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Effect of polymer fibres reinforcement on selected properties of asphalt mixtures

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Abstract

The paper presents selected results of the research program concerning fibre reinforced asphalt concrete. Aramid-polyalphaolefin fibres was used in this study. Selected properties responsible for low temperature cracking and resistance to permanent deformation are presented in this paper. Low temperature cracking susceptibility was evaluated with the results obtained from bending test of rectangular beams with constant rate of deformation and semi-circular bending test based on fracture mechanics theory. Performance in high temperatures was assessed by master curves of dynamic modulus. Obtained results indicated that evaluated fibres can improve low temperature pavement performance.

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Keywords: fibres reinformcement; asphalt mixture; low-temperature cracking; dynamic modulus, SPT, fracture mechanics; SCB test.

1. Introduction

In recent years, different ways of improving asphalt pavements performance are gaining more and more popularity. One of such technologies is using fibres as a reinforcement in asphalt mixtures, which derives from cement concrete fibre reinforcement. Various types of fibres are known to be used in this application. These include both synthetic (glass, carbon, polymer) and natural (hemp, coir, jute, sisal, flax) fibres [1]. Main function of fibres incorporated into asphalt mixture is to increase tensile strength which can result in higher strain energy responsible for fracture characteristics [2]. As a result, asphalt mixtures with fibres addition tend to be more resistant to

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permanent deformation and have higher tensile strength [3] what is important for resistance to low temperature cracking.

It should be noted that the idea of using fibres in asphalt mixtures is not a new concept. In 1984 Button and Hunter [4] published a report concerning usage of synthetic fibres in asphalt mixtures. Ten different fibres types (both synthetic and organic) were tested in terms of Hveem and Marshall stability, resilient modulus, indirect tension, fatigue, creep and resistance to moisture damage. Field trials and observations were also conducted. In general, slight overall improvement was noticed (e.g. susceptibility to moisture damage) but some positive effects were attributed to higher binder content of mixtures with fibre additions. Clear potential in extending fatigue life and reducing crack propagation (partly confirmed by field trials) was also observed, but the cost effectiveness of evaluated technologies was considered as questionable. Since then a number of other experiments with using fibres in asphalt mixtures were carried out [3,5,6].

Recently, a composition of aramid-polyalphaolefin fibres has gained significant attention. It was originally developed in 1982 [7] as an additive to extend fatigue life of asphalt pavement. Present version of polymer fibres tested in this research was introduced in 2008 and since then was a subject of a several research programs.

An extensive testing of aramid-polyalphaolefin fibres was done by Kaloush et al. [8]. Subjected fibres were evaluated in terms of their influence on triaxial shear strength, resistance to permanent deformation measured by the results of dynamic creep test, dynamic modulus, fatigue life, thermal cracking and crack propagation. Two different fibres contents were tested – 0.45 kg and 0.9 kg per ton of asphalt mixture. In overall, mixtures with the addition of fibres showed better characteristics than reference mixtures, but fibre content was also a factor that affected final results. For dynamic modulus test, mixture with 0.45 kg fibre content presented higher moduli than reference mixture while adding 0.9 kg fibre content resulted in worse (i.e. lower modulus) characteristics. Flexural strength was also affected by fibres content in the same manner and it can be concluded that for certain properties there is an optimum fibre content after which adding more fibres can lead to unsatisfactory results. Kaloush also concluded that better performance of asphalt mixtures with discussed fibres can be also incorporated in pavement design process and pavement overall thickness can be reduced by using fibres [9,10]. Stempihar et al. [11] described the use of aramid fibres in open graded asphalt mixtures used for airfields pavements. According to his findings fibre-reinforced asphalt concrete improves dynamic modulus especially at higher temperatures and although the initial cost of the mixture is slightly higher than traditional mix, in overall this extra cost can be overcome by a minimal increase of pavement service life [11].

2. Experimental details

2.1. Methodology

The objective of the experiment was to determine the influence of polymer fibres addition on the selected properties of asphalt mixtures for wearing and binder course. The research program was defined to identify eventual differences between asphalt mixtures with and without reinforcing fibres. It included evaluation of parameters responsible for pavement behaviour in low temperatures and high temperatures.

