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The influence of fiber addition on fatigue life of mineral-asphalt composites for road pavement layers constructed using hot and warm mix asphalt technology

Abstract: Currently the warm mix asphalt production is increasingly being adopted in road construction. This technology allows for lower production and paving temperatures for asphalt pavements from 30°C to 50°C. Such a significant temperature reduction contributes to lower production costs and also reduces heat emissions into the atmosphere, which is crucial for environmental protection. One of the most important functional characteristics of road pavement layers is their fatigue life, which can be improved by adding fibers to asphalt mixtures. Aramid (AR), glass (GL), and polymer-basalt (PB) fibers are often used for dispersed reinforcement of asphalt mixtures. This paper analyzes the results of tests on hot mix asphalt mixtures containing these fibers, determining their impact on fatigue life. Polymer-basalt fibers were selected for further testing, as they have a very favorable effect on the fatigue resistance of asphalt concrete (AC) and high modulus asphalt concrete (HMAC) mixtures. The important material, technological and construction problem is to determine the effectiveness of adding fibers to asphalt mixtures in warm mix technology. The article presents the results of research on an innovative technology for the production and paving of asphalt mixtures with the simultaneous use of a selected polymer-basalt fibers, a binder fluxing agent in the form of an ecological bio-derived additive (bio-flux) and the process of foaming asphalt with water, which allows the production of a mineral-asphalt composite at a reduced temperature and with improved technical parameters. To confirm their high functional properties, this paper presents fatigue test results of samples of asphalt mixtures intended for the wearing course and the subbase course with the addition of polymer-basalt fibers, prepared in the laboratory and collected from an experimental road section. The test results showed that the use of the technology of producing and paving warm mix asphalt AC 11 for the wearing course and HMAC 22 for the subbase course, using polymer-basalt fibers, is highly beneficial in terms of ensuring high fatigue life.

Keywords: asphalt mixtures, fatigue life, polymer-basalt fibers, warm mix asphalt.

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1. INTRODUCTION

A crucial step in achieving the goal of combating climate change is pursuing pro-environmental policies that contribute to the development and application of technologies that ensure minimal energy consumption, reduced pollution, and environmental degradation. One effective measure in this regard is the application of asphalt mixtures with reduced process temperatures, i.e., those produced and paved using the “warm mix” method (WMA). This technology lowers the temperatures during production, transport, and paving of asphalt mixtures, and reduces carbon dioxide emissions into the atmosphere, which also impacts work conditions and safety during roadworks. The use of mixtures with reduced process temperatures offers numerous environmental, technological, and economic benefits.

A flexible road pavement is a special type of engineering structure due to the loads acting on it, the materials it is made of, and the operating conditions. A road pavement structure must be resistant to repeated (in the case of national roads, hundreds of millions of load-unload cycles) dynamic impacts from vehicle traffic, which generate time-varying stress and strain areas. Asphalt mixtures used for road pavements should be characterized by adequate durability. One of the most important functional characteristics of road pavement layers that guarantee durability is fatigue life. There are numerous literature findings, supported by the authors’ own research, indicating the effectiveness of using fibers as dispersed reinforcement in the asphalt mix, significantly improving fatigue resistance.

As a part of the “TECHMATSTRATEG 2” research project conducted at the Kielce University of Technology and Warsaw University of Technology, a new material and technological solution was developed. The key features of this concept include:

- the use of dispersed reinforcement in the mineral-asphalt composite to increase the durability of the pavement structure,
- the use of special asphalt binders, including highly modified ones, to improve the viscoelastic properties of the mineral-asphalt composite,
- the use of water-foaming technology for the asphalt binder during the production of the asphalt-mineral composite to lower process temperatures,

- the addition of an ecological bio-derived additive (bio-flux) to the binder to support the foaming process and improve the workability and compaction of the mixtures at reduced process temperatures.

The paper presents the results of laboratory tests on the fatigue life of hot mix asphalt (HMA) samples with various fibers and confirms the effectiveness of these fibers in improving the fatigue resistance of the mixtures. The results of fatigue life tests on hot mix asphalt mixtures for the wearing course and subbase course, with the addition of polymer-basalt fibers, were also presented. The research results showed that the use of warm mix production technology of mineral-asphalt composites with the addition of polymer-basalt fibers is technologically justified and is very beneficial in terms of ensuring high fatigue life.

2. STATE OF ART ON THE FATIGUE LIFE OF ASPHALT MIXTURES WITH FIBER ADDITIVES AND WARM MIX TECHNOLOGY

Research has been conducted for many years to determine the effect of dispersed reinforcement in asphalt mixtures on their properties [1-7]. This work has shown that the use of various types of natural and synthetic fibers can, under certain conditions, provide benefits in terms of increased tensile strength, fracture toughness, and fatigue life. However, research results indicate that the application of this type of additive is related with a deterioration in the workability of the asphalt composite during production and paving, leading to a deterioration in its compactability [8-12]. Insufficient compaction of asphalt layers reduces their resistance to water and frost, reduces fatigue life, and increases the rutting, which in turn shortens their service life.

There are few studies on the use of fiber additives in mixtures with reduced technological temperatures. Research was conducted at the Kielce University of Technology on the modification of asphalt binders intended for water foaming in order to improve their properties by using additives such as Fischer-Tropsch synthetic wax or surfactants based on fatty acid amines [13-15]. Research conducted on asphalt mixtures confirmed the possibility of using the technology of foaming binders with water to produce asphalt composites intended for the upper layers of road pavement structures (i.e., the wearing course, binder course, and subbase). One of the solutions developed as a result of the work conducted in this field at

the Kielce University of Technology was registered with a patent: “Method of producing asphalt concrete using reduced temperature technology”.

Research on asphalt mixtures reinforced with polymer-basalt fibers using hot mix technology was conducted at the Warsaw University of Technology under a grant from the National Centre for Research and Development, entitled “Innovative hybrid FRP composite reinforcement for infrastructure structures with increased durability” [16]. Based on the research results, it was found that the fatigue life of asphalt mixtures using hot mix technology increased by over 70% compared to the mixture without added fibers.

Research conducted at the Warsaw University of Technology has shown that the addition of bio-derived additive (bio-flux) causes asphalt liquefaction, which is particularly important for improving the workability of asphalt mixtures during technological processes [7]. An additional advantage of bio-flux is its refreshing properties, which enable the use of larger amounts of recycled material containing aged binder in asphalt mixtures. Studies have shown that even at low content (2.5%), the bio-derived additive favorably changes the binder properties at low temperatures, and thanks to the polymerization phenomenon occurring over time, high-temperature properties also remain at an appropriate level [17-19]. The reduction in binder stiffness caused by the additive positively affects the fatigue life of hot-mix asphalt mixtures [8].

