5	59.0	66.0	72.4	78.0	82.8	86.0	87.7	88.2
2	0.96	0.00	0.040	47.8	54.9	60.4	63.3	67.1	71.3	76.2	80.2	82.3
3	0.93	0.05	0.025	44.7	50.7	55.6	59.7	60.4	61.0	60.6	58.6	55.1
4	0.92	0.08	0.000	41.5	47.9	53.3	56.2	59.6	57.6	52.8	46.4	40.1
5	0.88	0.08	0.040	42.3	48.1	52.5	55.1	55.7	54.5	52.6	49.2	44.2

3.3. MULTIPLE STRESS CREEP RECOVERY TESTS

Figs. 5 and 6 present the results of the multiple stress creep recovery tests performed on the asphalt mastics. The results of the tests presented in the diagrams were carried out at shear stress of 3.2 kPa and 25.6 kPa. The non-recoverable compliance J_{nr} values obtained measuring the asphalt mastics were much lower than in the case of typical asphalt binder test results – all results were lower than 0.5 kPa^{-1}, therefore it was decided to present the results as MPa^{-1}.

In the analyzed experiments, the values of non-recoverable creep compliance decreased with increasing dosage of rubber powder and synthetic fiber. In the extreme case, an approx. 100-fold reduction in the J_{nr} parameter was obseved (comparing experiments 1 and 5). In all cases, the heating of asphalt mastics for 1 hour resulted in a decrease of the J_{nr} values, which in some cases were further reduced after the second hour of heating – particularly in case of experiments 4 and 5 with the highest synthetic fiber content. By comparing the results presented in Figs. 5a and 5b some observations about the susceptibility to the increase of the shear stress of the mastics can be made. In each of the cases analyzed, an increase in the value of J_{nr} was observed after increasing the shear stress to 25.6 kPa as expected. However, the relationships observed at the stress of 3.2 kPa were maintained at the stress of 25.6 kPa, which allows us to conclude that the introduction of additives in the form of rubber powder and synthetic fiber to the asphalt mastic did not have a negative effect on this characteristic.

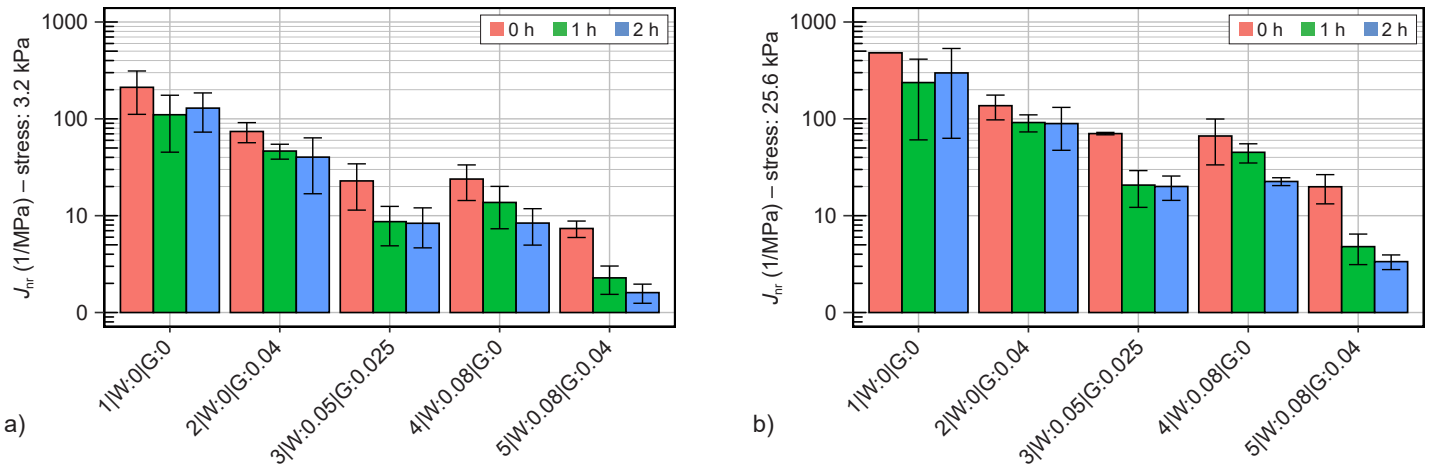

Fig. 5. Non-recoverable compliance J_{nr} values determined at 60°C and at stresses of: a) 3.2 kPa, b) 25.6 kPa

