

## THE EFFECT OF FIBER REINFORCEMENT ON THE HIGH-TEMPERATURE PERFORMANCE OF WARM MIX ASPHALT PRODUCED USING WATER-FOAMING TECHNOLOGY

Anna CHOMICZ-KOWALSKA\*, Karolina JANUS

*Kielce University of Technology, Kielce, Poland*

Received 18 February 2026; revised 3 March 2026; accepted 3 March 2026

**Abstract.** The paper presents an evaluation of the influence of fiber type and content on the properties of mineral-asphalt mixtures produced using foamed bitumen technology. The effects of selected factors, including the type of asphalt binder, the type of fibers, and their content, on the high-temperature performance of AC 11 asphalt concrete mixtures intended for wearing courses were analyzed. Aramid fibers and polymer-basalt fibers, applied in varying amounts, were used as dispersed reinforcement. The study also included a reference mixture produced and compacted using conventional Hot-Mix Asphalt (HMA) technology. In contrast, Warm-Mix Asphalt (WMA) mixtures with foamed bitumen were manufactured at a temperature reduced by 30 °C compared to the reference mixture. The evaluated basic properties of the asphalt mixtures included air void content and moisture sensitivity, determined using the indirect tensile strength ratio after one freeze-thaw cycle. High-temperature performance was assessed based on resistance to rutting, expressed by the wheel tracking slope and proportional rut depth, as well as the stiffness modulus determined by the static creep test. The obtained results indicate that reducing the production temperature of asphalt concrete mixtures by 30 °C is feasible through the application of dispersed fiber reinforcement while maintaining performance parameters comparable to those of the reference HMA mixture.

**Keywords:** asphalt concrete, Warm Mix Asphalt (WMA), dispersed reinforcement, fibers, high-temperature performance.

### 1. Introduction

The continuous increase in traffic volume leads to accelerated deterioration of road pavements and necessitates the development of more durable structural and material solutions. To meet these challenges, it is essential to apply technologies that ensure enhanced resistance of pavements to heavy traffic loads as well as to variable climatic conditions. There are several approaches to improving the durability of road pavements while simultaneously minimizing their negative impact on the natural environment (Milad et al., 2022; Stępień & Maciejewski, 2022, Stępień et al., 2026; Sukhija et al., 2022). One solution consistent with these assumptions is the combination of Warm-Mix Asphalt (WMA) technology incorporating water-foamed asphalt binder (Chomicz-Kowalska, 2017; D'Angelo, 2008; Maciejewski et al., 2022) with the application of dispersed reinforcement. Moreover, widely observed climate change should be taken into account, as a continuous increase in the average annual air temperature is being recorded. As a result, the investigation of high-temperature performance parameters of

mineral-asphalt mixtures is becoming increasingly important. This trend leads to an extension of periods with elevated temperatures and a shortening of the winter season. Studies indicate (Gong et al., 2022) that over the next 20 years, pavement resistance to permanent deformation is expected to deteriorate by approximately 9–40% due to changing climatic conditions worldwide.

Currently in Poland, the range of extreme pavement surface temperatures for wearing courses extends from –30 °C to 60 °C. It is estimated that, in terms of ensuring pavement resistance to rutting, the asphalt binder accounts for approximately 40% of this performance characteristic (Gaweł et al., 2014; Krzywiński et al., 2018). Therefore, greater emphasis should be placed on conducting high-temperature performance tests of mineral-asphalt mixtures, particularly with respect to the type of asphalt binder used.

The properties of mineral-asphalt mixtures incorporating dispersed fiber reinforcement are closely related to the characteristics of the fibers, such as their shape, surface condition, ability to form chemical or physical bonds through adsorption, and their thermal stability.

\* Corresponding author. E-mail: [akowalska@tu.kielce.pl](mailto:akowalska@tu.kielce.pl)

The selection of appropriate fibers is therefore crucial for the final performance of the mixture. The application of dispersed fiber reinforcement contributes to the improvement of several key properties of mineral-asphalt mixtures. Fiber-reinforced mixtures exhibit increased resistance to permanent deformation and enhanced fatigue durability (Jaskuła et al., 2017; Mahrez et al., 2003). These properties make such mixtures suitable for use in road pavements subjected to traffic loads ranging from light to very heavy. Furthermore, mineral-asphalt mixtures modified with fibers are particularly suitable for applications in areas exposed to extreme traffic loading, such as bus bays, parking areas, maneuvering yards, internal roads, pavement sections within intersections, and additional climbing lanes.