Research on bio-derived fluxes conducted at the Warsaw University of Technology culminated in the granting of a patent entitled “Fluxed Asphalt and a Method for Producing Fluxed Asphalt”. Bio-derived fluxes developed on Warsaw University of Technology were successfully used in a asphalt mixture containing reclaimed asphalt in the binder layer of a road pavement constructed using traditional hot-mix technology. This was implemented as part of the APSE grant at the Warsaw University of Technology entitled “Use of Eco-Friendly Materials for a New Concept of Asphalt Pavements for a Sustainable Environment” (7th Framework Programme of the European Union, implemented in 2016).

Research on a new mineral-asphalt composite within the “Techmatstrateg 2” project identified the phenomenon that occurs during the foaming process of asphalt binder in the presence of bio-flux (with varying levels of bio-flux and foaming water) and its effect on the rheological properties of the asphalt mixture as a function of loading

time and temperature [17-18, 20]. The results showed that the addition of bio-flux favorably softens asphalt binders. It was also found that some mix stiffening indices significantly depended on the degree of polymer modification and the bio-flux content. Furthermore, the foaming process in paving grade bitumens and polymer-modified binders did not contribute to additional binder stiffening. The research also showed that the use of fiber reinforcement in asphalt mixtures resulted in lower stiffening of warm mixes compared to hot mixes.

A review of the literature and the authors’ own experience indicates that the use of fibers in asphalt composites contributes to increased fatigue life. The use of warm mix technology with bio-flux additives creates the opportunity to implement an environmentally friendly technology while simultaneously improving the fatigue resistance of composites.

3. MATERIALS AND METHODS

In the study, two types of asphalt mixtures were tested: asphalt concrete (AC) for the wearing course and high modulus asphalt concrete (HMAC) for the subbase course. The mixtures were produced using the standard hot mix method (HMA) and the warm mix method (WMA), which involved the use of foamed asphalt and a fluxing additive. Samples were prepared from the asphalt mixture produced in the laboratory and from the experimental road section. The grading of the tested mixtures is presented in Fig. 1, and the grading limits were adopted in accordance with the domestic requirements contained in WT-2 2014 [21].

The compositions of the asphalt mixtures are presented in Table 1. Crushed limestone aggregates and gabbro were used in the wearing course mixture with a maximum grain size of 11, and crushed limestone aggregates were used in the subbase course mixture with a maximum grain size of 22. The binder content in the AC mixture was 5.4% (w/w), and in the HMAC mixture it was 5.0% (w/w). Both mixtures contained an adhesive agent at a rate of 0.3% by weight of binder.

Table 1. Composition of the asphalt mixtures

Component / Mixture type	AC	HMAC
Nominal max. aggregate size [mm]	11	22
Dusts [% (m/m)]	7.5	5.5
Fine aggregates 0.063-2 mm [% (m/m)]	28.0	20.8
Coarse aggregates [% (m/m)]	64.5	73.7
Bituminous binder content [% (m/m)]	5.4	5.0

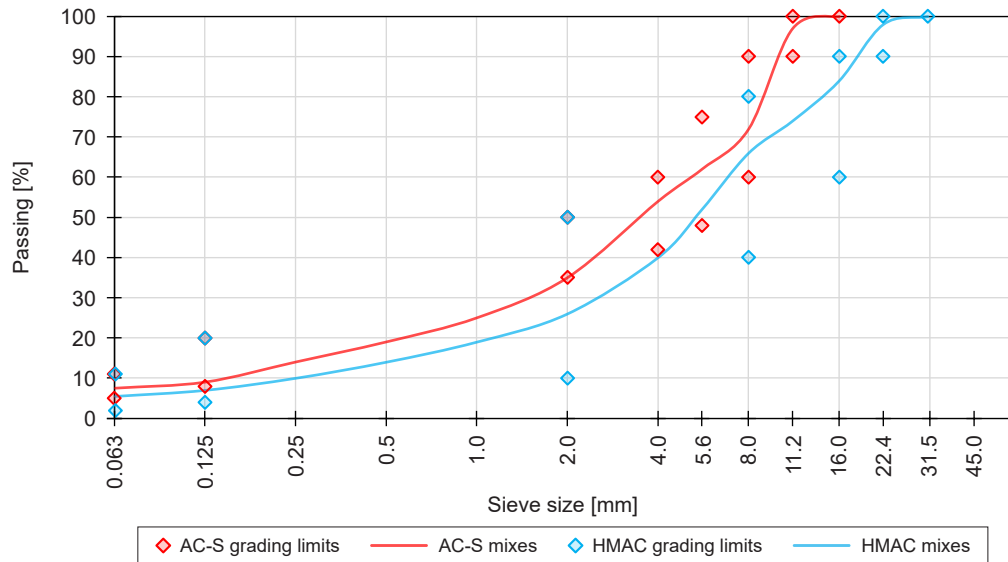


Fig. 1. Grading of the AC and HMAC mixtures

In the first stage, fatigue tests were performed on two types of hot mix asphalt mixtures: asphalt concrete (AC) for the wearing course and high modulus asphalt concrete (HMAC) for the subbase course, with the following types of asphalt binders and fibers:

AC for the wearing course:

- 50/70 + 0.3% polymer-basalt fibers,
- 50/70 + 0.3% aramid fibers,
- PMB 45/80-55 + 0.3% polymer-basalt fibers,
- PMB 45/80-55 + 0.3% aramid fibers,
- PMB 45/80-80 + 0.3% polymer-basalt fibers,
- PMB 45/80-80 + 0.3% aramid fibers,

HMAC for the subbase layer:

- 20/30 + 0.2% polymer-basalt fibers,
- 20/30 + 0.2% glass fibers,
- PMB 25/55-60 + 0.2% polymer-basalt fibers,
- PMB 25/55-60 + 0.2% glass fibers.

The percentage of fiber additives in asphalt mixtures was determined based on literature analysis and the authors' own experience from the experimental road section [16]. In the first stage of laboratory tests, it was decided to select polymer-basalt and aramid fibers as an additive to strengthen the asphalt mixture for the wearing course, due to their beneficial properties in improving resistance to permanent deformation while ensuring high fatigue

resistance. The use of aramid fibers to improve the mechanical, economic, and environmental properties of asphalt mixtures has been the subject of numerous research studies [22-30].