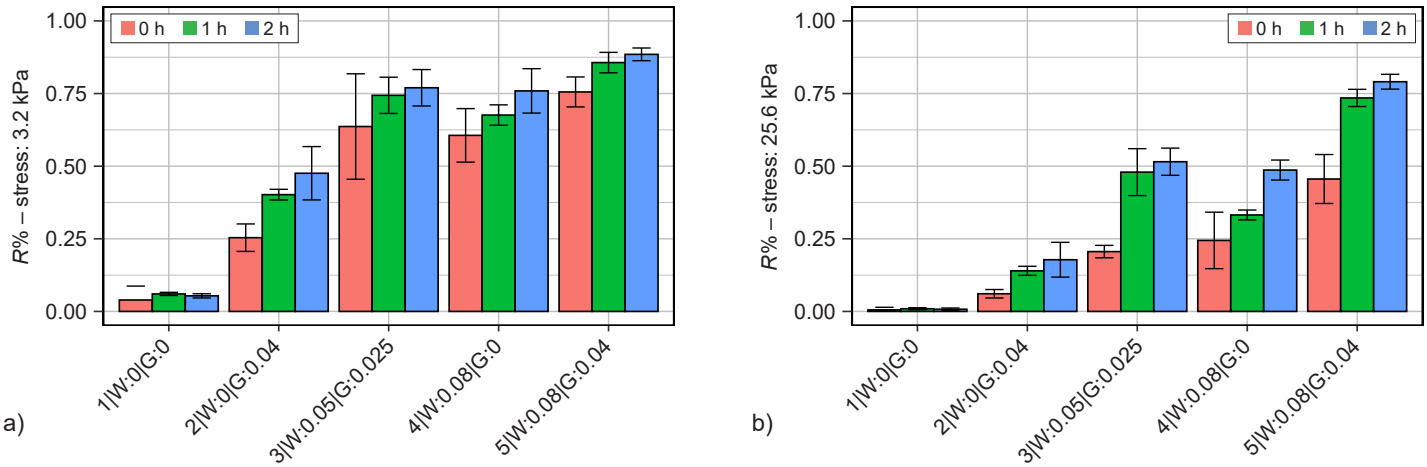

Fig. 6. Recovery values *R*% determined at 60°C and at stresses of: a) 3.2 kPa, and b) 25.6 kPa

As shown in Fig. 6, it can be stated that the addition of rubber powder and synthetic fiber in the composition of asphalt mastics resulted in a significant increase in the *R*% recovery values obtained in the MSCR study. As can be seen in Fig. 6a, the asphalt mastic based on the paving grade bitumen without the ELT derived additives was characterized by *R*% values not exceedingly approx. 7%, while the addition of rubber powder alone in experiment 2 caused an increase of this value to 25% immediately after its addition. A further increase in *R*% after one hour and two hours of heating the material at a temperature of 175°C was observed. In experiments 3, 4 and 5, recovery values exceeding 50% were obtained and they also increased with the exposure of the material to high temperatures. Subjecting the mastics to a shear stress of 25.6 kPa in all cases resulted in a decrease in the observed values of *R*% recovery, which is a typical observation also in the case of polymer modified asphalt binder tests. The largest reductions in *R*% were observed when the mastics were tested immediately after mixing with rubber powder and synthetic fibers. In the case of experiments 3 and 4, high recovery values of up to approx. 50% were obtained after prolonged exposure of the material to heat. The highest values of *R*% recovery were achieved in experiment 5 and even under the 25.6 kPa shear stress the recovery exceeded 75% after one and two hours of heating at 175°C.