The subject of this paper is the evaluation of the influence of dispersed fiber reinforcement (polymer-basalt and aramid fibers), the type of asphalt binder used, and the applied production technology on the high-temperature performance of mineral-asphalt mixtures. The fibers selected for the study contribute to an increase in the stiffness of asphalt mixtures at high service temperatures, thereby improving resistance to rutting, while not causing excessive stiffening of these mixtures at low temperatures (Alnadish & Aman, 2019; Krayushkina et al., 2016; Wu et al., 2007; Zhang, 2022; Zheng et al., 2014). The assessment of the impact of fiber type and content on the properties of mineral-asphalt mixtures was conducted using asphalt concrete mixtures designed for the wearing course, with a maximum aggregate size of 11 mm (AC 11S). The experimental program began with the selection of three distinct asphalt binders: a conventional paving-grade bitumen 50/70, a polymer-modified bitumen 45/80-55, and a highly polymer-modified bitumen 45/80-80. This deliberate choice of binders enabled a systematic evaluation of whether the incorporation of dispersed reinforcement enhances mixture performance irrespective of the base binder's rheological character (conventional vs. modified). The mixtures were produced using two technologies: conventional Hot-Mix Asphalt (HMA) and Warm-Mix Asphalt (WMA) with water-foamed bitumen. In the WMA process, compaction was performed at temperatures reduced by 30 °C compared to the corresponding HMA mixture, allowing assessment of the combined effects of lower production temperatures and fiber addition on high service temperatures (resistance to permanent deformation, creep static modulus).

## 2. Tested materials and methodology

### 2.1. Experimental program

The objective of the study was to determine the effect of the composition of AC 11 mineral-asphalt mixtures intended for the wearing course of road pavements, incorporating dispersed fiber reinforcement and produced

using Warm-Mix Asphalt (WMA) technology with water-foamed bitumen, on their performance, with particular emphasis on high-temperature properties.

The research involved a comparison of the properties of WMA mixtures with those of a reference mixture produced using conventional Hot-Mix Asphalt (HMA) technology. The influence of the type and content of fibers, as well as the type of asphalt binder used-which, as previously mentioned, significantly affects the high-temperature performance of mineral-asphalt mixture was analyzed. Mineral-synthetic and synthetic fibers with a length of 12 mm were applied as dispersed reinforcement (Figure 1, Table 1), while road bitumen and polymer-modified bitumens were used as binders in the study. The following factors were analyzed:

- *type and amount of fibers:*
  - polymer-basalt PB: 0.15%, 0.3%, 0.6%,
  - aramid AR: 0.05%, 0.1%, 0.2%,
- *type of bitumen:*
  - road bitumen RB: 50/70,
  - polymer modified bitumen PMB: 45/80-55,
  - highly modified bitumen HMB: 45/80-80.

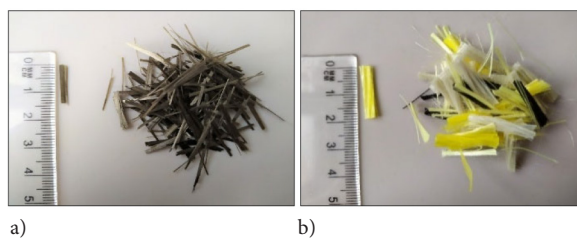


Figure 1. Investigated fiber reinforcement: a) polymer-basalt fibers; b) aramid fibers

Table 1. Fiber parameters (Fiore et al., 2015; Zych, 2010)

Parameter	Polymer-basalt fibers	Aramid fibers
Density (Mg/m <sup>3</sup> )	2.6	1.4
Diameter (mm)	0.01–0.02	0.008–0.012
Tensile strength (MPa)	2800	3000

The aramid fibers shown in Figure 1b belong to the group of polymeric materials derived from aromatic polyamides (Derkowski & Zych, 2004). Asphalt mixtures incorporating aramid fibers were first developed in 1982 as additives aimed at improving the fatigue durability of asphalt concrete (Forta Asphalt Fiber, n.d.). Aramid fibers are often blended with polyolefin fibers or coated with wax to ensure proper dispersion within mineral-asphalt mixtures (Nazzal et al., 2021). In contrast, polymer-coated basalt fibers (Figure 1a) combine the inherent strength of basalt rock with the flexibility and durability of polymers. Basalt fibers are considered a “green” alternative to glass and carbon fibers due to their high ecological compatibility, recyclability, significantly lower energy consumption, and lower cost (Duan et al., 2025).