2.2. Materials

Three different asphalt mixtures were tested, all based on Polish requirements described in document WT:2-2014 [12] according to PN-EN 13108-1 [13]: asphalt concrete for wearing course AC 11 S obtained by mixing granite and limestone aggregate with 5.6% (by weight) of neat bitumen 50/70 for medium traffic load category, asphalt concrete for binder course AC 16 W obtained by mixing granite aggregate with 4.6% (by weight) of neat bitumen 35/50 and polymer modified bitumen PmB 25/55-60 for medium and heavy traffic load category. Due to the character of the research, it was decided not to implement anti-striping agent in composition of used asphalt concretes, in order to avoid any possible influence of its presence on test results. Volumetric properties, water sensitivity according to the standard PN-EN 12697-12 [14] and Appendix 1 of the document WT-2 2014 [12] and rutting resistance according to the standard PN-EN 12697-22 [15] of used asphalt mixtures are presented in Table 1, both for reference mixtures and for mixtures with fibres.

Table 1. Properties of asphalt mixtures used in the research.

Parameter	AC11S 50/70	AC11S 50/70 FF	AC 16 W 35/50	AC 16 W 35/50 FF	AC 16 W PmB 25/55-60	AC 16 W PmB 25/55-60 FF
Binder content, %	5.6	5.6	4.6	4.6	4.6	4.6
Fibres content, by weight of asphalt mixture, %	0.0	0.05	0.0	0.05	0.0	0.05
Air voids in Marshall specimens [%]	2.6	2.8	5.5	6.2	6.8	7.0
Voids fill with bitumen VFB [%]	83.4	82.8	65.8	62.6	60.5	59.7
Voids in the mineral aggregate VMA [%]	15.9	16.0	16.0	16.7	17.1	17.3
Water sensitivity, ITSR [%]	91	100	64	71	90	88
Rutting resistance, method B in air, 60 °C, 10 000 cycles						
WTS_{AIR}, [mm/1000 cycles]	13.6	12.1	4.3	4.5	3.3	2.9
PRD_{AIR}, [%]	0.23	0.20	0.05	0.07	0.03	0.04

The additive product was a mix of aramid-polyalphaolefin fibres, which are designed for use as reinforcement in asphalt mixtures for pavement structures. The type of fibres used in this research is recommended for typical hot asphalt mixtures (there are also variants intended for warm and cold asphalt mixtures), which temperature of production and compaction is within the range of 121°C to 190°C. The length of the fibres is 19 mm (see Fig. 1a).

In accordance with recommendations of the manufaturer, fibres were added to hot aggregate with a dosage rate of 0.05% by weight of asphalt mixture (0.5 kg of fibres for 1000 kg of asphalt mixture) before adding bitumen.

Fig. 1. a) Loose fibres, b) Fibres in laboratory mixed asphalt concrete, c) Fibres in plant mixed asphalt concrete, (all photos by Ł.Mejłun).

2.3. Sample preparation

Asphalt mixtures for tests were prepared in laboratory mixer in accordance with standard PN-EN 12697-35 [25]. Before compaction asphalt mixtures were conditioned to simulate the process of short-time aging in accordance with the procedure given in the Appendix 2 of the WT-2:2014 guidelines [12]. The conditioning process consisted of sujecting the loose material to the temperature of 135°C for two hours and then for one hour at the temperature of compaction.

Four different methods of compaction were used: specimens fabricated at the design stage of asphalt mixtures to verify volumetric properties were compacted with the use of Marshall hammer according to standard PN-EN 12697-30 [26]. Specimens for assessment of resistance to low temperature cracking by fracture toughness were compacted with the use of gyratory compactor according to standard to PN-EN 12697-31 [27]. Parameters of the compaction process in gyratory compactor were set to obtain target density in the range of 98-100% of Marshall density. Specimens for assessment of resistance to low temperature cracking by bending test with constant rate of deformation (Judycki method) were compacted with the use of roller compactor according to standard PN-EN

12697-33 [28]. Parameters of the compaction process were also set to obtain target density of 98-100% of Marshall density.

The compaction temperature for asphalt mixtures prepared with bitumen 35/50 and 50/70 was 135°C ± 5°C, whereas for asphalt mixtures with modified bitumen it was 145°C ± 5°C.

No difficulties in mixing or compacting of asphalt mixtures with fibres were observed. Also there was no need to prolong the process of mixing due to added fibres. It could be observed that for each type of asphalt concrete reinforcing fibres caused less mixture segregation and better coating of coarse aggregate particles by mastic. It should be noted that in the close-up, the appearance of the mixtures produced in field conditions (in asphalt plant) which were tested previously was different than the appearance of the mixture mixed in laboratory mixer. More uniform degree of fibres distribution and their finer presence was observed in plant mixtures, while fibres in laboratory produced mixtures were more concentrated (see fig. 1b and 1c).

