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THE INFLUENCE OF DISPERSED REINFORCEMENT IN THE FORM OF BASALT FIBERS ON THE STIFFNESS MODULUS OF ASPHALT CONCRETE

WPŁYW ZBROJENIA ROZPROSZONEGO W POSTACI WŁÓKIEN BAZALTOWYCH NA MODUŁ SZTYWNOŚCI BETONU ASFALTOWEGO

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Abstract

This article analyzes the effect of dispersed reinforcement in the form of basalt fibers on the stiffness modulus of asphalt concrete. The research program included an AC 16W mineral-asphalt mixture intended for a binder course reinforced with 30 mm long basalt fibers at 0.5% and 1.5% by weight, as well as options with adjusted asphalt content. Laboratory tests showed that the addition of basalt fibers significantly increases the stiffness of the mixture across the entire tested temperature range from 5°C to 40°C, achieving in the 1.5% variant (AC_1.5%) Sm modulus values nearly twice as high as those of the reference mineral-asphalt mixture (R). It was also noted that changing the binder content led to a significant reduction in stiffness at the analyzed temperatures, which may protect the pavement against low-temperature cracking. Despite differences in composition, all tested mixtures maintained high water resistance at 91–98%, confirming that proper dosing of basalt fibers without excess binder yields the most durable structure resistant to permanent deformation.

Keywords: asphalt concrete; basalt fibers; stiffness modulus; IT-CY method; temperature sensitivity

Streszczenie

W niniejszym artykule przeanalizowano wpływ zbrojenia rozproszonego w postaci włókien bazaltowych na moduł sztywności betonu asfaltowego. Program badań obejmował mieszankę mineralno-asfaltową typu AC 16W, przeznaczoną na warstwę wiążącą, zbrojoną włóknami bazaltowymi o długości 30 mm w ilości 0,5% i 1,5% masy, a także warianty z zmodyfikowaną zawartością asfaltu. Badania laboratoryjne wykazały, że dodatek włókien bazaltowych znacząco zwiększa sztywność mieszanki w całym badanym zakresie temperatur (od 5°C do 40°C); w przypadku wariantu z 1,5% dodatkiem włókien (AC_1,5%) uzyskano wartości modułu sztywności (Sm) niemal dwukrotnie wyższe niż dla referencyjnej mieszanki mineralno-asfaltowej (R). Odnotowano również, że zmiana zawartości lepiszcza prowadziła do istotnego obniżenia sztywności w analizowanych temperaturach, co może chronić nawierzchnię przed spękaniami niskotemperaturowymi. Mimo różnic w składzie, wszystkie badane mieszanki zachowały wysoką odporność na działanie wody (na poziomie 91–98%), co potwierdza, że właściwe dozowanie włókien bazaltowych – bez nadmiaru lepiszcza – pozwala uzyskać najbardziej trwałą strukturę, odporną na odkształcenia trwałe.

Słowa kluczowe: beton asfaltowy; włókna bazaltowe; moduł sztywności; metoda IT-CY; wrażliwość temperaturowa

