PIOTR RADZISZEWSKI[1)]
MICHAŁ SARNOWSKI[2)]
PIOTR POKORSKI[3)]

BITUMENS MODIFIED WITH THE ADDITION OF CRUMB RUBBER POWDER FROM RECYCLED CAR TIRES – RESEARCH AND PRACTICE

LEPISZCZA ASFALTOWE MODYFIKOWANE DODATKIEM MIAŁU GUMOWEGO ZE ZUŻYTYCH OPON SAMOCHODOWYCH – BADANIA I PRAKTYKA

STRESZCZENIE. Recykling materiałów w budownictwie drogowym jest ważnym zagadnieniem w aspekcie ochrony środowiska oraz optymalizacji kosztów przedsięwzięć drogowych. W celu poprawienia właściwości lepiszczy asfaltowych coraz częściej stosuje się modyfikację dodatkami rozdrobnionej gumy ze zużytych opon samochodowych. Uzyskane w wyniku tej modyfikacji lepiszcza gumowo-asfaltowe charakteryzują się, podobnie jak polimeroasfalty, polepszonymi właściwościami lepkosprężystymi. Wykazują one jednak wyższą niż polimeroasfalty odporność na działanie niskiej temperatury. Wykorzystanie rozdrobnionej gumy z recyklingu opon samochodowych jest uzasadnione również ze względów ekologicznych i stanowi najlepszy sposób zagospodarowania odpadów gumowych. W artykule przedstawiona została analiza porównawcza właściwości lepkosprężystych lepiszczy gumowo-asfaltowych, która obejmowała ocenę właściwości w zakresie niskich, średnich i wysokich temperatur. Lepiszcza poddano badaniom w zakresie podstawowych wymagań przewidzianych dla asfaltów modyfikowanych, badaniom konsystencji w zakresie temperatur technologicznych oraz zaawansowanym badaniom reologicznym w reometrze dynamicznego ścinania oraz reometrze zginanej belki. Przedstawione zostały przykłady zastosowania lepiszczy gumowo-asfaltowych w realizacjach odcinków drogowych w Polsce. W podsumowaniu sformułowane zostały wnioski dotyczące możliwości modyfikacji, właściwości oraz zastosowania lepiszczy asfaltowych modyfikowanych dodatkiem miału gumowego ze zużytych opon samochodowych.

SŁOWA KLUCZOWE: lepiszcze gumowo-asfaltowe, recykling opon samochodowych.

ABSTRACT. Recycling of waste materials in road construction is an important issue in terms of environmental protection and cost optimization of road construction. In order to improve the properties of asphalt binders, modification with the addition of crumb rubber powder from waste car tires is increasingly applied. The rubber modified binder obtained as a result of this modification is characterized, similarly to polymer modified bitumen, by improved viscoelastic properties. However, it is more resistant to low temperatures than polymer modified bitumen. The use of crumb rubber powder from recycled car tires is also justified for ecological reasons and is the best way to crumb rubber recycling. The paper presents a comparative analysis of the viscoelastic properties of rubberized asphalt binders, which included the assessment of properties in the range of low, medium and high temperatures. The binders were tested in terms of the basic requirements for modified binders, carrying out consistency tests in the range of technological temperatures and rheological tests in a dynamic shear rheometer and a bending beam rheometer. Examples of the use of rubber modified binder in the construction of road sections in Poland were presented. In the summary conclusions regarding the possibility of modification, properties and use of bitumens modified with the addition of rubber crumb from waste car tires were presented.

KEYWORDS: rubber modified binder, car tire, crumb rubber recycling.

DOI :10.7409/rabdim.023.036

1) Warsaw University of Technology, Warsaw; piotr.radziszewski@pw.edu.pl
2) Warsaw University of Technology, Warsaw; michal.sarnowski@pw.edu.pl
3) Warsaw University of Technology, Warsaw; piotr.pokorski@pw.edu.pl ✉

*) An extended version of the article from the Conference "Modern Road Pavements – MRP'2023" – Recycling in road pavement structures co-edited by Martins Zaumanis and Marcin Gajewski, published in frame of the Ministry of Education and Science project No. RCN/SP/0569/2021/1

1. INTRODUCTION

Road pavement should be durable, safe, and its construction and maintance should meet the requirements of sustainable development and environmental protection. Environmental protection and sustainable development are the basic principles of global development from the point of view of the economy and transport in Poland, the European Union and the world. These rules require the use of recycled materials. Research work on the reuse of materials for the production of asphalt mixtures has been carried out for many years in Poland and around the world. The most frequently used materials in recycling are: reclaimed asphalt, rubber waste, steel waste, textile and plastic waste. The climatic conditions in Poland, in respect of the use of road pavements, are unfavorable due to the temperature crossing zero more than a hundred times during the year. Low temperatures in winter and high temperatures in summer are characteristic in the European climate zone in Poland. For this reason, the binders used for asphalt mixtures should be characterized by a wide temperature range of viscoelasticity. In order to ensure the durability of pavements resistant to low-temperature cracks in winter, permanent deformations in summer and resistance to fatigue, it is necessary to use high-quality binders. The use of waste materials often leads to a reduction in the functional properties of binders and asphalt mixtures. The use of recycled materials, in addition to the benefits resulting from their reuse, should also ensure the production of binders and asphalt mixtures with comparable or better properties than those produced exclusively from new materials. This problem is a current topic of research and development projects. Crumb rubber powder from used car tires is one of the most promising modifiers used to improve the properties of road bitumen. Due to the specific climatic conditions in Poland, it is justified to use rubber-modified binder for all construction layers of road and bridge pavements as much as possible. The addition of rubber powder can be a very effective modifier, expanding the range of viscoelasticity of binders and asphalt mixtures, delaying the aging processes, and improving the functional properties of road pavements in a wide range of operating temperatures [4, 5, 6]. It should be emphasized that the use of rubber powder from used car tires to modify bitumen meets the requirements of environmental protection and sustainable development. The technology of asphalt modification with the crumb rubber can still be considered innovative and progressive. The paper presents the results of testing of binders with the addition of rubber powder from used car tires, indicating the possibility of obtaining binders with properties comparable to polymer modified bitumens, representing the best properties at low and high operating temperatures.