A comparative analysis was performed with respect to reference mixtures without fiber addition, produced using both WMA technology and conventional HMA technology. The production processes of HMA and WMA mixtures were similar, with the only differences resulting from the applied temperatures and the form of the asphalt binder: foamed ( $f$ ) for WMA and non-foamed ( $n-f$ ) for HMA. The compaction process of the specimens differed depending on the production technology and the type of asphalt binder used, particularly with respect to temperature. Hot-mix asphalt mixtures produced with 50/70 road bitumen were compacted at a temperature of 135 °C, whereas mixtures incorporating PMB and HMB binders were compacted at 145 °C. In the case of WMA technology, these temperatures were reduced by 30 °C (WMA<sub>30</sub>).

## 2.2. Methodology

The following parameters were determined according to the Technical Guidelines (General Directorate for National Roads and Motorways [GDNRM], 2014), and the EN 13108-1 standard (European Committee for Standardization [ECS], 2016a) for the analysis of the factors of AC 11:

- air void content ( $V_a$ , %) to EN 12697-8 (ECS, 2018a)
- moisture resistance with one freezing cycle according to Testing Instruction attached as Schedule 1 to TG-2 and according to EN 12697-12 (ECS, 2018b), on the basis of the assessment of the indirect tensile strength for a set of wet specimens ( $ITS_w$ , kPa) and a set of dry specimens ( $ITS_d$ , kPa) and the indirect tensile strength ratio ( $ITSR = ITS_w/ITS_d \cdot 100$ , %),
- resistance to permanent deformation according to EN 12697-22 (ECS, 2020), based on the assessment of the wheel-tracking slope ( $WTS_{AIR}$ , mm/1000 cycles) and the proportional rut depth after 10,000 test cycles ( $PR-D_{AIR}$ , %),
- resistance to permanent deformation according to EN 12697-22 (ECS, 2020), based on the assessment of the rutting rate ( $WTS_{air}$ , mm/1000 cycles) and the proportional rut depth after 10,000 test cycles ( $PR-D_{air}$ , %),
- creep static modulus, CSM (MPa) at +40 °C according to EN 12697-25 (ECS, 2016b) method A and Road and Bridge Research Institute, 1995).

The static creep modulus test was performed using the uniaxial compression method (Figure 2). The test involves applying an axial static load to the specimen with a magnitude of  $100 \pm 2$  kPa. After the loading phase, the specimen is unloaded over a period of 10 minutes, and the relaxation of the mixture is recorded.

Depending on the type of test, the specimens were compacted using different methods: impact compaction (for air void content and moisture resistance tests), static compaction with a plate compactor (for rutting tests), and rotational compaction using a gyratory compactor (for creep testing).

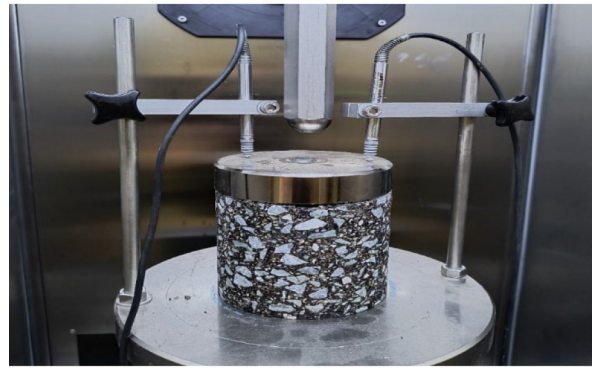


Figure 2. Specimen during the static creep modulus test

## 2.3. Materials and mix design procedure

The mixture design was based on the national requirements TG-2 for AC 11 mixtures intended for wearing courses subjected to traffic loads above KR5 (design pavement life of 20 years  $> 7.30 \times 10^6$  ESALs in accordance with the Polish standard (Judycki et al., 2014)). The composition and grading of the designed asphalt concrete mixture are shown in Figure 3 and summarized in Table 2.

Mineral-asphalt mixtures were produced using aggregates from two types of rock: limestone and gabbro. The filler and fine aggregates (0/2 mm and 0/4 mm) were limestone, whereas the remaining coarse aggregates were sourced from gabbro rock.

To ensure uniform distribution of the fibers within the asphalt mixture, the mineral components and asphalt binder were preheated in an oven to the required temperature (depending on the applied technology: HMA or WMA<sub>30</sub>). The fibers were dosed using the dry mixing method - directly into the hot aggregate prior to the addition of the asphalt binder. This sequence enables mechanical separation and even dispersion of the fibers by the aggregate grains during the initial mixing stage.