Polymer-basalt fibers and glass fibers were also used to reinforce the base layer. Polymer-basalt fibers are considered a universal additive that improves the fatigue life and rutting resistance of asphalt mixtures intended for all layers of the pavement structure. Glass fibers were used due to their relatively low price compared to aramid fibers, and their potential to increase the fatigue life of the lower layers of the pavement structure, which, due to their increased thickness, require significantly more fiber additions.

In the second stage, fatigue tests were also performed on two types of asphalt mixtures produced using the warm mix technology: asphalt concrete (AC) for the wearing course and high modulus asphalt concrete (HMAC) for the subbase course, using the asphalt binder and fiber type selected in the first stage.

Reinforcement of the mixtures was achieved by using cut fibers, the length of which varied depending on the maximum aggregate grading in the mixture: 12 mm in the AC mixtures (maximum aggregate grading 11 mm) and 24 mm in the HMAC mixtures (maximum aggregate grading 22 mm).

Fiber content and length were optimized after preliminary tests in hot mixes, as were the mix compositions (grain size, bituminous binder content) [6, 9, 31]. Hot mixes (WMA) contained foamed bituminous binders, which were produced and added using a laboratory foaming device [17].

In hot mix production technology, bituminous binders were modified by the use of a bio-derived additive (bio-flux). The production process of this additive involves oxidizing fatty acid methyl esters in the presence of a cobalt catalyst and cumene hydrogen peroxide. Detailed information on the properties and origin of the additive, as well as the preparation of the modified bituminous binders, is provided in [17]. An evaluation of the additive and bituminous binders using Fourier Transform Infrared Spectroscopy (FTIR) is provided in [18].

The production of WMA mixtures was carried out at temperatures reduced by 20°C. The compaction of WMA mixtures was carried out at temperatures 30°C lower than in the case of HMA. The tested mixtures were subjected to short-term oven ageing (STOA) at 135°C for 2 hours, and mixing was performed after 1 and 2 hours, as described in detail in [21].

The asphalt mixture used in the first stage of testing was produced in the laboratory, while in the second stage, the mixture was collected during construction of the experimental

road section from the wearing course and the subbase course before compaction. Beam samples were cut from slabs compacted in the laboratory using a plate compactor, and some samples were cut directly from the subbase course of the experimental road section. The beam samples were fatigue tested using the 4PB-PR method, determining the stiffness modulus according to PN-EN 12697-26 and fatigue life according to PN-EN 12697-24 at 10°C. Fatigue tests were performed in a DTS-30 universal testing machine. The stiffness modulus was measured at the 100 loading cycle at a controlled strain of 50 $\mu\text{m/m}$. The fatigue life of the mixtures was tested at strains ranging from 150 $\mu\text{m/m}$ to 250 $\mu\text{m/m}$.

4. RESULTS

4.1. ANALYSIS OF THE RESULTS OF THE FIRST STAGE OF FATIGUE LIFE TESTS OF ASPHALT MIXTURES WITH THE ADDITION OF VARIOUS FIBERS

The test results of the stiffness modulus and fatigue life of asphalt concrete for the wearing course with paving grade bitumen and two types of polymer modified bitumen and the addition of two types of fibers are presented in Figs. 2 and 3. For comparison, the Figs. 2 and 3 also present the test results of mixtures without fibers.

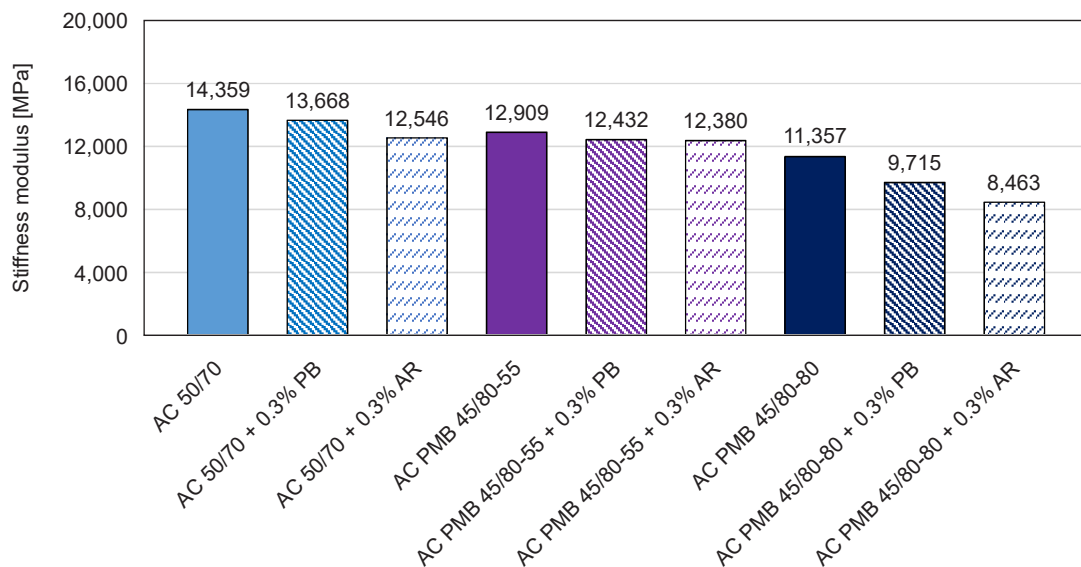


Fig. 2. Stiffness modulus of asphalt concrete for the wearing course with selected asphalt binders and polymer-basalt (PB) and aramid (AR) fibers