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1. INTRODUCTION

The history of basalt fibers dates back to the 1960s, when the Soviet Union began developing this material as part of its space program, where its exceptional durability and resistance to extreme conditions were recognized. Today, these fibers are valued by road engineers for their ability to reduce thermal cracking and improve the stability of mineral-asphalt mixtures [1]. To improve the durability and performance of pavements, engineers and scientists have been using various methods to modify mineral-asphalt mixtures for years. One of the most effective solutions is the use of dispersed reinforcement in the form of fibers [2]. Among various reinforcement materials, basalt fibers are gaining increasing recognition as a natural, eco-friendly, and non-toxic alternative to synthetic and glass fibers [3]. Studies show that the introduction of basalt fibers into basalt fiber asphalt concrete (BFAC) alters the viscoelastic properties of the mineral-asphalt mixture, which directly translates into an increase in its dynamic modulus and stiffness [3]. A review article [4] presented results regarding the use of recycled fibers (PET), which were dosed at 0%, 2%, 4%, 6%, 8%, and 10% relative to the asphalt content. The test results showed that the optimal fiber content is in the range of 4–6%, or specifically 6% by weight relative to the asphalt. In his study [5], researcher Mahrez evaluated the fatigue properties and deformation of mixtures reinforced with glass fibers. Glass fibers were used to improve the fatigue resistance and deformation (rutting) resistance of mineral-asphalt mixtures. Artur Kowalczyk and his co-authors, in a scientific article [6], used fibers recycled from glass and carbon geogrids in amounts of 0.2%, 0.6%, and 1.0% by weight to investigate their effect on crack propagation resistance and the physical and mechanical properties of asphalt concrete. Cellulose fibers are mainly used in SMA (stone matrix asphalt) and OGFC (open-graded friction-course) mixtures to stabilize the binder and prevent it from washing out of the aggregate during transport and construction [7]. Researcher Tapkin investigated the effect of these fibers on the properties of asphalt and their behavior in a creep test [4], [8]. Polypropylene fibers are widely used as a reinforcing agent to strengthen asphalt concrete. In the article, fibers increase the strength, ductility, and durability of the mixture. The presented literature review indicates the validity of seeking answers regarding the influence of dispersed reinforcement in mineral-asphalt mixtures in the form of fibers. The literature review did not reveal any information on the effect of basalt fibers on the stiffness modulus of asphalt concrete. The topic appears to be of scientific interest, as demonstrated in the article regarding the assessment of the effect of dispersed reinforcement in the form of basalt fibers on the stiffness modulus of asphalt concrete.

2. MATERIALS AND METHODS

2.1. Basalt fibers

Basalt fibers were used to evaluate the effect of dispersed reinforcement in the form of basalt fibers on the stiffness modulus of asphalt concrete. The production process for basalt fibers involves melting the basalt raw material at a temperature of approximately 1500°C, then transforming it by drawing it through small-diameter holes, which results in the formation of thin fibers that are subsequently cut into pieces of the appropriate length [9]. Basalt fibers have good resistance to acids and alkalis, low thermal conductivity, and weather resistance, and are characterized by hydrophobic properties [10]. Fibers 30 mm in length were used in the study. According to the manufacturer's information, the properties of the fibers used in the study change at a temperature of 160°C. The basalt fibers were properly conditioned before being added to the mineral-asphalt mixture. The fibers were added to the mineral-asphalt mixtures to assess their impact on the mechanical properties of AC 16W in the context of the effect of dispersed reinforcement in the form of basalt fibers on the stiffness modulus of asphalt concrete.

Figure 1 shows an example photograph of the basalt fibers under analysis.



Fig. 1. Basalt fibers 30 mm in length [W. Ściga]

2.2. Design of the mineral-asphalt mixture

Before proceeding with the design of the mineral-asphalt mixtures, a qualitative analysis was conducted on all the components used, including mineral aggregates, asphalt granules, the binder, and the basalt-based synthetic fiber additive. The limit curve method was used to design the mineral-asphalt

mixture, which allowed for achieving a gradation meeting the requirements [11] for mixtures intended for the binder course. The gradation curves for the AC 16W KR 3-4 mixture are shown in Figure 2.

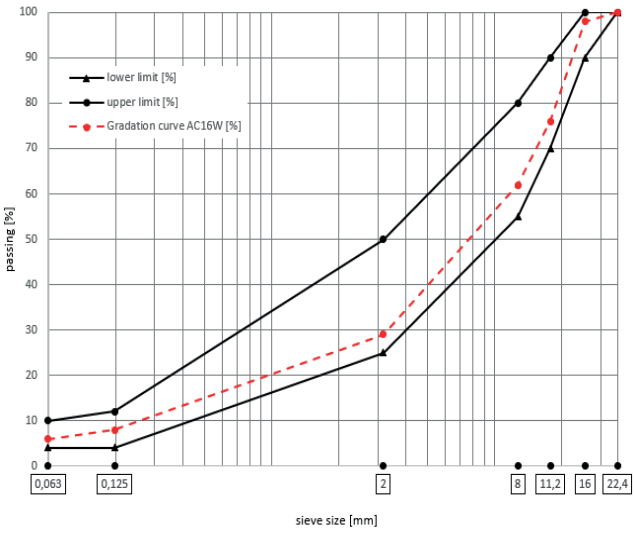


Fig. 2. Gradation curve of the AC 16W KR 3-4 mineral mixture

Table 1 shows the sieve sizes and particle size distribution of the mineral mixture under test.