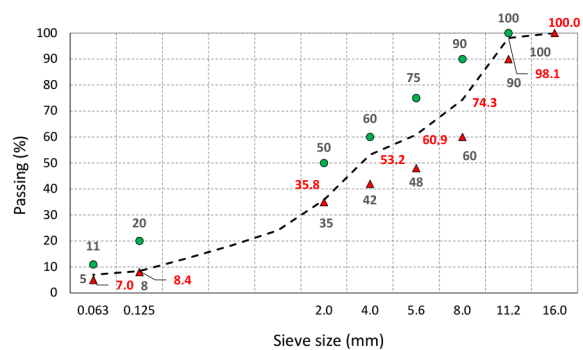


Figure 3. Composition and grading of AC 11 mixture with marked limiting points

During the asphalt concrete mixture design stage, basic properties of the asphalt binders were determined (Table 3) to confirm their suitability for producing AC 11 mixtures intended for wearing courses. The tests

included penetration at 25 °C according to EN 1426 (ECS, 2015a), softening point according to EN 1427 (ECS, 2015b), Fraass breaking point according to EN 12593 (ECS, 2015c), and elastic recovery for PMB and HMB according to EN 13398 (ECS, 2017). All tested asphalt binders met the requirements of EN 12591 (ECS, 2009) and PN-EN 14023:2011/Ap2:2020-02 (Polski Komitet Normalizacyjny, 2011).

Table 2. Composition of asphalt concrete mixtures

Materials	Mineral mixture (% m/m)	Bituminous mixture (% m/m)
Filler	5.0	4.7
Crushed fine continuously graded aggregate 0/2 mm	19.0	18.0
Crushed fine continuously graded aggregate 0/4 mm	18.0	17.0
Coarse aggregate 2/5 mm	17.0	16.1
Coarse aggregate 4/8 mm	15.0	14.2
Coarse aggregate 8/11 mm	26.0	24.6
Bitumen: 50/70, 45/80-55, 45/80-80	–	5.4
Wetfix BE, adhesive agent	–	0.3% by bitumen mass

Table 3. Basic properties (mean  $\pm$ 95% confidence intervals) of the asphalt binders used in the study along with the requirements (Reqs)

Type of bitumen	Pen (0.1 mm)	$T_{R\&B}$ (°C)	$T_{Fraass}$ (°C)	ER (%) <sup>*</sup>
50/70 <sub>n-f</sub>	65 $\pm$ 1.19	48.8 $\pm$ 0.25	-13 $\pm$ 0.43	–
50/70 <sub>f</sub>	66 $\pm$ 1.45	46.3 $\pm$ 0.72	-11 $\pm$ 0.83	–
Reqs	50–70	46–54	$\leq -8$	–
45/80–55 <sub>n-f</sub>	70 $\pm$ 1.36	58.3 $\pm$ 0.32	-17 $\pm$ 0.83	75 $\pm$ 0.50 (83 $\pm$ 0.74)
45/80–55 <sub>f</sub>	65 $\pm$ 1.47	56.2 $\pm$ 0.62	-17 $\pm$ 0.83	84 $\pm$ 0.43 (82 $\pm$ 0.43)
Reqs	45–80	$\geq 55$	$\leq -15$	$\geq 50$
45/80–80 <sub>n-f</sub>	72 $\pm$ 1.04	95.2 $\pm$ 0.53	-23 $\pm$ 0.83	98 $\pm$ 0.50 (95 $\pm$ 0.25)
45/80–80 <sub>f</sub>	71 $\pm$ 1.6	92.2 $\pm$ 0.61	-22 $\pm$ 0.71	97 $\pm$ 0.43 (91 $\pm$ 0.43)
Reqs	45–80	$\geq 80$	$\leq -18$	$\geq 60$

Note: \* Values in parentheses correspond to the asphalt binders after RTFOT aging.

For the WMA mixtures, all binders were foamed with the addition of water, with the optimal content determined based on measurements of the basic physical properties of the foam – maximum expansion ( $ER_m$ ) and half-life ( $T_{1/2}$ ) and taking into account the binder temperature. For 50/70 road bitumen, the foaming temperature ( $T$ ) was set at 140 °C, while for PMB and HMB

it was 150 °C and 155 °C, respectively. The Foaming Water Content ( $FWC$ ) was 1.5% for RB and PMB and 3.0% for HMB. Under these conditions ( $T$ ,  $FWC$ ), the asphalt foam exhibited the most favorable characteristics, including the highest expansion rates and the longest half-life durations.