2. STATE OF THE ART

A binder with the addition of crumb rubber is defined as a mixture of bitumen and rubber powder from used car tires, in which the rubber reacts with hot bitumen, significantly increasing its volume [7, 8, 9]. Rubber powder is understood as crumb rubber with a grain size of up to 2.0 mm. Binder modified with the addition of rubber (according to the European terminology, rubber modified binder) can be divided into two basic types: asphalt rubber and terminal blend (according to US terminology). The industrial technology for producing rubber-modified binder using asphalt rubber technology was developed in the USA by McDonald in the mid-1960s. Asphalt rubber binder contains at least 15% rubber and can be produced with the addition of crumb rubber (e.g. in the USA in Arizona and Texas) or with the addition of crumb rubber and with an additive containing a high content of natural rubber and plasticizers (e.g. in the USA in the state of California). Binders of this type are produced directly at the asphalt mixture plant and should be immediately used for the production of mixtures or for other applications [13–18]. Bitumen modified with the addition of rubber is available on the Polish market as an asphalt rubber binder and is produced with the addition of rubber powder in the amount of 15–17% [20–24]. The asphalt rubber binder is produced in special mobile units, cooperating with the asphalt hot mix plants. The crumb rubber is mixed with hot bitumen in a mixer using a high-speed shear head, and then the asphalt rubber- binder matures in a heated circulation tank for about 1–2 hours, where further swelling and devulcanization of the rubber takes place. After maturing, the asphalt rubber binder should be used for the production of rubber-asphalt mixtures or other applications as soon as possible and should not be kept at elevated temperature for too long (over 10 hours). [1, 2]. Terminal blend binder is obtained by modifying the bitumen with the addition of small fractions of rubber powder (grain size up to 1.0 mm) in an amount of up to 10% and the addition of a small polymer content. This binder is produced in a refinery and can be stored for a long time, provided it is mixed. In Poland, a technology for the production of two types of polymer-rubber-asphalt binders has been developed, differing in hardness 25/55 and 45/80. Based on research conducted around the world since the 1970s, it has been shown that the properties of the asphalt rubber binder depend on many factors, including: the type of bitumen, the characteristics of the rubber additive, the time and temperature of producing the asphalt rubber binder, the method and intensity of mixing process, properties of the additives used [3, 11, 12, 25]. The research results also showed that the use of used car tires to modify binders is the most effective and ecologically justified method of managing rubber waste [6, 19, 26, 27, 28, 29].

At the Warsaw University of Technology and the Białystok University of Technology, the authors have been conducting research on the use of asphalt rubber binders for the construction of road pavements for many years. The issue of using rubber powder from waste car tires has been the subject of many publications [1–9, 21–24]. Analyzing the results of own research, conclusions can be drawn regarding the beneficial effect of modification with a rubber additive on the properties of binders:

– reduced temperature sensitivity (improved penetration index),
– significant increase viscosity,
– extended temperature range of viscoelasticity,
– increased elasticity at positive temperatures,
– improved binder properties at low temperatures,
– reduced sensitivity of the binder to aging.

As a result of using binders with the addition of crumb rubber to asphalt mixtures, road pavement layers with these mixtures are also characterized by many advantages compared to standard pavement layers, such as [2, 15–20, 30]:

– increased fatigue life,
– increased resistance to low-temperature cracking,
– improved resistance to rutting,
– improved anti-slip properties,
– reduced noise from car traffic,
– reduced road pavement maintenance costs.

To summarize the state of art and own experience, it should be stated that the most effective method of material recycling of waste car tires is their use as a modifier in asphalt rubber binders. This method of bitumen modification makes it possible to design a binder with properties at least comparable to those of traditional polymer-modified binders.

3. MATERIALS AND RESEARCH METHODOLOGY

The research plan required taking into account, in addition to bitumen modified with the addition of rubber powder, also two comparative binders – polymer modified bitumens commonly used in Poland, characterized on the one hand by the best low-temperature properties and, on the other hand, by the best properties in the field of high operating temperatures. PMB 25/55-60 was chosen as a comparative binder with good low-temperature properties, and PMB 45/80–65 was chosen as a comparative binder with good low-temperature properties. Binders modified with the addition of rubber powder used in laboratory tests included an asphalt rubber binder designed by the authors (rubber powder content of 17% m/m, base bitumen grade 70/100) and polymer-rubber-asphalt binders PMB 25/55-60 CR and PMB 45/80-55 CR, which were produced in the refinery. The asphalt rubber binder was produced in the process of modifying paving grade bitumen with the addition of rubber powder from car tires in the laboratory of the Warsaw University of Technology. In the production of asphalt rubber binder, laboratory special equipment was used to modify base bitumen with the addition of crumb rubber. Laboratory equipment for bitumen modification enables the selection of the optimal technology for modifying bitumen with rubber. The equipment ensures that the adopted temperature conditions are maintained during modification and adequate ventilation, which is important when using rubber additives. It also meets the safety requirements for personnel operating the modification process. The laboratory equipment for modifying base bitumen with the addition of rubber (Fig. 1) consists of the following components:

– a high shear dispersing device,
– low-speed mixer with a speed range of 50–1200 rpm,
– contact thermometer,
– containers 2000 ml and 5000 ml,
– ceramic heating plate with accessories,
– telescopic tripod (2 pcs.).