Table 1. Particle size distribution of the mineral mixture

Screen hole size	Passing % (m/m)	Grain size cut-off points	
		Lower	Top
31.5 mm	**100**	–	–
22.4 mm	**100**	100	100
16.0 mm	**98**	90	100
11.2 mm	**76**	70	90
8.0 mm	**62**	55	80
5.6 mm	**52**	–	–
4.0 mm	**44**	–	–
2.0 mm	**29**	25	50
0.125 mm	**8**	4	12
0.063 mm	**6**	4	10

The composition of the mineral-asphalt mixtures is presented in Table 2.

Table 2. Percentage composition of the AC 16W mix

Material	Rock name, Binder, Additive	AC 16W 35/50 Percentage [%] Mineral Mixture (w/w)	AC 16W 35/50 Percentage [%] Mineral-Asphalt Mixture (w/w)
Aggregate 8/16 mm	Dolomite	37.0	35.4
Aggregate 2/8 mm	Dolomite	25.0	23.9
Aggregate 0/4 mm	Dolomite	36.0	34.4
Limestone filler	Limestone	2.0	1.9
Bitumen 35/50	–		4.4
Adhesive			0.1
Total			100.0

This design of the mineral-asphalt mixture compositions ensures the stability of the mixtures and allows for a clear assessment of the effect of basalt fibers on the properties of asphalt concrete.

2.3. Experimental and Research Plan

The purpose of this article is to analyze the effect of dispersed reinforcement in the form of basalt fibers on the mechanical properties of asphalt concrete. The study focuses on evaluating the stiffness modulus and its variation over a wide temperature range from 5°C to 40°C. The experiment aims to determine the optimal percentage of fibers in the range from 0.5% to 1.5% to achieve the most favorable mechanical properties of asphalt concrete. Figure 3 presents a detailed experimental plan for the designed mineral-asphalt mixtures based on the amount of added fibers and the amount of additional asphalt.

The experimental design presented (Fig. 3) concerns the investigation of the properties of mineral-asphalt mixtures (AC 16W) with the addition of basalt fibers. The main objective of the study is to compare a reference sample with mixtures modified with different fiber contents (0.5% and 1.5%). The scheme also includes variants with added asphalt, which allows for an assessment of the binder's influence on the effectiveness of dispersed reinforcement within the asphalt concrete structure. This experimental design enables a precise determination of how the fiber dosage and adjustments to the asphalt content affect the technical parameters of the pavement.

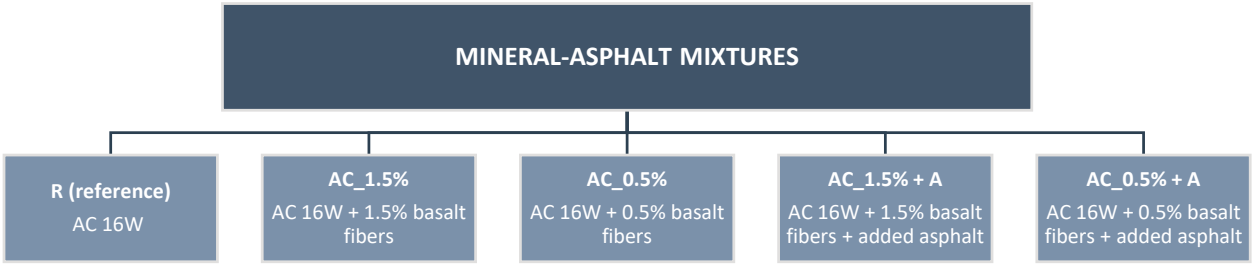


Fig. 3. Experimental setup for evaluating the effect of dispersed basalt fiber reinforcement on the stiffness modulus of asphalt concrete

Figure 4 shows the performance curves of the tested mixtures in terms of asphalt adjustment.