4. CONCLUSIONS

The results presented in this paper regarding the performance of asphalt mastics consisting of 50/70 paving grade bitumen, limestone filler, fine rubber powder (0/2 mm) and synthetic fiber allow to formulate the following general conclusions regarding the effects of the analyzed ELT-derived materials:

1. They significantly increase the dynamic viscosity of asphalt mastic; the magnitude of this effect depends on the test temperature – the increase in viscosity resulting from the use of additives was lesser at lower temperatures (e.g. 125°C) than at higher temperatures (e.g. 175°C).
2. They significantly affect the rheological character of the asphalt mastic, improving its high-temperature properties and giving it elastic properties similar to those seen in polymer modified bitumen – e.g. significant recovery values (in the range of 50-80%).
3. The performance of asphalt mastics evaluated in this article remained stable throughout the analyzed time of high temperature exposure (175°C, up to 2 hours) – in some cases significant improvement with time was observed.

In all analyzed cases, a beneficial effect of the conditioning time of mastics containing synthetic fiber and/or rubber powder was found. The investigated time span included the time from the mixing of these components up to two hours, under a high temperature corresponding to the production temperature of the SMA mixture with a 50/70 asphalt binder. The largest changes in the performance of the masks were observed after 1 hour of conditioning, with further beneficial changes occurring after the second hour of heating. The observed results allow us to conclude that after mixing of asphalt binder and mineral filler with the rubber powder and synthetic fibers, the asphalt binder is affected rapidly, both with rubber

contained in rubber powder and small fractions of rubber contained in the synthetic fiber mixture.

The observed effects, e.g. in terms of changes in the values of dynamic shear moduli at high and low temperatures (large increases and small changes respectively) and phase angles, allow us to conclude that the additives changed the properties of asphalt mastics, resulting in performance which would be expected if polymer modified bitumen were used. While the independent addition of the rubber powder significantly reduced the values of phase angles in the middle range of the complex moduli, the addition of synthetic fiber affected both the middle and lower ranges of the stiffness moduli (corresponding to high temperatures and long loading times).

As shown by the results of MSCR multiple stress creep tests, the use of additives in the composition of mastics increased their sensitivity to changes in shear stress, but despite this, mastics with ELT derived additives exhibited manyfold lower values of non-recoverable compliance even at high shear stresses than the reference asphalt mastic without additives under low shear stresses. The additives introduced into the mastic significantly increased the measured values of elastic recovery of the tested samples, and in the case of experiment 5, a very good retention of the R% recovery value was observed (up to approx. 75%) at high shear stresses.

To sum up, it should be stated that studies aimed at assessing the impact of the use of materials from the processing of ELT used car tires have shown that they have a positive effect on the properties of asphalt mastics in the context of their use in SMA mixtures with paving grade bitumen used as a binder. Future work in this area should include evaluation of the above-mentioned additives in terms of their effects on the fatigue properties of asphalt mastics, studies including long-term ageing and tests conduced at larger scales – using actual asphalt mixtures.

CONFLICT OF INTERESTS

Some of the authors are employed by a company that manufactures the materials investigated in this article.