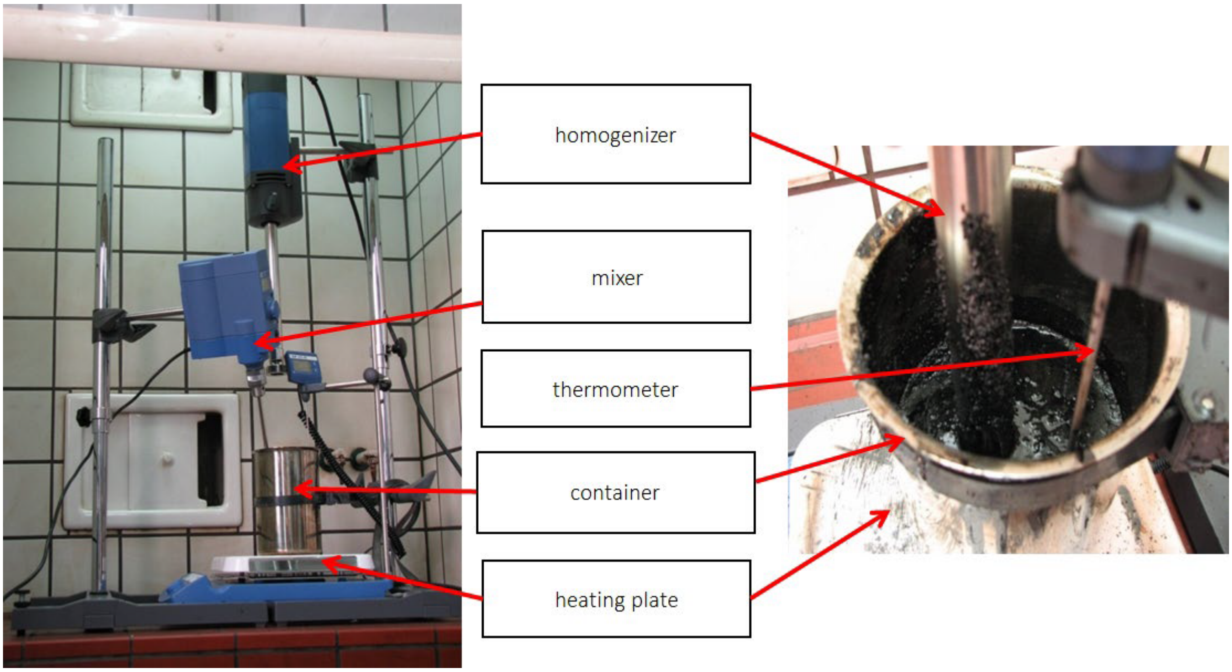

Fig. 1. Equipment for laboratory modification of bitumen with the addition of crumb rubber

The high shear dispersing device includes:

- homogenizer with a speed range of 500–10.000 rpm,
- grinding head with a diameter of 45 mm and a grinding range of at least 25–50 μm,
- grinding head with a diameter of 45 mm and a grinding range of at least 40–100 μm.

The modification equipment allows to modify bitumen with the addition of crumb rubber. During the process, it was possible to control the modification time, temperature and sequence and duration of individual modification stages, as well as the method of adding modifying additives into the binder. In the first stage of the modification process, modifying additives were added into the hot binder and distributed evenly using the blades of a low-speed mixer or grinding head. In the next stage of modification, the rubber particles were additionally shredded using a homogenizer. The maturation stage consisted of heating the binder at the modification temperature while slowly mixing it. This stage simulated the storage of the binder in a working tank with circulation, during which the process of devulcanization and increasing volume of the rubber continued. Due to the economic aspect, the total modification time did not exceed 60 minutes. As a part of the research plan, an evaluation of the properties of modified bitumen at low and high pavement operating temperatures was planned. To evaluate the properties of low-temperature binders, the results of standard tests (breaking point according to Fraass method) and functional tests obtained from the BBR bending beam rheometer were used. Creep stiffness test method in the BBR rheometer of low-temperature binder consisted in determining the value of the stiffness modulus after 60 seconds of loading and determining the m-value, which characterizes the slope of the tangent to the stiffness modulus versus time graph. To test binders in the BBR rheometer at negative temperatures, beams were prepared from material previously subjected to RTFOT (rolling thin film oven test) and PAV (pressure aging vessel) aging processes. The test temperature ranged from -6°C to -30°C. The evaluation of the properties of binders at high temperatures was determined on the basis of standard tests – elastic recovery (at 25°C), penetration (at 25°C), softening point, viscosity (at 90°C) and the results of rheological tests obtained in the DSR dynamic shear rheometer (from 20°C to 60°C). The value of the complex shear modulus and the value of the phase angle δ between the stress and the strain were determined. The dynamic shear rheometer (DSR) test was carried out in the range of linear viscoelasticity of the binder.

4. PROPERTIES OF BINDERS MODIFIED WITH THE ADDITION OF RUBBER POWDER IN THE RANGE OF LOW OPERATING TEMPERATURES

Figure 2 shows the results of low-temperature tests according to Fraass method of asphalt rubber binder, polymer-rubber-asphalt binder (PMB45/80-55 CR) and polymer modified bitumen (PMB 45/80-55) with good properties at low temperatures.