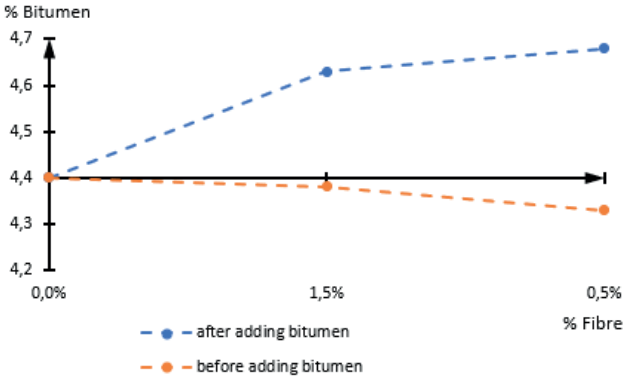


Fig. 4. Bitumen content in mixtures before and after binder adjustment

The envelope in Figure 4 represents the analyzed data range in terms of quantity. The starting point is the reference mix (0% fibers) with a bitumen content of 4.4%. The lower curve represents the change in the mixture's properties without accounting for asphalt adjustment, i.e., an increase in the fiber dosage, which results in a decrease in the amount of asphalt. At a dosage of 0.5% fibers, the asphalt content drops to 4.38%, while at 1.5% fibers, it decreases to 4.33%. In contrast, the upper curve represents the change in mixture properties taking into account the asphalt adjustment. After adding 0.3% asphalt to mixtures reinforced with basalt fibers, the total binder content increases. For the mixture with 0.5% fibers, this value is 4.68%, and for the variant with 1.5% fibers, it reaches 4.63%. To assess the impact of basalt fibers as reinforcement on the properties of asphalt concrete, a complete set of standard tests was conducted to determine whether the asphalt concrete mixtures meet the requirements of the guidelines [11, 12].

The scope of the tests on mineral-asphalt mixtures involved the evaluation of their physical, mechanical, and volumetric properties, a summary of which, along with the relevant standards, is presented in Table 3.

Table 3. Tested parameters of the AC 16W

Tested parameter	Standard	Number of specimens and compaction conditions
Void characteristics of bituminous specimens (Va)	EN 12697-8 [13]	Number of specimens: 5 Compaction: Marshall compactor, 2 × 75 blows
Indirect tensile strength (ITSDRY)	EN 12697-23 [14]	Number of specimens: 5 Compaction: Marshall compactor, 2 × 75 blows
Water sensitivity of bituminous specimens (ITSR)	EN 12697-12 [15]	Number of specimens: 10 Compaction: Marshall compactor, 2 × 75 blows
Stiffness (IT-CY)	EN 12697-26 [16]	Number of specimens: 5 Compaction: Marshall compactor, 2 × 75 blows

After conducting the preliminary tests on the asphalt concrete, it was possible to proceed to the main phase of the study, which involved determining the stiffness modulus (Sm) in the IT-CY indirect tensile test on cylindrical specimens, carried out in accordance with the test method described in the PN-EN 12697-26 standard [16]. All specimens were prepared under laboratory conditions and compacted using a Marshall rammer, with 75 blows applied to each side (2 × 75) [18]. The specimens were conditioned at the test temperature prior to testing. The stiffness modulus an extremely important parameter for mixtures used in road pavement layers. To determine this parameter in the AC 16W mixture, a test was conducted using the IT-CY indirect tensile test method. The test was performed in accordance with the provisions of the PN-EN 12697-26 standard [16]. The horizontal displacement is 5±2 µm, and the load rise time is 124±4 ms.