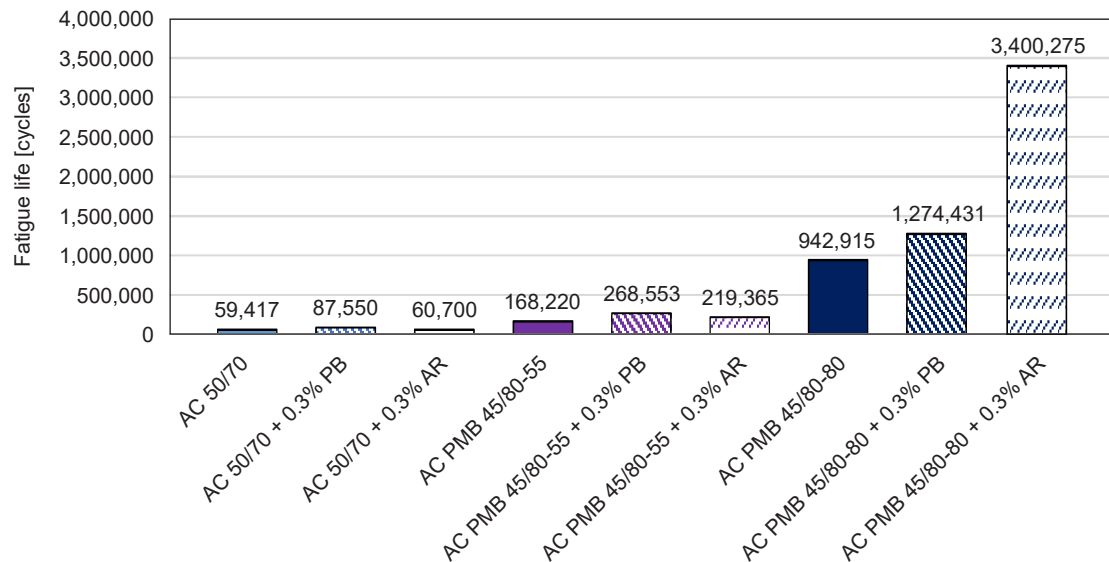


Fig. 3. Fatigue life of asphalt concrete for the wearing course with selected asphalt binders and polymer-basalt (PB) and aramid (AR) fibers

Based on the analysis of the stiffness modulus test results presented in Fig. 2, it can be concluded that the addition of fibers to asphalt concrete reduces its stiffness. The greatest reduction in stiffness was observed in mixtures with polymer-modified binders, particularly those with highly modified binders (approximately 25% to 32%). It should be mentioned that asphalt mixtures with lower stiffness show higher fatigue resistance, as shown in Fig. 3.

The test results presented in Fig. 3 clearly confirm the beneficial effect of fibers on the increased fatigue life of asphalt concrete, both with polymer-basalt and aramid fibers. In the case of asphalt mixtures with 50/70 paving grade bitumen, a significant increase in fatigue life was observed with the use of polymer-basalt fibers, reaching 47%. For mixtures with modified binders, the greatest increase in fatigue life was observed with highly modified asphalt with aramid fibers (261%). This significant increase is likely explained, in addition to the aramid fibers' effective inhibition of microcracking in the asphalt composite, by their good affinity to the highly modified binder.

Comparing the tested asphalt mixtures in terms of fatigue life improvement, the following classification can be obtained:

- AC 50/70 with AR fibers (2.2%),
- AC PMB 45/80-55 with AR fibers (30%),

- AC PMB 45/80-55 with PB fibers (30%),
- AC PMB 45/80-80 with PB fibers (35%),
- AC 50/70 with PB fibers (47%),
- AC PMB 45/80-80 with AR fibers (261%).

Taking into account the construction of pavement with the highest fatigue resistance, it is recommended to use asphalt concrete mixtures with a highly modified binder for the wearing course, preferably with the addition of aramid fibers. Good properties have also polymer-basalt fibers.

The results of tests of the stiffness modulus and fatigue life of high modulus asphalt concrete for the subbase layer with 20/30 paving grade bitumen and polymer-modified binder 25-55/60 and the addition of two types of fibers are presented in Figs. 4 and 5. For comparison, the results of tests of mixtures without fibers are also presented in the Figs. 4 and 5.

Based on the analysis of the stiffness modulus test results presented in Fig. 4, it should be concluded that the addition of fibers to high modulus asphalt concrete does not reduce its stiffness, as is the case with asphalt concrete (the difference in stiffness modulus values does not exceed 9%). The Fig. 4 shows that the parameter differentiating the stiffness modulus test results for high modulus asphalt concrete is not the type of fiber, but the type of asphalt binder.

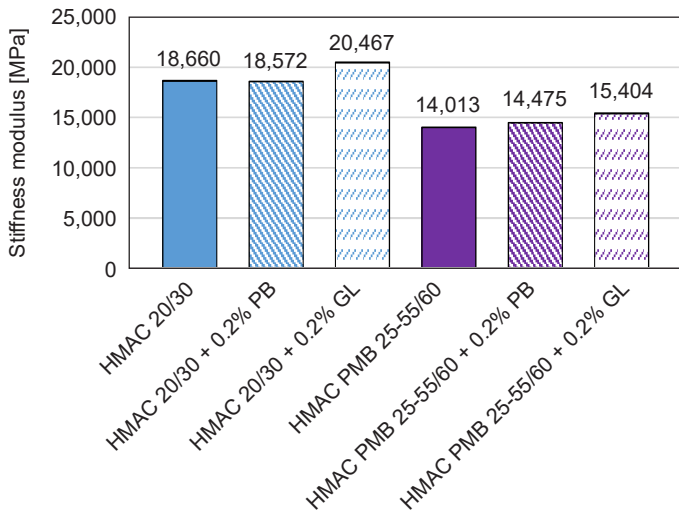


Fig. 4. Stiffness modulus of high modulus asphalt concrete for the subbase layer with selected asphalt binders and polymer-basalt (PB) and glass (GL) fibers

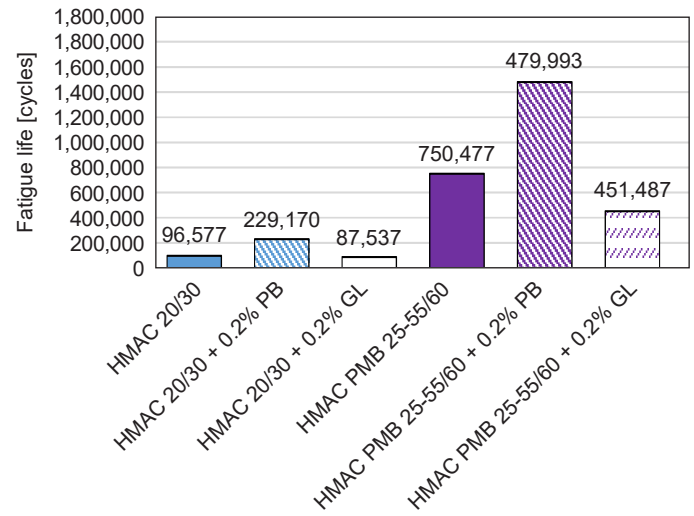


Fig. 5. Fatigue life of high modulus asphalt concrete for the subbase layer with selected asphalt binders and polymer-basalt (PB) and glass (GL) fibers

Comparing the tested asphalt mixtures in terms of increased fatigue life, the following classification can be obtained:

- HMAC PMB 25/55-60 with GL fibers (−40%),
- HMAC 20/30 with GL fibers (−9.6%),
- HMAC PMB 25/55-60 with PB fibers (97%),
- HMAC 20/30 with PB fibers (137%).

For a pavement subbase layer with increased fatigue life, using a high modulus asphalt concrete mixture, it is recommended to use polymer-modified binder with the addition of polymer-basalt fibers as a binder (Fig. 5).