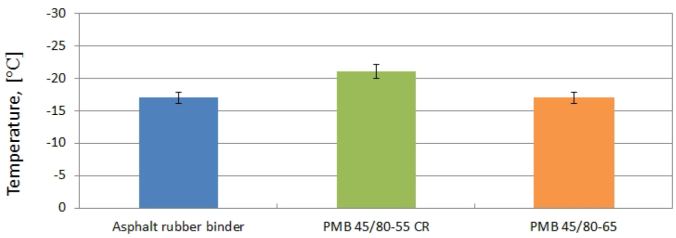

Fig. 2. Fraass breaking point

Results in Fig. 2. show that the asphalt rubber binder is characterized by a breaking point comparable to the breaking point of the PMB 45/80-55, which has the most favorable low-temperature properties among the polymer modified bitumens produced in Poland. An even more favorable breaking point was obtained in tests of a polymer-rubber-asphalt binder. This can be explained by the favorable properties of binders with the addition of rubber resulting from the improvement of the viscoelastic properties of the base binders as a result of modification with rubber by reducing the value of the elastic component and increasing the viscous component. Thanks to this, bitumen modified with the addition of rubber becomes less brittle at negative temperatures and more resistant to cracking. In the case of the PMB 45/80-55 CR binder, the reduction in the breaking point temperature may result from the additional effect of the interaction of the polymer and rubber in the modification process.

Based on the results of low-temperature binder tests according to BBR, presented in Fig. 3–5, it should be concluded that bitumens modified with the addition of crumb rubber powder were classified to the same lower functional type PG-22. Figures 3–5 show that due to the stiffness S=300 MPa, the asphalt rubber binder has a much lower temperature compared to polymer modified bitumen (-21.8°C compared to -15.7°C). By SuperPave requirements the low-temperature properties

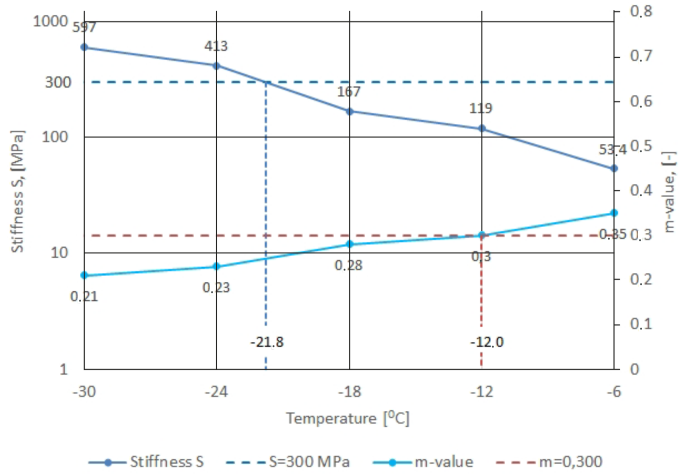

Fig. 3. Stiffness and m-value – asphalt rubber binder

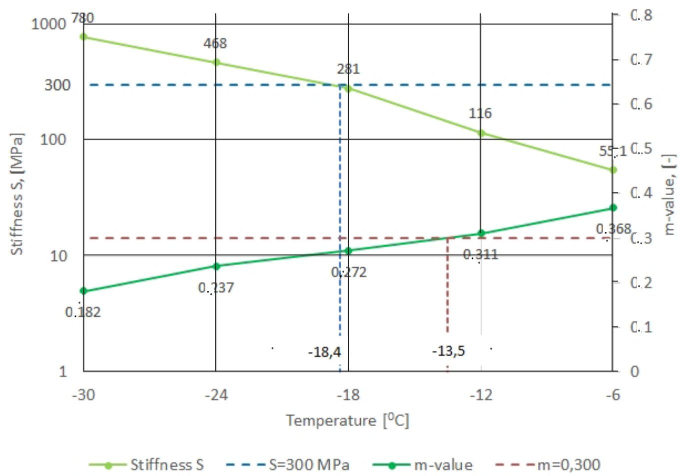

Fig. 4. Stiffness and m-value – polymer-rubber-asphalt binder

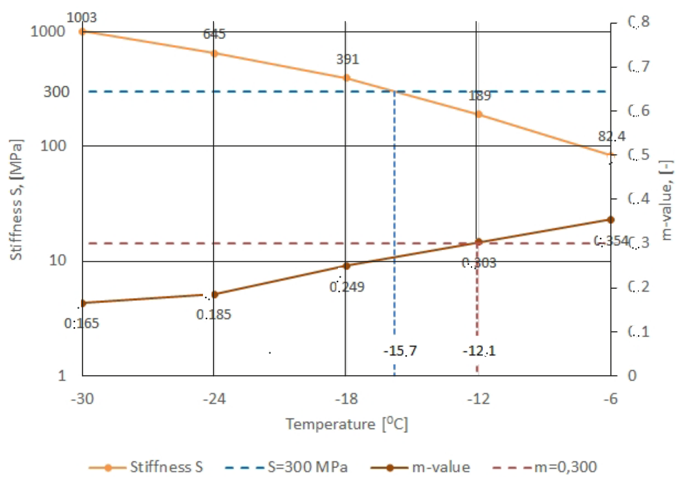

Fig. 5. Stiffness and m-value – polymer modified bitumen

are determined by the m-value which is a measure of the increase in stiffness, which is comparable for binders with the addition of rubber and polymer modified bitumen. This proves that all tested binders are characterized by similar stress relaxation.

In summary, it should be stated that the use of the addition of crumb rubber from waste car tires allows the production of binders modified due to their low-temperature properties which are superior to polymer modified bitumen with the best properties in this respect.