The modulus of elasticity is determined using equation (1), and Poisson's ratio is determined using equation (2):

$$S_m = \frac{F \cdot (\nu + 0.27)}{z \cdot h} \quad (1)$$

$$\nu = 3.59 \cdot \frac{z}{\Delta V} - 0.27 \quad (2)$$

where:
S_m – sample stiffness modulus [MPa];
F – maximum force applied to the specimen [N];
ν – the temperature-dependent Poisson's ratio;
z – amplitude of the sample's horizontal displacement under load [mm];
h – sample thickness [mm];
ΔV – maximum vertical displacement of the specimen (corresponding to the maximum horizontal displacement) [mm].

When examining equation (2), a relationship should be noted. An increase in sample thickness and strain leads to a decrease in internal stress, which directly affects the stiffness modulus (S_m). The Figure 5 shows a test setup for determining the stiffness modulus using the IT-CY method.



Fig. 5. Test setup ready for stiffness modulus testing using the IT-CY method [W. Ściga]

3. ANALYSIS OF RESULTS

The assessment of the effect of basalt fiber reinforcement on the stiffness modulus of asphalt concrete was preceded by an evaluation of the basic properties, which are presented in Table 4.

Table 4. Results of basic tests on mineral-asphalt mixtures

Mixture name	V_m [%]	ITS_{DRY} [MPa]	ITSR [%]
R (reference)	5.9	1.382	98
AC_1.5%	3.9	1.734	97
AC_0.5%	6.9	1.746	91
AC_1.5% + A	6.4	0.768	98
AC_0.5% + A	5.6	1.508	94

When comparing the results of the reference mixture (R) with the other variants modified with basalt fibers, it can be observed that the highest indirect tensile strength (ITS_DRY), exceeding 1.7 MPa, was achieved by the AC_1.5% and AC_0.5% mixtures. In turn, the addition of asphalt to the mineral-asphalt mixtures, designated as "+ A," significantly influenced the material properties, which is particularly evident in the case of the AC_1.5% + A mixture. This variant achieved a void content of 6.4% and the lowest indirect tensile strength, equal to 0.768 MPa. Despite these differences in void content and indirect tensile strength, most of the tested samples exhibited very good water resistance, as the ITSR index for all mixtures remained at a high level ranging from 91% to 98%.

To conduct a detailed analysis of the mechanical properties, the stiffness modulus was determined using the IT-CY indirect tensile test at three temperatures 5°C, 25°C, and 40°C in accordance with the PN-EN 12697-26 standard [16].

Figure 6 shows the results of the stiffness modulus determined using the indirect tensile method for the three temperatures tested.

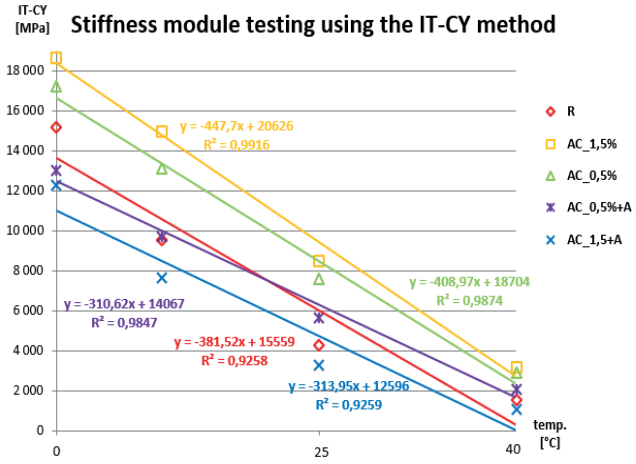


Fig. 6. Results of the Sm (IT-CY) stiffness modulus as a function of temperature

The stiffness modulus results determined using the IT-CY method revealed a clear correlation with the temperature at which the test was conducted. The highest values were recorded at 5°C, while the lowest were at 40°C, indicating a shift in the ratio between the elastic and viscous responses of the material at high temperatures. The results for the mineral-asphalt mixture with 1.5% basalt fibers and additional asphalt (AC_1.5%+A) showed the lowest stiffness at each of the analyzed temperatures. In contrast, the highest results at each tested temperature were recorded for the mineral-asphalt mixture with an additional 1.5% basalt fibers (AC_1.5%). The graph presents an analysis of the thermal sensitivity of the mixtures, where the coefficients for the variable "x" determine the rate of decrease in the stiffness modulus as temperature increases.