REFERENCES

[1] Towards net zero – A decarbonization roadmap for the asphalt industry. European Asphalt Pavement Association (EAPA), Bruksela, 2024, https://horizoneuropencpportal.eu/sites/default/files/2025-01/eapa-towards-net-zero-2024.pdf (available: 10.08.2025)

[2] *Shacat J.*, *Willis R.*, *Ciavola B.*: The carbon footprint of asphalt pavements. The Road Forward, SIP-109, National Asphalt Pavement Association, Greenbelt, MD, USA, 2024, https://www.asphaltpavement.org/uploads/documents/Climate/NAPA-SIP109-TheCarbonFootprintOfAsphaltPavements-March2024.pdf (available: 10.08.2025)

[3] *Fetting C.*: The European green deal. European Sustainable Development Network (ESDN), ESDN Report, Vienna, 2020, https://www.esdn.eu/fileadmin/ESDN_Reports/ESDN_Report_2_2020.pdf (available 10.08.2025)

[4] *Li K.*, *Yan X.*, *Pu J.*, *Wang Y.*, *Chen Y.*, *Fang K.*, *Hu J.*, *Yang Y.*: Quantitative evaluation on the energy saving and emission reduction characteristics of warm mix asphalt mixtures. Construction and Building Materials, **407**, 2023, Article ID: 133465, DOI: 10.1016/j.conbuildmat.2023.133465

[5] *Lee H.*, *Nguyen L.N.*, *Sturlini E.*, *Kim Y.I.*: Cool mix asphalt – redefining warm mix asphalt with implementations in Korea, Italy and Vietnam. Infrastructures, **10**, 1, 2025, Article ID: 24, DOI: 10.3390/infrastructures10010024

[6] *Malinowski S.*, *Pacholak R.*, *Kołodziej K.*, *Woszuk A.*: Application of NaP1 zeolite modified with silanes in bitumen foaming process. Materials, **17**, 23, 2024, Article ID: 5902, DOI: 10.3390/ma17235902

[7] *Maciejewski K.*, *Chomicz-Kowalska A.*, *Remisova E.*: Effects of water-foaming and liquid warm mix additive on the properties and chemical composition of asphalt binders in terms of short-term ageing process. Construction and Building Materials, **341**, 2022, Article ID: 127756, DOI: 10.1016/j.conbuildmat.2022.127756

[8] *Chomicz-Kowalska A.*, *Maciejewski K.*, *Iwański M.M.*: Study of the simultaneous utilization of mechanical water foaming and zeolites and their effects on the properties of warm mix asphalt concrete. Materials, **13**, 2, 2020, Article ID: 357, DOI: 10.3390/ma13020357

[9] *Bueche N.*, *Probst S.*, *Eskandarsefat S.*: Warm-mix asphalt containing reclaimed asphalt pavement: A case study in Switzerland. Infrastructures, **9**, 5, 2024, Article ID: 79, DOI: 10.3390/infrastructures9050079

[10] *Zhang Z.*, *Fang Y.*, *Yang J.*, *Li X.*: A comprehensive review of bio-oil, bio-binder and bio-asphalt materials: Their source, composition, preparation and performance. Journal of Traffic and Transportation Engineering (English Edition), **9**, 2, 2022, 151-166, DOI: 10.1016/j.jtte.2022.01.003

[11] *Iwański M.*, *Chomicz-Kowalska A.*, *Maciejewski K.*, *Iwański M.M.*, *Radziszewski P.*, *Liphardt A.*, *Król J.B.*, *Sarnowski M.*, *Kowalski K.J.*, *Pokorski P.*: Warm mix asphalt binder utilizing water foaming and fluxing using bio-derived agent. Materials, **15**, 24, 2022, Article ID: 8873, DOI: 10.3390/ma15248873

[12] End-of-life tire recycling and collection statistics. European Tyre and Rubber Manufacturers' Association (ETRMA), Bruksela, 2019, https://www.etrma.org/wp-content/uploads/2021/05/20210511_ETRMA_PRESS-RELEASE_ELT-2019.pdf (available: 10.08.2025)

[13] *Landi D.*, *Marconi M.*, *Meo I.*, *Germani M.*: Reuse scenarios of tires textile fibers: An environmental evaluation. Procedia Manufacturing, **21**, 2018, 329-336, DOI: 10.1016/j.promfg.2018.02.128