### 3. Results and discussion

#### 3.1. Physical and mechanical parameters

The air void content ( $V_a$ ) in the Marshall-compacted specimens was the first parameter analyzed. The average values, together with the 95% confidence intervals ( $CI$ ), are presented in Table 4 (*mixtures failing to meet the specified criteria are highlighted in red*).

The lowest air void contents were observed in the reference HMA mixtures. A reduction in the production temperature by 30 °C resulted in poorer compaction of the specimens, as indicated by an increase in  $V_a$ . Furthermore, the addition of fibers and increasing their content – both polymer-basalt and aramid – led to higher air void contents in the tested mixtures.

Table 4. Results of air void content of asphalt concrete mixtures

Type of technology	Type of bitumen	Type of fibers	Fiber content (%)	Mean values $\pm$ 95% CI
Air void content $V_a$ (%)				
HMA	50/70	REF	0	2.27 $\pm$ 0.133
HMA	45/80-55	REF	0	2.75 $\pm$ 0.157
HMA	45/80-80	REF	0	2.91 $\pm$ 0.133
WMA_30	50/70	REF	0	2.90 $\pm$ 0.236
WMA_30	45/80-55	REF	0	3.19 $\pm$ 0.383
WMA_30	45/80-80	REF	0	3.41 $\pm$ 0.176
WMA_30	50/70	AR	0.05	2.94 $\pm$ 0.258
WMA_30	45/80-55	AR	0.05	3.41 $\pm$ 0.268
WMA_30	45/80-80	AR	0.05	3.43 $\pm$ 0.207
WMA_30	50/70	AR	0.1	3.03 $\pm$ 0.124
WMA_30	45/80-55	AR	0.1	3.37 $\pm$ 0.310
WMA_30	45/80-80	AR	0.1	3.71 $\pm$ 0.190
WMA_30	50/70	AR	0.2	3.48 $\pm$ 0.195
WMA_30	45/80-55	AR	0.2	3.96 $\pm$ 0.184
WMA_30	45/80-80	AR	0.2	4.30 $\pm$ 0.350
WMA_30	50/70	PB	0.15	3.17 $\pm$ 0.268
WMA_30	45/80-55	PB	0.15	3.46 $\pm$ 0.343
WMA_30	45/80-80	PB	0.15	3.61 $\pm$ 0.205
WMA_30	50/70	PB	0.3	3.41 $\pm$ 0.252
WMA_30	45/80-55	PB	0.3	3.60 $\pm$ 0.173
WMA_30	45/80-80	PB	0.3	3.88 $\pm$ 0.107
WMA_30	50/70	PB	0.6	4.13 $\pm$ 0.184
WMA_30	45/80-55	PB	0.6	4.78 $\pm$ 0.333
WMA_30	45/80-80	PB	0.6	5.33 $\pm$ 0.297

Among all the analyzed mixtures, only the WMA\_30 mixture with HMB binder and 0.2% AR fibers did not meet the target range (2–3% according to GDNRM, 2014), exceeding the maximum allowable air void content of 3.0%. At the upper limit of the required  $V_a$  range was also the WMA\_30 mixture with the same fiber content but 45/80-55 binder. Moreover, none of the mixtures containing the maximum polymer-basalt fiber content (0.6%) met the requirement, regardless of the binder type used. In all cases, increasing fiber content and reducing the production temperature led to higher air void contents. Specimens produced with polymer-modified binders exhibited noticeably higher values of this parameter.

The next parameter analyzed was the resistance of asphalt concrete mixtures to water and frost (Table 5, Figure 4), with respect to the production technology as well as the type and content of fibers.

With regard to the water and frost resistance tests and the results of the indirect tensile strength measurements, it was observed that the reference mixtures produced using conventional HMA technology exhibited the highest  $ITS_d$  values and  $ITSR$  indices, regardless of the type of asphalt binder used. In all analyzed cases, a reduction in the production temperature of the asphalt mixtures resulted in a decrease in both parameters.