5. PROPERTIES OF BINDERS MODIFIED WITH THE ADDITION OF RUBBER POWDER IN THE RANGE OF MEDIUM AND HIGH OPERATING TEMPERATURES

The results of standard tests in medium and high temperatures for penetration, softening point and elastic recovery and viscosity were analyzed. Evaluation of rheological properties in relation to the assessment of the resistance of modified binders in the range of high operating temperatures is possible based on test results in a DSR dynamic shear rheometer. Asphalt rubber binders and polymer-rubber-asphalt binder (PMB 25/55-60 CR) were tested in a DSR rheometer, determining the complex modulus and the phase angle between stress and strain. Fig. 6 shows the penetration results before and after RTFOT technological aging, determined at a temperature of 25°C, which is a measure of the hardness and consistency of binders. Figure 6 shows that the asphalt rubber binder and the polymer-rubber-asphalt binder before aging are characterized by higher penetration than the polymer modified binder 25/55-60. As a result of the RTFOT technological aging process, all tested binders increased their hardness and after this process they are characterized by a similar level of penetration.

A measure of the consistency of binders at high operating temperatures is the softening point, the results of which are shown in Fig. 7. The figure shows that the asphalt rubber binder, compared to other tested binders, is characterized by the lowest softening temperature before aging. After the aging process, the softening temperature of this binder increases significantly, reaching a level that meets the standard requirements for binders modified with elastomers of hardness 25/55 (≥60°C) before technological aging. It should be stated that the high increase in the consistency of the asphalt rubber binder results from the structure of the binder, which is not fully homogeneous. The binder contains particles of swollen rubber that is only partially dissolved. As a result of RTFOT aging, the swollen rubber particles are subjected to further thermal treatment, a more homogeneous binder is obtained and, as a result, the consistency increases.

The polymer-rubber-asphalt binder 25/55-60 CR is characterized by a lower softening point before and after aging compared to the PMB 25/55-60, but it should be stated that it meets the standard requirements for polymer binder of this hardness. The smaller increase in the softening point of this binder compared to the asphalt rubber binder may be due to the presence of swollen polymer and rubber particles in the binder, which interact to limit the oxidation reaction and make aging slower.

Figure 8 presents the results of elastic recovery as a measure of elasticity of bitumens modified with the addition of crumb rubber. The data presented in the figure show that all tested binders are characterized by a favorable, high elastic recovery. The asphalt rubber binder behaves particularly favorably and was the only one to show an increase in elastic recovery as a result of the technological aging process. This may indicate good properties, taking into account the assessment of

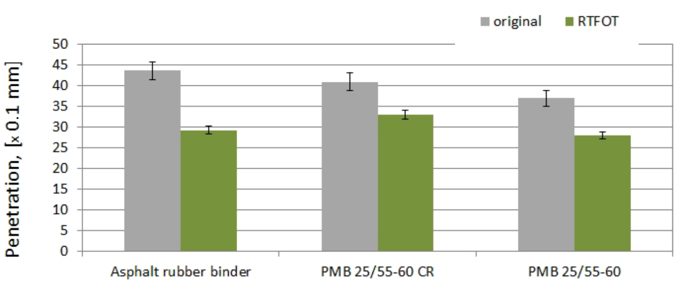

Fig. 6. Penetration at 25°C – modified bitumens

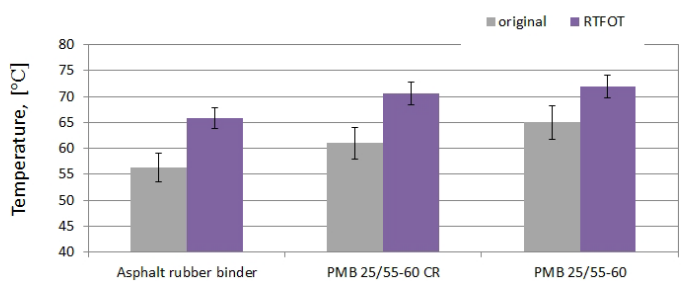

Fig. 7. Softening point – modified bitumens

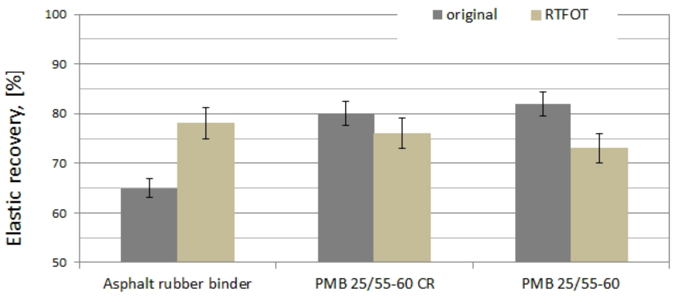

Fig.8. Elastic recovery – modified bitumens

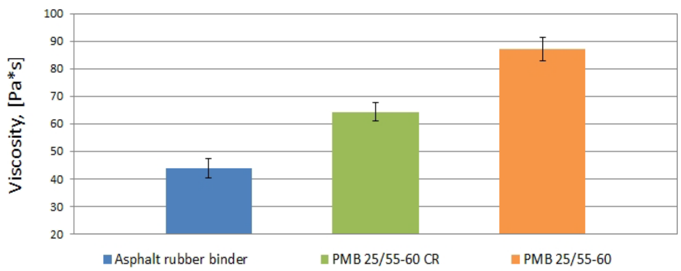

Fig. 9. Viscosity at 90°C – modified bitumens

the resistance to permanent deformation of the asphalt mixture with this binder. The polymer-rubber-asphalt binder also has good properties in terms of elastic recovery; its elastic recovery has decreased slightly after aging process. As a result of aging, the greatest change in elastic recovery occurred in the polymer modified bitumen test, but despite this, this result should be considered favorable from the point of view of the binder's resistance to permanent deformation.