4.2. SECOND STAGE FATIGUE TESTS AND CONSTRUCTION OF THE EXPERIMENTAL ROAD SECTION

Based on the analysis of the results from the first-stage hot mix asphalt testing, the type of asphalt binder and fibers for the second-stage hot mix asphalt testing were

selected. The following asphalt mixes were selected for the wearing course and subbase of the road pavement structure with increased fatigue life using the warm mix technology:

- for the wearing course, AC 11 with PMB 45/80-80 binder + 0.3% polymer-basalt fibers + 3% bio-flux, foamed asphalt,
- for the subbase, HMAC with PMB 25/55-60 binder + 0.2% polymer-basalt fibers + 2% bio-flux, foamed asphalt.

In the warm mix technology, a bio-flux additive was used to support the asphalt foaming process, The amount of bio-flux was determined on the basis of laboratory tests, the results of which are presented in [11, 13].

Table 2 presents data on the asphalt mixtures used in the second stage of the tests, including comparative mixtures without fiber additions, made using the hot mix technology (HMA).

Table 2. Technological parameters of asphalt mixtures

Properties	AC (HMA)	AC (WMA)	HMAC (HMA)	HMAC (WMA)
Bituminous binder type	45/80-80 (neat)	45/80-80 + 3% Bio-flux (foamed)	25/55-60 (neat)	25/55-60 + 2% Bio-flux (foamed)
Foaming water content [%]	–	2.0	–	2.0
Mixing temperature [°C]	180	160	180	160
Compaction temperature [°C]	145	115	145	115

As part of the research project, an experimental road section was constructed. Two pavement structures were used on parallel traffic lanes: a reference and an innovative one. In the reference section, hot mixes were used in the wearing course and subbase course, while in the innovative section, warm mixes using foamed asphalt, bio-flux additive, and polymer-basalt fibers were used in the wearing course and subbase. In both sections, the same standard hot mix was used in the binder course. The mix compositions were determined through previous laboratory tests and technological trials conducted in the laboratory and at an asphalt mixing plant equipped with a module for asphalt foaming and basic equipment for dosing the bio-flux additive. Table 3 presents the characteristics of the mixes used in the sections of the experimental road section.

Table 3. Road section diagram

Layer	Reference section	Innovative section
Wearing course, 4 cm	Mixture type: AC PMB 45/80-80 (HMA) Sec Fiber content: 0% Bioflux: 0% Production temperature: 180°C Compaction start temperature: 145°C	Mixture type: AC PMB 45/80-80 + 0,3% PB (WMA) Sec Fiber content: 0.3% 12 mm basalt fiber Bioflux: 3% Production temperature: 160°C Compaction start temperature: 115°C
Binder course, 5 cm	Mixture type: HMAC (HMA) Bitumen: 25/55-60 Production temperature: 180°C Compaction start temperature: 145°C	Mixture type: HMAC (HMA) Bitumen: 25/55-60 Production temperature: 180°C Compaction start temperature: 145°C
Subbase course, 9 cm	Mixture type: HMAC PMB 25/55-60 (HMA) Sec Bitumen: 25/55-60 Fiber content: 0%, Bioflux: 0% Production temperature: 180°C Compaction start temperature: 145°C	Mixture type: HMAC PMB 25/55-60 + 0,2% PB (WMA) Sec Bitumen: 25/55-60 Fiber content: 0.2% 24 mm basalt fiber Bioflux: 2% Production temperature: 160°C Compaction start temperature: 115°C

Fig. 6 shows the experimental road section from which asphalt mixtures were obtained for fatigue testing. Fig. 6a illustrates the paving of the HMAC subbase course, and Fig. 6b shows the compaction of the AC wearing course.



Fig. 6. Experimental road section

The experimental sections have been constructed over four days in June and July. The temperatures during paving of the asphalt base and wearing courses were 20°C and 22°C with cloudy and sunny weather. The production of the innovative mixtures in the plant was facilitated by adding the fibers to the mixer manually, packaged in thin plastic bags, before the asphalt binder, with the total mixing time extended by 10 s.

4.3. ANALYSIS OF FATIGUE LIFE TEST RESULTS OF SAMPLES FROM THE LABORATORY AND THE EXPERIMENTAL ROAD SECTION

The test results of the asphalt concrete mixture for the wearing course from the experimental section are presented in Fig. 7 (stiffness modulus) and Fig. 8 (fatigue life).

The test samples were prepared in the laboratory from the asphalt mixture taken before compaction of the wearing course (AC (HMA) Lab for hot mix technology and AC (WMA) Lab for warm mix technology).

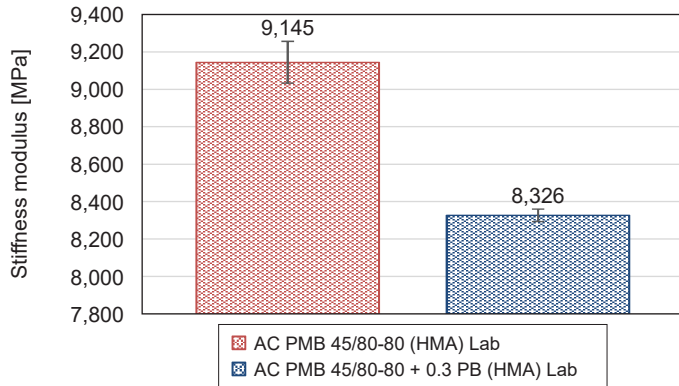


Fig. 7. Test results of the stiffness modulus of the asphalt concrete mixture from the wearing course of the experimental road section

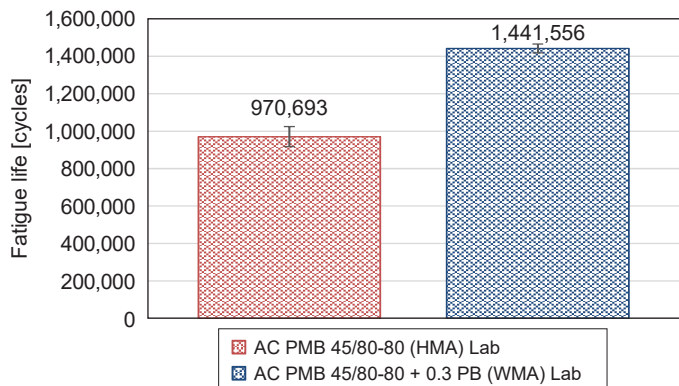


Fig. 8. Test results of the fatigue life of the asphalt concrete mixture from the wearing course of the experimental road section

Based on the analysis of the stiffness modulus test results presented in Fig. 7, it can be concluded that the addition of fibers to asphalt concrete using warm mix technology results in a decrease in stiffness compared to asphalt concrete produced with hot mix technology without the addition of fibers. The difference in stiffness modulus values does not exceed 9%.