Table 5. Results of indirect tensile strength of AC 11 mixtures

Type of technology	Type of bitumen	Type of fibers	Fiber content (%)	Mean values ± 95% CI
Indirect Tensile Strength $ITS_d$ (kPa)				
HMA	50/70	REF	0	738.89±45.86
HMA	45/80-55	REF	0	794.26±23.77
HMA	45/80-80	REF	0	829.03±25.87
WMA_30	50/70	REF	0	610.96±42.83
WMA_30	45/80-55	REF	0	665.71±40.29
WMA_30	45/80-80	REF	0	679.29±39.34
WMA_30	50/70	AR	0.05	592.39±42.92
WMA_30	45/80-55	AR	0.05	697.04±48.25
WMA_30	45/80-80	AR	0.05	695.37±45.82
WMA_30	50/70	AR	0.1	604.65±30.70
WMA_30	45/80-55	AR	0.1	745.59±30.90
WMA_30	45/80-80	AR	0.1	870.60±33.07
WMA_30	50/70	AR	0.2	583.42±27.29
WMA_30	45/80-55	AR	0.2	725.57±26.13
WMA_30	45/80-80	AR	0.2	824.36±43.85
WMA_30	50/70	PB	0.15	644.42±39.27
WMA_30	45/80-55	PB	0.15	773.73±32.59
WMA_30	45/80-80	PB	0.15	655.60±43.74
WMA_30	50/70	PB	0.3	662.80±41.09
WMA_30	45/80-55	PB	0.3	832.37±26.46
WMA_30	45/80-80	PB	0.3	739.27±47.53
WMA_30	50/70	PB	0.6	590.06±43.56
WMA_30	45/80-55	PB	0.6	768.65±46.65
WMA_30	45/80-80	PB	0.6	660.54±50.14

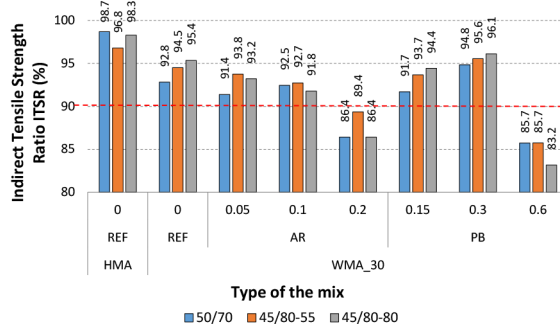


Figure 4. Results of indirect tensile strength ratio  $ITSR$  of AC 11 mixture

It should be noted that not all mixtures met the criterion for water and frost resistance. WMA\_30 mixtures containing the highest fiber contents, regardless of fiber type (AR: 0.2%, PB: 0.6%) and independently of the asphalt binder used, did not satisfy the  $ITSR > 90\%$  requirement (GDNRM, 2014). This outcome was likely influenced by the reduced workability and compactability of these mixtures due to the simultaneous application of lower production and compaction temperatures, combined with the increased fiber content.

Mixtures with lower fiber concentrations (AR: 0.05%, 0.1%; PB: 0.15%) achieved  $ITSR$  values comparable to the WMA\_30 reference mixture. Among the mixtures produced at temperatures 30 °C lower than conventional HMA, the highest water resistance indices were obtained for mixtures containing 0.3% polymer-basalt fibers. The use of polymer-modified and highly modified binders generally improved both of the analyzed parameters in most cases.

### 3.2. High-temperature performance parameters

#### 3.2.1. Rutting resistance

The rutting resistance of asphalt mixtures is assessed based on the rut formed in a rectangular specimen due to cyclic loading by a wheel under a specified temperature. The test was conducted using the air method (Procedure B) in a small-scale wheel tracking device. The standard testing temperature in Poland is 60 °C.

The results of the permanent deformation resistance measurements are expressed as the rut depth, the proportional rut depth ( $PRD$ ) (Figure 5), and the rutting rate (Figure 6). Error bars indicate the 95% confidence interval.

All WMA\_30 mixtures with dispersed fiber reinforcement exhibited a slight increase in proportional rut depth ( $PRD$ ), indicating a deterioration of this parameter, regardless of the fiber type, fiber content, or the type of asphalt binder used. Similar to the results observed for water and frost resistance, mixtures containing the highest amounts of PB and AR fibers showed the highest  $PRD$  values and did not meet the target requirement ( $PRD_{air} \leq 7.0$  according to GDNRM, 2014). This

outcome was likely influenced by reduced workability and compactability of the asphalt mixtures due to the combined effect of excessive dispersed fiber content and lowered production temperatures.