[14] *Bianco I.*, *Panepinto D.*, *Zanetti M.*: End-of-life tyres: Comparative life cycle assessment of treatment scenarios. Applied Sciences, **11**, 8, 2021, Article ID: 3599, DOI: 10.3390/app11083599

[15] *Landi D.*, *Marconi M.*, *Bocci E.*, *Germani M.*: Comparative life cycle assessment of standard, cellulose-reinforced and end-of-life tires fiber-reinforced hot mix asphalt mixtures. Journal of Cleaner Production, **248**, 2020, Article ID: 119295, DOI: 10.1016/j.jclepro.2019.119295

[16] *Chowdhury A.*, *Button J.W.*, *Bhasin A.*: Fibers from recycled tires as reinforcement in hot mix asphalt. College Station, Report No. SWUTC/06/167453-1, TX, USA, 2006, http://swutc.tamu.edu/publications/technicalreports/167453-1.pdf (available: 10.08.2025)

[17] *Putman B.J.*, *Amirkhanian S.N.*: Utilization of waste fibers in stone matrix asphalt mixtures. Resources, Conservation and Recycling, **42**, 3, 2004, Article ID: 265274, DOI: 10.1016/j.resconrec.2004.04.005

[18] *Pais J.C.*, *Ferreira A.*, *Santos C.*, *Pereira P.*, *Lo Presti D.*: Preliminary studies to use textile fibers obtained from recycled tires to reinforce asphalt mixtures. Romanian Journal of Transport Infrastructure, **7**, 2, 2018, 14-30, DOI: 10.2478/rjti-2018-0009

[19] *Bocci E.*, *Prosperi E.*: Recycling of reclaimed fibers from end-of-life tires in hot mix asphalt. Journal of Traffic and Transportation Engineering (English Edition), **7**, 5, 2020, 678-687, DOI: 10.1016/j.jtte.2019.09.006

[20] *Valdes-Vidal G.*, *Calabi-Floody A.*, *Mignolet-Garrido C.*, *Bravo-Espinoza C.*: Enhancing fatigue resistance in asphalt mixtures with a novel additive derived from recycled polymeric fibers from end-of-life tyres (ELTs). Polymers, **16**, 3, 2024, Article ID: 385, DOI: 10.3390/polym16030385

[21] *Calabi-Floody A.*, *Mignolet-Garrido C.*, *Valdés-Vidal G.*: Evaluation of the effects of textile fibre derived from end-of-life tyres (TFELT) on the rheological behaviour of asphalt binders. Construction and Building Materials, **360**, 2022, Article ID: 129583, DOI: 10.1016/j.conbuildmat.2022.129583

[22] *Sybilski D.*: Zastosowanie odpadów gumowych w budownictwie drogowym. Przegląd Budowlany, **5**, 2009, 37-44, https://www.przegladbudowlany.pl/2009/05/2009-05-pb-37-44_sybilski.pdf (available in Polish: 10.08.2025)

[23] *Jurczak R.*: Nawierzchnia z dodatkiem gumy (i włókien) po 18 latach eksploatacji. Drogownictwo, **77**, 2-3, 2022, 35-39, https://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-58f379ae-d265-416c-a960-8fe410014714 (available in Polish: 10.08.2025)

[24] *Chomicz-Kowalska A.*: Laboratory testing of low temperature asphalt concrete produced in foamed bitumen technology with fiber reinforcement. Bulletin of the Polish Academy of Sciences Technical Sciences, **65**, 6, 2017, 779-790, DOI: 10.1515/bpasts-2017-0086

[25] *Zankowicz W.*, *Zaprzalski P.*: SMAPOL® otwiera nowe perspektywy poprawy trwałości nawierzchni asfaltowych. Drogowo-Mostowy.pl, 2024, https://drogowo-mostowy.pl/smapol-otwiera-nowe-perspektywy-poprawy-trwalosci-nawierzchni-asfaltowych/ (available in Polish: 10.08.2025)