Figure 9 shows the results of determining the dynamic viscosity of the tested modified bitumens. All binders are characterized by high viscosity and therefore no viscosity result was obtained in the Brookfield apparatus at 60°C, typical of high operating temperatures. Figure 9 shows that at the test temperature of 90°C the asphalt rubber binder and polymer-rubber-asphalt binder before aging are characterized by lower viscosity compared to polymer modified bitumen. Viscosity at temperatures ≥ 90°C characterizes binders primarily from the point of view of technological processes for producing asphalt mixtures. Lower viscosity values at these temperatures are beneficial from the point of view of the production of the asphalt mixture and paving process.

Figure 10 presents the results of testing binders modified with the addition of rubber powder in a dynamic shear rheometer, i.e. the absolute value of the complex modulus and the phase angle. Fig. 10 shows that at a high operating temperature of 60°C, all tested binders are characterized by a similar value of the complex modulus, while a lower favorable value of the phase angle at this temperature is demonstrated by binders modified with the addition of rubber powder. At high operating temperatures, due to the resistance to permanent deformations, a high value of the complex modulus is more advantageous. Taking into account the obtained results of the determination of the complex modulus, it can be concluded that the tested binders are characterized by similar resistance to permanent deformation. It is worth emphasizing that the asphalt rubber binder has the best result in terms of the value of the phase angle between stress and strain, which proves that the elastic properties are retained to the greatest extent at a high operating temperature of 60°C.

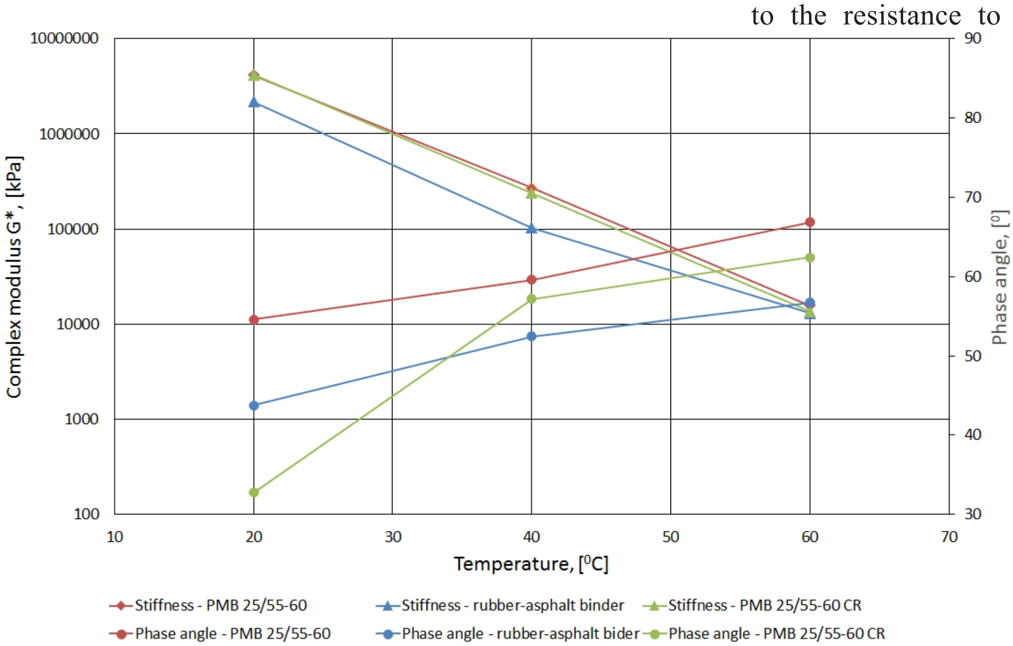

Fig. 10 Complex modulus and phase angle – modified bitumens

6. EXAMPLES OF THE USE OF CRUMB RUBBER FROM WASTE CAR TIRES FOR BINDERS MODIFICATION IN ROAD CONSTRUCTION IN POLAND

Many years of research experience of scientists from the Warsaw University of Technology in the field of technology for modifying bitumens with rubber from waste car tires for the construction of durable and ecological pavements have made the Warsaw University of Technology a leading center dealing with this topic. Over the last ten years, Strabag, independently, the Lotos refinery have approached the Research Team of the Warsaw University of Technology with proposals for cooperation in the development of innovative technologies for modifying bitumen with rubber from used car tires. The Warsaw University of Technology Team conducted scientific research on new asphalt rubber and polymer-rubber-asphalt binders. The result of this work was the development of a new generation of binders, characterized by improved properties in the entire range of operating temperatures, characteristic of the climatic conditions of Central and Eastern Europe. The results of scientific research were used, among others, to develop, together with Strabag, a technology for the production of a new asphalt rubber binder used for asphalt mixtures resistant to aging processes and to fatigue. The Warsaw University of Technology and TPA were partners in the project "Development and implementation of an innovative, environmentally friendly technology for modifying road bitumens with rubber", co-financed by the Innovative Economy Operational Program. Joint projects of both centers led to the implementation of an innovative and pro-ecological technology for modifying bitumen with rubber from waste car tires. The use of a new type of asphalt rubber binder with a crumb rubber content of over 15% allowed for improved resistance to permanent deformations and low-temperature cracking of asphalt mixtures used for wearing course of road pavements. The fatigue resistance has also been improved in the case of asphalt mixtures for the base course. The asphalt rubber binder developed as part of the project was used in asphalt mixtures in a total of several locations. An example of the use of this technology is Parzniewska Street in Pruszków (Fig. 11.). Four surface structures were used there with asphalt rubber- mixtures in various layers, including an anti-fatigue layer.