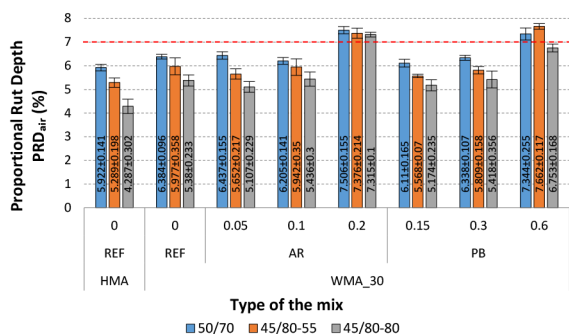


Figure 5. Results of proportional rut depth of AC 11 mixture

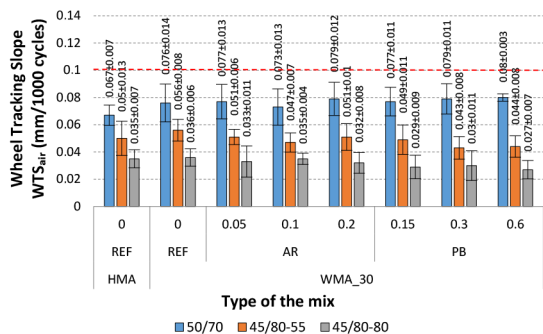


Figure 6. Results of wheel tracking slope of AC 11 mixture

Analysis of the rutting rate ( $WTS_{air}$ ) showed that the addition of dispersed fibers, regardless of type, binder, or production technology (HMA or WMA<sub>30</sub>), did not significantly affect this parameter. The lowest  $WTS_{air}$  values were observed in mixtures produced with highly modified 45/80-80 binder, independent of production technology or fiber type and content. All analyzed mixtures met the specified criterion ( $\leq 0.10$  according to GDNRM, 2014).

### 3.2.2. Creep static modulus

The analysis of the results for the above parameters ( $V_a$ ,  $ITSR$ ,  $PRD_{air}$ ,  $WTS_{air}$ ) allowed the scope of further testing to be limited, excluding mixtures with the highest fiber contents (PB 0.6% and AR 0.2%), as they did not meet the performance requirements for an AC 11 asphalt concrete mixture intended for a wearing course under heavy traffic (TG-2). Mixtures produced with increased fiber content in any technology exceeded the allowable air void content, which was associated with higher susceptibility to rutting and insufficient water and frost resistance.

The static creep modulus tests enabled a precise assessment of the influence of the asphalt binder type, the type and content of dispersed fiber reinforcement, and

the effect of reducing production and compaction temperatures by 30 °C compared to conventional technology on high-temperature properties.

Figure 7 presents the results of the creep modulus tests for asphalt concrete mixtures in terms of production technology (HMA, WMA<sub>30</sub>) and fiber type and content (PB, AR). Subsequent figures show the time-dependent strain under a compressive stress of 0.1 MPa (creep curves) for mixtures grouped according to the asphalt binder used: RB (Figure 8), PMB (Figure 9), and HMB (Figure 10). Error bars represent the 95% confidence interval.

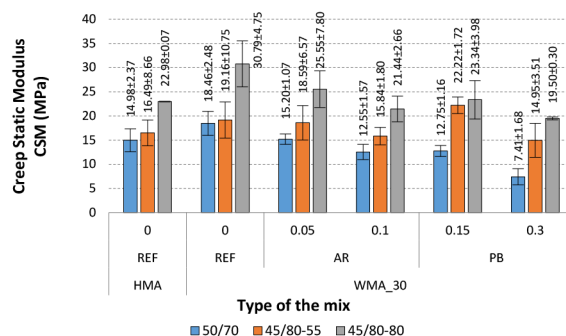


Figure 7. Results of creep static modulus of AC 11 mixture

Analysis of the static creep modulus values showed an increase with the change in asphalt binder type, from road bitumen to polymer-modified bitumen 45/80-55 and then to highly modified bitumen 45/80-80, in most cases regardless of the production technology or fiber content. The highest values were consistently observed for mixtures containing the highly modified binder. An increase in fiber content, regardless of fiber type, resulted in a decrease in the analyzed property.

Comparing the reference mixtures (HMA vs. WMA<sub>30</sub>), an increase in the creep modulus was noted for all binder types in mixtures produced and compacted at a temperature reduced by 30 °C.