2.4. Test methods

Resistance to low temperature cracking was assessed by two methods. The first one evaluated results obtained from the bending beam test with constant rate of deformation performed at temperature -20°C according to the method developed by Judycki [16], [17], [18]. In this test, a concentrated load was applied at the midspan of a simply supported beam 50x50x300 mm with constant rate of beam deflection 1.25 mm/min. The bending force and the strain at the bottom of the beam were recorded during the test. The following values were calculated from the test: ε_{ult} – critical strain at break, R_{rz} – bending strength, S – stiffness modulus. There are no official requirements concerning these parameters. In general for asphalt mixtures, (a) higher critical strain at break, (b) higher strength and (c) lower stiffness means better low temperature performance. Lower stiffness limits thermal and traffic induced stresses at low temperatures. Higher strength increases resistance to cracking of asphalt layer.

The second method of evaluating resistance to low temperature cracking was based on fracture mechanics theory. Fracture toughness was evaluated with the use of semi-circular bending test performed according to standard PN-EN 12697-44 [19]. The original test methodology described by standard PN-EN 12697-44 was modified based on literature review [20]–[23]. Method described in standard PN-EN 12697-44 is based only on determining the resistance of asphalt mixtures to fracture K_{IC} which is calculated on the basis of maximum force recorded during bending of the specimen. For further classification of mixtures in terms of fracture properties, an additional value of the J-integral was calculated, which characterizes the critical strain energy release rate.

The semi-circular specimen was subjected to vertical displacement applied monotonically by laboratory press. The specimen was supported by metal frame that allowed to obtain three-point bending load configuration. During the test, load and vertical displacement were continuously recorded. The displacement rate was 1 mm/min. Specimen and loading frame during the test were placed in thermostatic chamber of the press to maintain constant desired test temperature -20°C. Specimens witch three notch depth were tested: 10mm, 20mm and 30mm.

Critical stress intensity factor K_{IC} was calculated on the basis of the value of maximum load recorded at the corresponding vertical displacement. Strain energy to failure U was calculated as the area under the $F(d)$ relationship and from the analysis of the graph that illustrate relationship between strain energy U and notch depth a. After the test, an equation of linear regression in which the slope of the function is the derivative $\mathrm{d}U/\mathrm{d}a$ as a change of strain energy with changing of notch depth was determined from the relationship $U(a)$. Testing procedure was implemented in Poland by Szydłowski and Judycki [30].

The third method to assess the influence of fibres was based on evaluation of dynamic modulus from the Asphalt Mixture Performance Tester/Simple Performance Tester (AMPT/SPT) apparatus according to American guidelines NCHRP 9-29 project [24]. The dynamic modulus test was conducted in order to obtain the characteristics of asphalt mixtures in the form of Master Curves. For each type of mixture, 3 samples for each of 3 testing temperatures were tested in frequency range from 25 Hz to 0,01 Hz. In total, 9 samples were tested for each mixture. Testing methodology was implemented in Poland by Jaczewski and Mejłun [29].

The dynamic modulus test was based on axial haversin loading of cylindrical specimen by vertical force with given frequencies and measuring the deformation by three LVDT transducers mounted on the lateral surface of the specimens. LVDT transducers were spaced every 120°. View of the AMPT/SPT apparatus is shown in Figure 3.

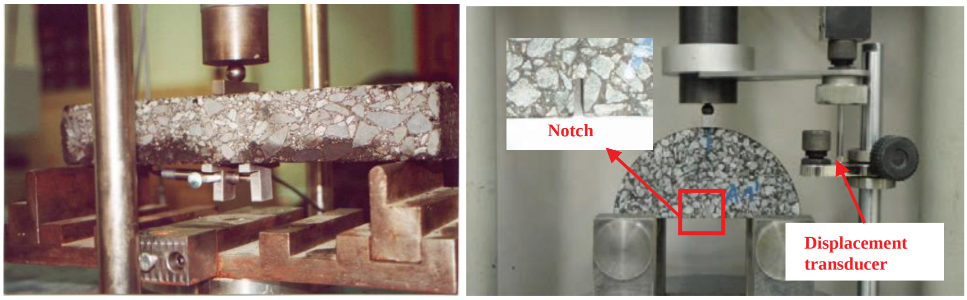

Fig. 2. View of the specimen during a) beam bending and b) semi-circular bending test at low temperatures.

Fig. 3. View of the AMPT/SPT apparatus.

3. Results

3.1. Bending beam test

Test results of resistance to low temperature cracking according to a modified method of bending beam test developed by Judycki are presented in Table 2.