The Warsaw University of Technology Team also conducted research in cooperation with the Lotos refinery on the introduction into industrial production of an innovative polymer-rubber-asphalt binder of the terminal-blend type, characterized by colloidal stability, enabling the transport and storage of the binder for at least 7 days. The activities of the researchers contributed to the introduction of a new product to the market by Lotos Asfalt, i.e. Modbit CR binder. Since launching industrial production of a new product Lotos Asfalt has produced and sold more than 4 000 tons of Modbit CR binder. Construction companies in the road sector have built more than 100 km of road pavements across the country using this binder.

7. SUMMARY

The construction of asphalt pavements for roads with various traffic load categories requires the use of appropriate quality binders with an extended range of viscoelasticity and the use of appropriate material and technological solutions. Rubber from waste car tires is a modifying additive that can effectively improve the properties of

Fig. 11 Pavement construction layer with asphalt rubber binder, Parzniewska Street in Pruszków

binders. A very advantageous solution is to obtain binders with properties comparable to typical polymer modified bitumens, representing the best properties in the range of low and high operating temperatures. The laboratory tests and analyzes carried out in this area allowed for the following conclusions to be drawn:

- modification of bitumen with the addition of crumb rubber from used car tires allows to obtain binders as: asphalt rubber binder (17% crumb rubber addition) and polymer-rubber-asphalt binder PMB 45/80-55CR characterized by improved low-temperature properties even exceeding the properties of polymer modified bitumen PMB 45/ 80-60 belonging to the group of binders with the best properties in terms of resistance to low temperatures, this especially applies to the results of brittle temperature tests and the results of stiffness tests in the BBR rheometer,
- the tested binders with the addition of crumb rubber from used car tires are characterized by comparable properties in the range of average operating temperatures compared to the PMB 25/55-60 polymer modified bitumen, which belongs to the group of binders with improved properties in this temperature range, a similar level of penetration after technological aging and a favorable high elastic recovery,
- the tested binders with the addition of crumb rubber from used car tires are characterized by comparable properties in the range of high operating temperatures compared to the PMB 25/55-60, which is included in the group of binders with improved properties in this temperature range; at high operating temperatures, all tested binders are characterized by a similar value of the complex modulus G*, while a lower favorable value of the phase angle at this temperature is demonstrated by bitumens modified with the addition of rubber powder.

The authors of the paper have been conducting research on the use of asphalt rubber binders for the construction of road pavements for many years. They performed extensive research on asphalt mixtures with these binders, which showed that asphalt mixtures with a binder modified with crumb rubber, both in asphalt rubber and terminal blend technology, have numerous advantages over standard mixtures.

Research on the use of crumb rubber in road construction confirms that it is possible to improve the technical characteristics of asphalt rubber mixtures whose functional properties may exceed those at low and medium temperatures (fatigue life) of traditional mixtures using polymer modified binders, without reducing the properties of the mixtures at high operating temperatures. For this reason, the technology using rubber-modified binders should be considered promising. The use of binder technology with the addition of crumb rubber from waste car tires is justified for technological, economic and social reasons because it effectively manages environmentally harmful waste.

REFERENCES

[1] *Radziszewski P., Sarnowski M.*: Technologia nowoczesnych nawierzchni asfaltowych. Wydawnictwo Naukowe PWN, Warszawa, 2023

[2] *Radziszewski P., Sarnowski M., Król J. i in.*: Właściwości asfaltów modyfikowanych gumą i mieszanek mineralno-gumowo-asfaltowych. Wydawnictwo Komunikacji i Łączności, Warszawa, 2017

[3] *Horodecka R., Kalabińska M., Piłat J., Radziszewski P., Sybilski D.*: Utilisation of Scrap Rubber for Bitumen and Asphalt Concrete Modification in Poland. Proceedings of the Conference Asphalt Rubber 2000, Portugalia, 14–17 November 2000

[4] *Horodecka R., Kalabińska M., Piłat J., Radziszewski P., Sybilski D.*: Wykorzystanie zużytych opon samochodowych w budownictwie drogowym. IBDiM, Warszawa, 2002, Ser. Studia i Materiały z. 54

[5] *Radziszewski P.*: Zmiany właściwości lepkosprężystych lepiszczy modyfikowanych i mieszanek mineralno-asfaltowych w wyniku procesu starzenia. Politechnika Białostocka, Białystok, 2007

[6] *Radziszewski P., Kalabińska M., Piłat J.*: Comparative analysis of bitumen – rubber binder and Polish standard bitumen properties. Asphalt Rubber 2003 Conference, Brasilia, Brasil, 2003, 337–346

[7] *Radziszewski P., Kalabińska M., Piłat J.*: The rheological behavior of rubber asphalt binder. Proceedings of the twelfth International Conference on Solid Waste Technology and Management, Philadelphia, U.S.A., 17–20 November 1996, Session 3D: Rubber Tire Wastes

[8] *Radziszewski P.*: Modyfikacja lepiszczy asfaltowych miałem gumowym. Drogownictwo, 2, 1995, 44–48

[9] *Radziszewski P., Piłat J., Ziółkowski R.*: Influence of scrap rubber amount on rubber-asphalt viscoelastic properties. Proceedings of the 26th International Conference on Solid Waste Technology and Management, Philadelphia, USA, 21–24 March 2004