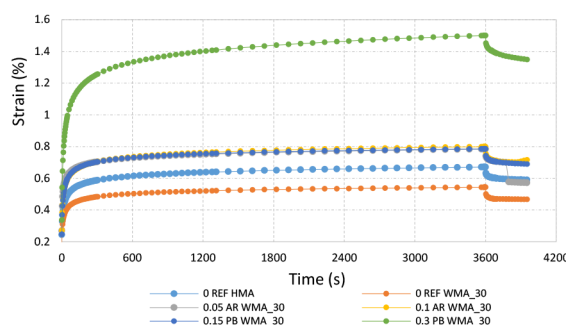


Figure 8. Creep curves of asphalt concrete mixtures with 50/70 road bitumen

The creep curves confirm that the highest stiffness (lowest deformation – highest creep modulus) was observed for the reference mixtures (without fibers) produced using the low-emission WMA<sub>30</sub> technology,

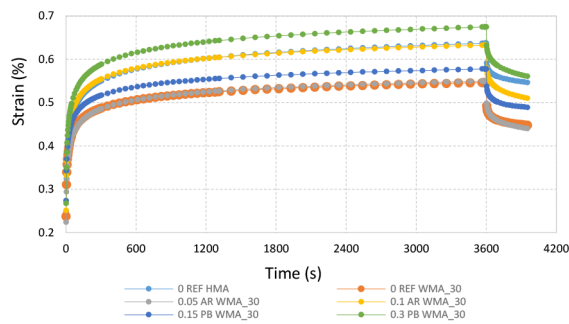


Figure 9. Creep curves of asphalt concrete mixtures with 45/80-55 polymer modified bitumen

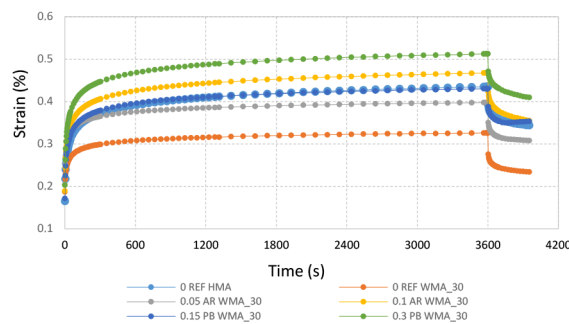


Figure 10. Creep curves of asphalt concrete mixtures with 45/80-80 highly modified bitumen

regardless of the asphalt binder type. In contrast, the highest susceptibility to deformation (largest strains and lowest creep moduli) was recorded for the WMA<sub>30</sub> + 0.3% PB mixtures. Evaluating the effect of fiber type, it can be stated that, in most cases, mixtures with aramid fibers exhibited more favorable high-temperature properties.

#### 4. Conclusions

Based on the results of the tests on asphalt concrete mixtures containing dispersed fiber reinforcement, produced using conventional HMA technology and WMA<sub>30</sub> technology (with foamed bitumen at a reduced temperature of 30 °C), and considering fiber type and content as well as the type of asphalt binder (paving-grade bitumen and polymer-modified bitumens 45/80-55 and 45/80-80), the beneficial effects of polymer-basalt and aramid fibers in WMA<sub>30</sub> technology were confirmed.

The most pronounced influence of dispersed fiber reinforcement was observed mainly in mixtures with polymer-modified binders, whereas mixtures with paving-grade bitumen 50/70 showed reduced performance compared to the reference HMA mixture. This stronger reinforcing effect in polymer-modified binders is likely due to their higher viscosity and greater elasticity, which improve fiber-bitumen adhesion, enhance stress distribution along the fibers, and create a more cohesive and resilient matrix within the mixture. Among the mixtures

produced at reduced temperatures, the greatest improvements in high-temperature properties – specifically resistance to permanent deformation (lower wheel-tracking slope  $WTS_{air}$  and higher creep modulus – were achieved in mixtures reinforced with aramid fibers at a dosage of 0.05% (AR 0.05%) and polymer-basalt fibers at 0.15% (PB 0.15%). These improvements were in the range, for both optimum concentration fibers, of 6–17% lower rut depth ( $WTS_{air}$ ) values (for WMA<sub>30</sub> with HMB) and 13–35% (for WMA<sub>30</sub> with PMB and HMB) higher creep modulus compared to the unreinforced HMA reference mixtures. These findings confirm the positive reinforcing effect of the selected fibers on high-temperature performance characteristics in WMA<sub>30</sub> technology, particularly in terms of enhanced resistance to rutting and better resistance to creep deformation under repeated loading.

In summary, the greatest positive effect of dispersed reinforcement was achieved at the lowest tested fiber dosages (0.05% AR and 0.15% PB). This allowed for maintaining an appropriate air void content (below 3.0%) while simultaneously maximizing stiffness and resistance to deformation.

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