[26] *Kołodziej K.*, *Bichajło L.*, *Siwowski T.*: Influence of composition and properties of mastic with natural asphalt on mastic asphalt mixture resistance to permanent deformation. Roads and Bridges – Drogi i Mosty, **20**, 1, 2021, 57-73, DOI: 10.7409/rabdim.021.004

[27] *Kong D.*, *Wu S.*, *Chen M.*, *Zhao M.*, *Shu B.*: Characteristics of different types of basic oxygen furnace slag filler and its influence on properties of asphalt mastic. Materials, **12**, 24, 2019, Article ID: 4034, DOI: 10.3390/ma12244034

[28] *Zeng M.*, *Wu C.*: Effects of type and content of mineral filler on viscosity of asphalt mastic and mixing and compaction temperatures of asphalt mixture. Transportation Research Record, **2051**, 1, 2008, 31-40, DOI: 10.3141/2051-05

[29] *Ryś D.*, *Jaskuła P.*, *Szydłowski C.*: Comprehensive temperature performance evaluation of asphalt mastics containing hydrated lime filler based on dynamic shear rheometer testing. Roads and Bridges – Drogi i Mosty, **23**, 4, 2024, 355-373, DOI: 10.7409/rabdim.024.017

[30] WT-2 Nawierzchnie asfaltowe na drogach krajowych. Mieszanki mineralno-asfaltowe. Wymagania techniczne. Generalna Dyrekcja Dróg Krajowych i Autostrad (GDDKiA), Załącznik do zarządzenia nr 54 GDDKiA z dnia 08.11.2014, Warszawa, 2014

Wpływ dodatku włóknisto-gumowego na właściwości reologiczne mastyksów asfaltowych

Streszczenie: W artykule przedstawiono wyniki badań wpływu składu dodatku włóknisto-gumowego, który jest obecnie produkowany na skalę przemysłową w Polsce i stosowany jako stabilizator do mieszanek mineralno-asfaltowych o nieciągłym uziarnieniu, takich jak SMA. Przedstawiono wpływ składu ww. dodatku na właściwości reologiczne mastyksów asfaltowych, składających się z asfaltu drogowego i wypełniacza wapiennego. Pierwszym składnikiem dodatku jest miał gumowy otrzymywany przez mielenie w temperaturze otoczenia, częściowo dewulkanizowany i aktywowany. Drugi element składa się z włókien syntetycznych pochodzących z kordów tekstylnych zużytych opon, które są oddzielane i przycinane na wymaganą długość podczas obróbki zużytych opon. W eksperymentach zmiennymi były zawartości dwóch składników dodatku. Oceniane charakterystyki obejmowały lepkość dynamiczną i charakterystyki reologiczne oceniane z wykorzystaniem reometru dynamicznego ścinania, w tym zespolonego modułu ścinania i kąta przesunięcia fazowego w oscylacyjnym ścinaniu, a także nieodwracalną podatność na pełzanie z oceną nawrotu sprężystego w badaniach cyklicznego pełzania z odprężeniem z przyrostowo rosnącymi wartościami naprężeń. Uzyskane wyniki odniesiono do mastyksu asfaltowego bez dodatku, składającego się wyłącznie z niemodyfikowanego asfaltu i wypełniacza mineralnego. Wyniki badań umożliwiły ocenę wpływu składników dodatku włóknisto-gumowego na charakterystyki reologiczne mastyksów asfaltowych, co pozwala na dalszy rozwój technologii poprawy właściwości mieszanek mineralno-asfaltowych w sposób środowiskowo zrównoważony oraz stwarza możliwości zwiększenia funkcjonalności tych dodatków.

Słowa kluczowe: granulat gumowy, kord tekstylny, mastyks asfaltowy, recykling opon samochodowych, zużyte opony samochodowe.