The test results presented in Fig. 8 clearly confirm the beneficial effect of polymer-basalt fibers on increasing the fatigue durability of asphalt concrete intended for the wearing course. A significant 49% increase in fatigue life was observed for fiber-reinforced asphalt concrete produced using warm mix technology. This substantial improvement in fatigue life can be primarily attributed to the synergistic action of polymer-basalt fibers with foamed asphalt supported by the addition of bio-flux.

The test results for the high modulus asphalt concrete mixture used in the subbase layer from the experimental road section are presented in Fig. 9 (stiffness modulus) and Fig. 10 (fatigue life). The samples were prepared in the laboratory from the asphalt mixture taken before compaction of the subbase layer (HMAC (HMA) Lab and HMAC + 0.2% PB (WMA) Lab) and cut from the subbase layer (HMAC (HMA) Sec and HMAC + 0.2% PB (WMA) Sec).

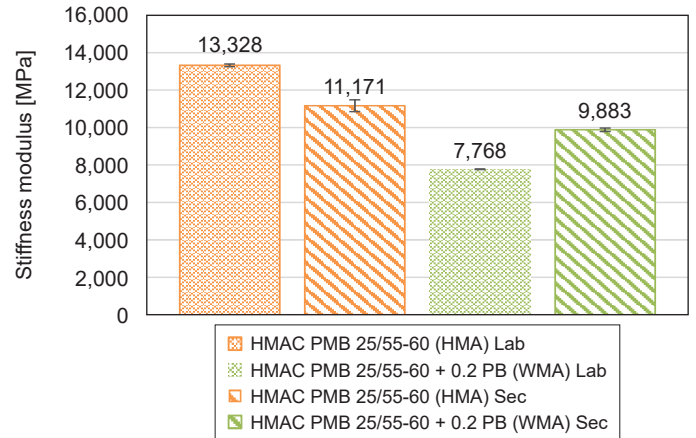


Fig. 9. Test results of the stiffness modulus of the high modulus asphalt concrete mixture from the subbase course of the experimental road section

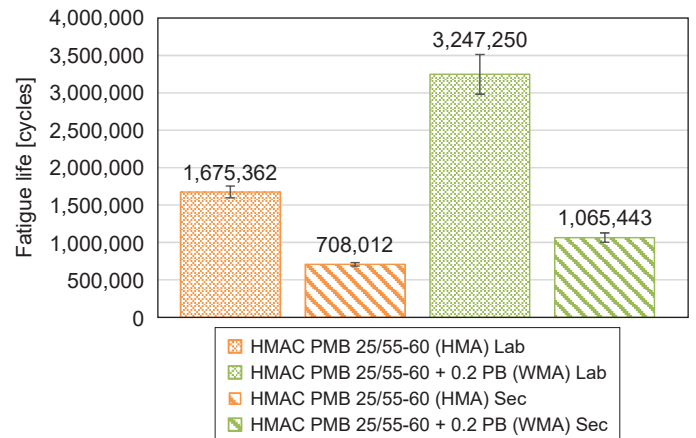


Fig. 10. Test results of the fatigue life of the high modulus asphalt concrete mixture from the sub subbase course of the experimental road section

Based on the analysis of stiffness modulus test results presented in Fig. 9, it can be concluded that the addition of fibers to high modulus asphalt concrete produced using warm mix technology leads to a reduction in its stiffness (with differences in stiffness modulus values ranging from 12% to 40%). This difference is more pronounced when

comparing laboratory-compacted samples to those taken from the road section. This is most likely due to the heterogeneity of the asphalt mixture collected from the paver hopper, caused by increased anisotropy in the fiber-containing material formed during the production process.

Fig. 9 shows a significant difference in stiffness modulus values between laboratory-compacted samples and those compacted in the subbase layer (ranging from 16% for samples compacted using hot mix technology to 27% for samples compacted using warm mix technology with polymer-basalt fibers). This can be explained by differences in air void content, which in the case of samples cut from the pavement containing fibers is approximately 1% higher compared to the other tested samples. The high modulus asphalt concrete mixture with added fibers, compacted in the experimental section in the subbase layer, exhibited 21% higher stiffness compared to samples of the same mixture compacted in the laboratory. This mixture had a higher air void content (3.9%) than the one compacted in the laboratory (2.7%).

The test results presented in Fig. 10 confirm the beneficial effect of polymer-basalt fibers in warm mix technology on increasing the fatigue life of high modulus asphalt concrete compared to hot mix technology. For laboratory-compacted samples, this increase amounted to 94%, while for samples cut from the pavement, the increase was 50%. Fig. 10 shows a significant difference – over 67% – in fatigue life between high modulus asphalt concrete samples with fibers cut from the subbase layer and those compacted in the laboratory. This difference results from a substantial variation in air void content between the samples cut from the subbase layer and those compacted in the laboratory, amounting to approximately 1.2%, as well as the possible influence of anisotropy related to the distribution of fibers within the composite structure.

5. CONCLUSIONS

Based on the conducted laboratory and field tests, as well as the analysis of the test results, the following conclusions can be drawn:

1. Polymer-basalt and aramid fibers have a positive impact on increasing the fatigue durability of hot mix asphalt concrete, no improvement in fatigue life was observed with the use of glass fibers.

2. For designing pavement structures with the highest fatigue resistance, it is recommended to use hot mix asphalt concrete with highly modified binders in the wearing course, preferably with the addition of aramid fibers, followed by polymer-basalt fibers.
3. The test results clearly confirmed the beneficial effect of polymer-basalt fibers on increasing the fatigue durability of high modulus hot mix asphalt concrete used in the subbase course. In the case of mixtures containing glass fibers, a reduction in fatigue durability of up to 40% was observed, both with paving grade bitumen and polymer-modified binder.
4. For subbase course layers requiring increased fatigue durability, it is recommended to use polymer-modified binder with the addition of polymer-basalt fibers in high modulus asphalt concrete mixtures.
5. The test results showed the beneficial effect of polymer-basalt fibers in combination with foamed asphalt supported by a bio-flux additive on improving the fatigue durability of warm mix asphalt concrete intended for the wearing course.
6. The test results showed that the use of polymer-basalt fibers in warm mix technology increases the fatigue durability of high modulus asphalt concrete used in the subbase course, compared to hot mix technology.