[10] *Shu X., Huang B.*: Recycling of waste tire rubber in asphalt and portland cement concrete: An overview. Construction and Building Materials, **67**, Part B, 2014, 217–224, DOI: 10.1016/j.conbuildmat.2013.11.027

[11] *Jamal M., Giustozzi F.*: Low-content crumb rubber modified bitumen for improving Australian local roads condition. Journal of Cleaner Production, **271**, 2020, DOI: 10.1016/j.jclepro.2020.122484

[12] *Roychand R., Gravina R.J., Zhuge Y., Ma X., Youssf O., Mills J.E.*: A comprehensive review on the mechanical properties of waste tire rubber concrete. Construction and Building Materials, **237**, 2020, DOI: 10.1016/j.conbuildmat.2019.117651

[13] Asphalt in Figures 2018. European Asphalt Pavement Association – EAPA. https://eapa.org/wp-content/uploads/2020/02/Asphalt-in-figures_2018.pdf (accessed on 11.8.2020)

[14] *Ding X., Chen L., Ma T., Ma H., Gu L., Chen T., Ma Y.*: Laboratory investigation of the recycled asphalt concrete with stable crumb rubber asphalt binder. Construction and Building Materials, **203**, 2019, 552–557, DOI: 10.1016/j.conbuildmat.2019.01.114

[15] *Picado-Santos L.G., Capitão S.D., Neves J.M.C.*: Crumb rubber asphalt mixtures: A literature review. Construction and Building Materials, **247**, 2020, DOI: 10.1016/j.conbuildmat.2020.118577

[16] *Deshmukh N.H., Kshirsagar D.Y.*: Utilization of rubber waste in construction of flexible pavement. International Journal of Advance Research and Development, **2**, 7, 2017, 70–77

[17] *Wulandari P.S., Tjandra D.*: Use of Crumb Rubber as an Additive in Asphalt Concrete Mixture. Procedia Engineering, **171**, 2017, 1384–1389, DOI: 10.1016/j.proeng.2017.01.451

[18] *Gong J., Liu Y., Wang Q., Xi Z., Cai J., Ding G., Xie H.*: Performance evaluation of warm mix asphalt additive modified epoxy asphalt rubbers. Construction and Building Materials, **204**, 2019, 288–295, DOI: 10.1016/j.conbuildmat.2019.01.197

[19] *Saberi K.F., Fakhri M., Azami A.*: Evaluation of warm mix asphalt mixtures containing reclaimed asphalt pavement and crumb rubber. Journal of Cleaner Production, **165**, 2017, 1125–1132, DOI: 10.1016/j.jclepro.2017.07.079

[20] *Jaskuła P., Ejsmont J., Stienss M., Ronowski G., Szydłowski C., Świeczko-Żurek B., Ryś D.*: Initial Field Validation of Poroelastic Pavement Made with Crumb Rubber, Mineral Aggregate and Highly Polymer-Modified Bitumen. Materials, **13**, 6, 1339, 2020, DOI: 10.3390/ma13061339

[21] *Radziszewski P., Piłat J., Plewa A.*: Influence of amount of crumb rubber of used car tires and heating time on rubber asphalt properties. Proceedings of the 26th International Conference on Solid Waste Technology and Management, Philadelphia, USA, 21–24 March 2004

[22] *Radziszewski P.*: Modelowanie trwałości zmęczeniowej modyfikowanych kompozytów mineralno-asfaltowych. Rozprawa habilitacyjna. Politechnika Białostocka, Białystok, 1997, Rozprawy naukowe nr 45

[23] *Radziszewski P., Piłat J.:* Mieszanki mineralno-gumowo-asfaltowe. Konferencja „Asphalt Rubber 2003". Drogownictwo, 5, 2004, 151–155

[24] *Radziszewski P., Piłat J., Sarnowski M., Kowalski K., Król J., Pokorski P., Liphardt A.*: Rozwiązania materiałowo-technologiczne izolacji i nawierzchni obiektów mostowych. Raport z pracy badawczej dla GDDKiA w Warszawie. Politechnika Warszawska, 2012

[25] *Radziszewski P., Piłat J., Sarnowski M., Kowalski K., Król J.*: Influence of high temperature on properties of materials used in bridge asphalt pavement structures. Roads and Bridges – Drogi i Mosty, **14**, 3, 2015, 175–191, DOI: 10.7409/rabdim.015.012

[26] *Yang X., You Z., Perram D., Hand D., Ahmed Z., Wei W., Sang L.*: Emission analysis of recycled tire rubber modified asphalt in hot and warm mix conditions. Journal of Hazardous Materials, **365**, 2019, 942–951, DOI: 10.1016/j.jhazmat.2018.11.080

[27] *Zhu H., Cai H., Yan J.., Lu Y.*: Life cycle assessment on different types of asphalt rubber pavement in China. National Engineering Laboratory for Advanced Road Materials, No.2200, Chengxin Road, Jiangning Science Park, Nanjing, China

[28] *Presti D.L.*: Recycled Tyre Rubber Modified Bitumens for road asphalt mixtures: A literature review. Construction and Building Materials, **49**, 2013, 863–881, DOI: 10.1016/j.conbuildmat.2013.09.007

[29] *Bocci E., Prospieri E.*: Recyclability of reclaimed asphalt rubber pavement. Construction and Building Materials, **403**, 133040, 2023, DOI: 10.1016/j.conbuildmat.2023.133040

[30] *Carpani C., Bocci E., Prosperi E., Bocci M.*: Evaluation of the rheological and performance behaviour of bitumen modified with compounds including crumb rubber from waste tires. Construction and Building Materials, **361**, 129679, 2022, DOI: 10.1016/j.conbuildmat.2022.129679