To assess the rate of change of the stiffness modulus, the coefficient "a" of the linear equation was analyzed. The results are presented in Table 5.

Table 5. Summary of the rates of change in the stiffness modulus

	a	b	R^2
R (reference)	398.93	16311	0.9379
AC_1.5%	444.59	20491	0.9908
AC_0.5%	413.26	18889	0.987
AC_1.5%+A	313.95	12596	0.9259
AC_0.5%+A	316.01	14300	0.9858

The highest value of this parameter, a = 444.59, was recorded for the AC_1.5% mixture, which means that it reacts most violently to thermal changes. In contrast, mixtures with additional asphalt (designated as AC_1.5%+A and AC_0.5%+A) exhibit significantly lower values of the *a* parameter, indicating greater stability and lower susceptibility to the effects of rising temperatures. The AC_1.5%+A mixture proved to be the most resistant to changes, with a coefficient of just a = 313.95. This comparison demonstrates that increasing the amount of asphalt effectively "smooths out" the material's characteristics, limiting the rate of stiffness loss.

To observe and compare changes in the stiffness of asphalt concrete containing basalt fibers across different temperature ranges, the average results for the analyzed AC mixtures are presented in Figures 7-9.

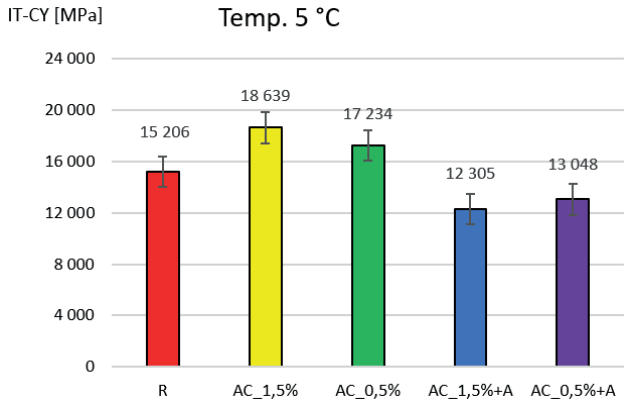


Fig. 7. Bar chart showing the IT-CY stiffness modulus at 5°C (the error bars indicate the standard deviation)

Figure 7 shows the IT-CY stiffness modulus values of the tested mixtures at a temperature of 5°C. The highest result (18.639 MPa) was obtained by the AC_1.5% mixture. The use of basalt fibers alone significantly increased the stiffness of the material compared to the reference mixture, suggesting improved stiffness under temperature conditions fluctuating around 5°C. However, a drastic decrease in stiffness is noticeable in the variants with additional asphalt (AC_1.5%+A and AC_0.5%+A), particularly in the case of the AC_1.5%+A mixture, which achieved the lowest value (12.305 MPa). This comparison of results shows that while fibers stiffen the structure, excess binder significantly increases the mixture's flexibility, which may protect the pavement against low-temperature cracking.

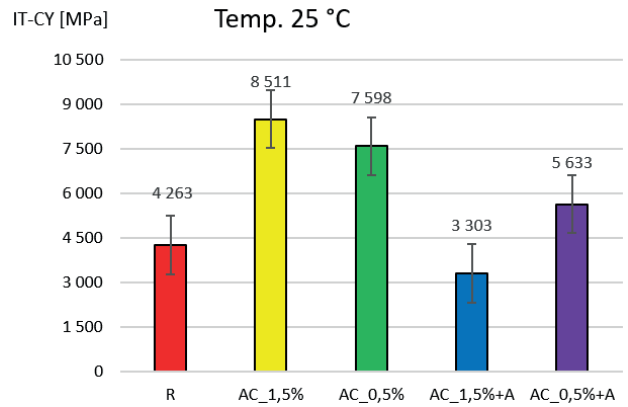


Fig. 8. Bar chart showing the IT-CY stiffness modulus at 25°C (the error bars indicate the standard deviation)