Laboratory and experimental road section test results indicate that the use of fibers in mineral-asphalt composites contributes to increased fatigue durability. Additionally, warm mix technology enhanced with bio-flux additives offers the potential to strengthen the improvement in fatigue resistance while enabling the implementation of environmentally friendly solutions. This innovative approach allows for the design and construction of road pavement structures with increased service life.

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REFERENCES

- [1] *Chen H., Xu Q., Chen S., Zhang Z.*: Evaluation and design of fiber-reinforced asphalt mixtures. *Materials and Desing*, **30**, 7, 2009, 2598-2603, DOI: 10.1016/j.matdes.2008.09.030
- [2] *Abiola O.S., Kupolati W.K., Sadiku R., Ndambuki J.*: Utilisation of natural fiber as modifier in bituminous mixes: A review. *Construction and Building Materials*, **54**, 2014, 305-312, DOI: 10.1016/j.conbuildmat.2013.12.037
- [3] *Qain S., Ma H., Feng J., Yang R., Huang X.*: Fiber reinforcing effect on asphalt binder under low temperature. *Construction and Building Materials*, **61**, 2014, 120-124, DOI: 10.1016/j.conbuildmat.2014.02.035
- [4] *Park P., El-Tawil S., Park S., Naaman A.E.*: Cracking resistance of fiber reinforced asphalt concrete at -20°C . *Construction and Building Materials*, **81**, 2015, 47-57, DOI: 10.1016/j.conbuildmat.2015.02.005
- [5] *Mansourian A., Razmi A., Razavi M.*: Evaluation of fracture resistance of warm mix asphalt containing jute fibers. *Construction and Building Materials*, **117**, 2016, 37-46, DOI: 10.1016/j.conbuildmat.2016.04.128
- [6] *Radziszewski P., Sarnowski M.*: *Technologia nowoczesnych nawierzchni asfaltowych*. Wydawnictwo Naukowe PWN, Warszawa, 2023 (in Polish)
- [7] *Liphardt A., Radziszewski P., Sarnowski M.*: Evaluation of the feasibility of incorporating higher RAP materials content in asphalt concrete with the use of additives that improve the workability of asphalt mixtures. *Roads and Bridges – Drogi i Mosty*, **22**, 4, 2023, 515-526, DOI: 10.7409/rabdim.023.032
- [8] *Iwański M., Chomicz-Kowalska A., Maciejewski K., Janus K., Radziszewski P., Liphardt A., Michalec M., Góral K.*: Stiffness evaluation of laboratory and plant produced foamed bitumen warm asphalt mixtures with fiber reinforcement and bio-flux additive. *Materials*, **16**, 5, 2023, Article ID: 1950, DOI: 10.3390/ma16051950
- [9] *Radziszewski P., Sarnowski M., Plewa A., Pokorski P.*: Properties of asphalt concrete with basalt-polymer fibres. *Archives of Civil Engineering*, **64**, 4, 2018, 197-209, DOI: 10.2478/ace-2018-0052
- [10] *Jaskuła P., Stienss M., Szydłowski C.*: Wpływ zbrojenia polimerowymi włóknami rozproszonymi na wybrane właściwości mieszanek mineralno-asfaltowych. *Drogownictwo*, **72**, 9, 2017, 275-280 (in Polish)
- [11] *Mashaan N., Karim M., Khodary F., Saboo N., Milad A.*: Bituminous pavement reinforcement with fiber: A review. *CivilEng*, **2**, 3, 2021, 599-611, DOI: 10.3390/civileng2030033
- [12] *Min-Jae K., Soonho K., Doo-Yeol Y., Hyunoh S.*: Enhancing mechanical properties of asphalt concrete using synthetic fibers. *Construction and Building Materials*, **178**, 2018, 233-243, DOI: 10.1016/j.conbuildmat.2018.05.070
- [13] *Iwański M., Chomicz-Kowalska A., Maciejewski K.*: Application of synthetic wax for improvement of foamed bitumen parameters. *Construction and Building Materials*, **83**, 2015, 62-69, DOI: 10.1016/j.conbuildmat.2015.02.060
- [14] *Chomicz-Kowalska A., Mrugała J., Maciejewski K.*: Evaluation of foaming performance of bitumen modified with the addition of surface active agent. *IOP Conference Series Materials Science and Engineering*, **245**, 3, 2017, Article ID: 032086, DOI: 10.1088/1757-899X/245/3/032086
- [15] *Chomicz-Kowalska A.*: Statistical methods for evaluating associations between selected foamed bitumen parameters. *Proceedings of the 6th International Conference: Bituminous Mixtures and Pavements*, Thessaoniki, Greece, 2015, *Bituminous Mixtures and Pavements VI*, Ed. A. Nikolaidis, CRC Press, London, 2015, 3-12
- [16] *Innowacyjne hybrydowe zbrojenie kompozytowe FRP do konstrukcji infrastrukturalnych o podwyższonej trwałości*. Program Badań Stosowanych (PBS), Narodowe Centrum Badań i Rozwoju (NCBR), Politechnika Warszawska, Raport z badań PBS3/A2/20/2015, 2015-2018 (in Polish)
- [17] *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, DOI: 10.3390/ma15248873
- [18] *Iwański M., Chomicz-Kowalska A., Maciejewski K., Iwański M.M., Radziszewski P., Liphardt A., Król J.B., Sarnowski M., Kowalski K.J., Pokorski P.*: Effects of laboratory ageing on the FTIR measurements of water-foamed bio-fluxed asphalt binders. *Materials*, **16**, 2, 2023, Article ID: 513, DOI: 10.3390/ma16020513
- [19] *Radziszewski P., Liphardt A., Sarnowski M., Kowalski K.J., Pokorski P., Konieczna K., Król J.B., Iwański M., Chomicz-Kowalska A., Maciejewski K., Iwański M.M., Michalec M.*: Ageing evaluation of foamed polymer modified bitumen with bio-flux additive. *Materials*, **16**, 6, 2023, Article ID: 2167, DOI: 10.3390/ma16062167
- [20] *Chomicz-Kowalska A., Iwański M., Maciejewski K., Iwański M.M., Radziszewski P., Liphardt A., Pokorski P., Król J.*: High performing WMA surface course and high modulus asphalt concretes evaluated using different stiffness moduli measuring methods. *8th E&E Congress Eurasphalt & Eurobitume*, Budapest, Hungary, 2024
- [21] *WT-2 2014 Nawierzchnie asfaltowe na drogach krajowych. Część I: Mieszanki mineralno-asfaltowe*. Wymagania techniczne. Załącznik do Zarządzenia nr 54 Generalnego Dyrektora Dróg Krajowych i Autostrad, GDDKiA, Warszawa 2014, https://edziennik.gddkia.gov.pl/eli/DU_GDDKIA/2014/54/ogl/pol/pdf (available in Polish: 01.06.2025)

- [22] Gupta A., Slebi-Acevedo C.J., Lizasoain-Arteaga E., Rodriguez-Hernandez J., Castro-Fresno D.: Multi-criteria selection of additives in porous asphalt mixtures using mechanical, hydraulic, economic, and environmental Indicators. *Sustainability*, **13**, 4, 2021, Article ID: 2146, DOI: 10.3390/su13042146
- [23] Mitchell M.R., Link R.E., Kaloush K.E., Biligiri K.P., Zeiada A., Rodezno M.C., Reed J.X.: Evaluation of fiber-reinforced asphalt mixtures using advanced material characterization tests. *Journal of Testing and Evaluation*, **38**, 4, 2010, 400-411, DOI: 10.1520/JTE102442
- [24] Klinsky L.M.G., Kaloush K.E., Faria V.C., Bardini V.S.S.: Performance characteristics of fiber modified hot mix asphalt. *Construction and Building Materials*, **176**, 2018, 747-752, DOI: 10.1016/j.conbuildmat.2018.04.221
- [25] Kassem H.A., Saleh N.F., Zalghout A.A., Chehab G.R.: Advanced characterization of asphalt concrete mixtures reinforced with synthetic fibers. *Journal of Materials in Civil Engineering*, **30**, 11, 2018, Article ID: 04018307, DOI: 10.1061/(ASCE)MT.1943-5533.0002521
- [26] Pszczola M., Szydłowski C., Jaczewski M.: Influence of cooling rate and additives on low-temperature properties of asphalt mixtures in the TSRST. *Construction and Building Materials*, **204**, 2019, 399-409, DOI: 10.1016/j.conbuildmat.2019.01.148
- [27] Wiśniewski D., Słowik M., Kempa J., Lewandowska A., Malinowska J.: Assessment of impact of aramid fibre addition on the mechanical properties of selected asphalt mixtures. *Materials*, **13**, 15, 2020, Article ID: 3302, DOI: 10.3390/ma13153302
- [28] Noorvand H., Castro S., Underwood B.S., Kaloush K.E.: Evaluating interaction of fibre reinforcement mechanism with mesostructure of asphalt concrete. *International Journal of Pavement Engineering*, **23**, 5, 2020, 1594-1611, DOI: 10.1080/10298436.2020.1813286
- [29] Xing X., Liu T., Pei J., Huang J., Li R., Zhang J., Tian Y.: Effect of fiber length and surface treatment on the performance of fiber-modified binder. *Construction and Building Materials*, **248**, 2020, Article ID, 118702, DOI: 10.1016/j.conbuildmat.2020.118702
- [30] Takaikaew T., Tepsriha P., Horpibulsuk S., Hoy M., Kaloush K.E., Arulrajah A.: Performance of fiber-reinforced asphaltconcreteswithvariousasphaltbindersinThailand. *Journal of Materials in Civil Engineering*, **30**, 8, 2018, Article ID: 04018193, DOI: 10.1061/(ASCE)MT.1943-5533.0002433
- [31] Radziszewski P., Sarnowski M.: Beton asfaltowy zbrojony włóknami FRP do naprawy nawierzchni betonowych. *Magazyn Autostrady*, 10, 2017, 38-41 (in Polish)

Wpływ dodatku włókien na trwałość zmęczeniową kompozytów mineralno-asfaltowych do warstw nawierzchni drogowej wykonywanych w technologii na gorąco i na ciepło

Streszczenie: Obecnie w coraz większym stopniu wprowadza się w budownictwie drogowym produkcję mieszanek mineralno-asfaltowych w technologii na ciepło. Ta technologia pozwala na obniżenie temperatury produkcji i wykonania nawierzchni asfaltowych od 30°C do 50°C. Tak znaczne obniżenie temperatury przyczynia się do niższych kosztów produkcji, ale także powoduje zmniejszoną emisję ciepła do atmosfery, co jest niezwykle ważne ze względu na ochronę środowiska. Jedną z ważniejszych cech funkcjonalnych warstw nawierzchni drogowej jest jej trwałość zmęczeniowa, którą można polepszyć stosując do mieszanek mineralno-asfaltowych włókna. Do zbrojenia rozproszonego mieszanek mineralno-asfaltowych często są stosowane włókna: aramidowe (AR), szklane (GL) i polimerowo-bazaltowe (PB). W artykule poddano analizie wyniki badań mieszanek mineralno-asfaltowych z tymi włóknami wykonanych w technologii na gorąco, na podstawie których określono ich wpływ na trwałość zmęczeniową. Do dalszych badań wybrano włókna polimerowo-bazaltowe, charakteryzujące się bardzo korzystnym wpływem na odporność na zmęczenie mieszanek betonu asfaltowego (AC) i betonu asfaltowego o wysokim module sztywności (ACWMS). Ważnym problemem materiałowo-technologiczno-konstrukcyjnym jest określenie efektywności działania dodatku włókien do mieszanek mineralno-asfaltowych w technologii na ciepło. W artykule przedstawiono wyniki badań nad innowacyjną technologią produkcji i wbudowania mieszanek mineralno-asfaltowych przy jednoczesnym zastosowaniu wybranego włókna polimerowo-bazaltowego, środka upłynniającego lepiszcze w postaci proekologicznego upłynniacza pochodzenia roślinnego (bio-fluxu) oraz procesu spieniania asfaltu wodą, co pozwala wytworzyć kompozyt mineralno-asfaltowy w obniżonej temperaturze i o poprawionych parametrach technicznych. W celu potwierdzenia wysokich właściwości funkcjonalnych w pracy przedstawiono wyniki badań zmęczeniowych próbek mieszanek mineralno-asfaltowych przeznaczonych do warstw: ścieralnej i podbudowy z dodatkiem włókien bazaltowych, wykonanych w laboratorium oraz pobranych z odcinka doświadczalnego. Wyniki badań wykazały, że zastosowanie technologii produkcji i wbudowania na ciepło betonu asfaltowego AC 11 do warstwy ścieralnej i ACWMS 22 do warstwy podbudowy, z zastosowaniem włókien polimerowo-bazaltowych, jest bardzo korzystne ze względu na zapewnienie wysokiej trwałości zmęczeniowej.

Słowa kluczowe: mieszanki mineralno-asfaltowe, technologia na ciepło, trwałość zmęczeniowa, włókna polimerowo-bazaltowe.