At 25°C, mixtures containing only basalt fiber additives (AC_1.5% and AC_0.5%) exhibit a modulus of stiffness nearly twice as high as that of the reference mixture, confirming their reinforcing effect on the structure. As at lower temperatures, the addition of asphalt

(AC_1.5%+A and AC_0.5%+A) results in a significant reduction in stiffness, with the AC_1.5%+A mixture achieving the lowest value of 3.303 MPa. These results demonstrate that the fibers effectively stiffen the mineral matrix at service temperatures, while adjusting the binder content allows for flexible tuning of the final mixture parameters. The error bars presented indicate varying repeatability of the results, particularly evident in the case of the softest variants.

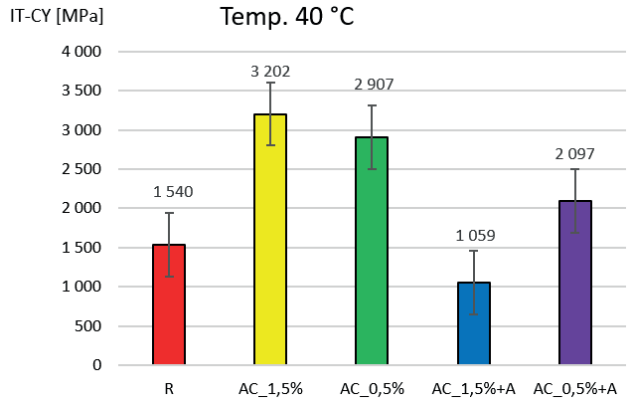


Fig. 9. Bar chart showing the IT-CY stiffness modulus at 40°C (the error bars indicate the standard deviation)

At a high temperature of 40°C (Fig. 9), the stiffness modulus of all mixtures decreased naturally; however, the fiber-reinforced variants (AC_1.5% and AC_0.5%) still maintained a significant advantage over the reference sample. The highest stiffness (3.202 MPa) was retained by the mixture with the highest fiber content (AC_1.5%), which confirms their key role in limiting permanent deformation under high pavement temperatures. In contrast, the AC_1.5%+A mixture achieved the lowest value (1.059 MPa), indicating this mixture's high susceptibility to high temperatures when the binder content is excessive. The graph as a whole demonstrates that optimal dosing of basalt fibers without excessively increasing the amount of asphalt yields the most durable structure under summer conditions.

4. CONCLUSIONS

Based on an analysis of test results for basalt fiber-reinforced mineral-asphalt mixtures, the following conclusions were drawn:

- The addition of 0.5% and 1.5% basalt fibers significantly increases the stiffness modulus of asphalt concrete compared to the reference mixture. The highest IT-CY values at each tested temperature were obtained for the mixture containing 1.5% fibers (AC_1.5%), confirming their effectiveness in stiffening the mineral-asphalt mixtures.
- Adjusting the binder content (AC_1.5%+A and AC_0.5%+A) results in a significant decrease in the stiffness modulus at all analyzed temperatures. These mixtures are characterized by greater deformability, which may affect the pavement's resistance to fatigue and low-temperature cracking.
- Based on the derived equations, it was found that fiber-reinforced mixtures (AC_1.5% and AC_0.5%) exhibit the highest thermal sensitivity (the highest "a" values). In contrast, the variants with additional asphalt (AC_1.5%+A and AC_0.5%+A) exhibit a significantly slower rate of stiffness decline as temperature increases, indicating greater stability of their parameters across a wide range of operating temperatures.
- In all cases analyzed, the modulus of elasticity decreases as the test temperature increases, which is typical for viscoelastic materials. However, even at 40°C, mixtures containing only fiber additives (AC_1.5% and AC_0.5%) retain nearly twice the stiffness of the reference sample (R – AC 16W), which may reduce the pavement's susceptibility to rutting.
- The results indicate that the mere addition of basalt fibers effectively stiffens the asphalt concrete structure, which is desirable in terms of rutting resistance; however, the addition of asphalt can be used to improve low-temperature cracking resistance at the expense of the layer's overall stiffness.

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