Table 2. Test results of resistance to low temperature cracking, bending beam test at -20°C.

Parameter	AC11S 50/70	AC11S 50/70 FF	AC 16 W 35/50	AC 16 W 35/50 FF	AC 16 W PmB 25/55-60	AC 16 W PmB 25/55-60 FF
Flexural strength R_{rz} [MPa]	8.10	8.36	6.29	6.32	6.51	7.00
Critical strain ε_{ult} [‰]	0.687	0.741	0.471	0.515	0.661	0.710
Modulus of flexural stiffness S [GPa]	12.50	11.54	13.74	12.10	10.02	10.16

3.2. Fracture mechanics parameters

Figure 4 presents relationship $U(a)$ between strain energy and notch depth. Equations of linear regression that were used to calculate the value of the integral J_C are also presented. J-integral was calculated using equation (1).

$$J_C = -\left(\frac{1}{B}\right)\frac{dU}{da} \tag{1}$$

Summary of the test results of fracture parameters are shown in Figure 5.

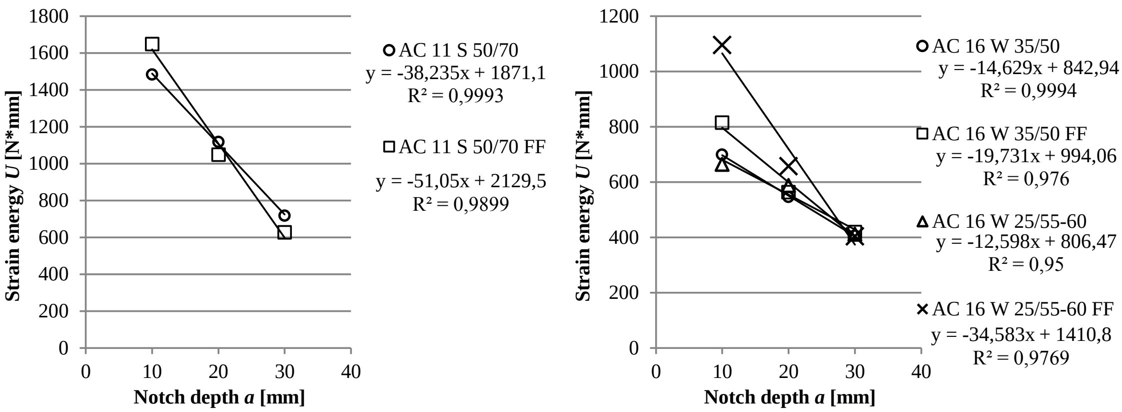

Fig. 4. Relationship $U(a)$ between strain energy and notch depth.

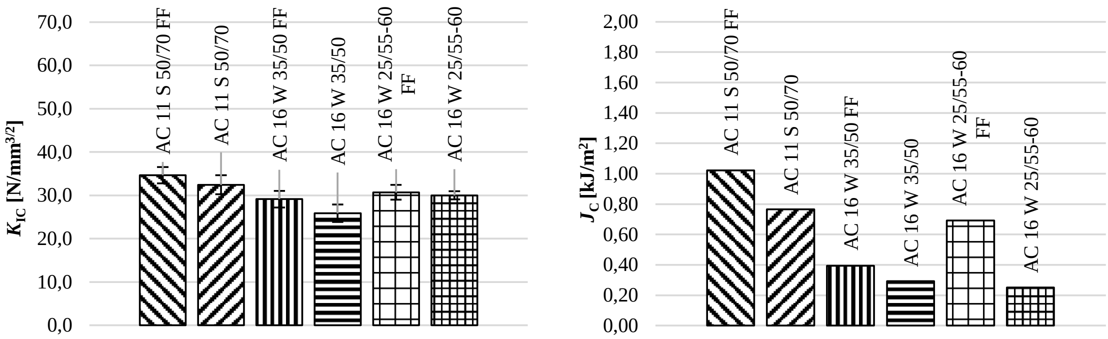

Fig. 5. Fracture toughness K_{IC} (for 10 mm notch depth) and J-integral of investigated asphalt concretes. Error bars present standard deviation.

3.3. Dynamic modulus test

Master Curves of stiffness modulus were developed using modified procedure presented in NCHRP 9-29 PP 02 [24] research report. The used equation (2) assumed that shift factor was calculated using Arrhenius equation.

$$\log\left|E^*\right| = \delta + \frac{(Max - \delta)}{1 + e^{\beta + \gamma\left\{\log f + \frac{\Delta E_a}{19.14714}\left[\frac{1}{T} - \frac{1}{T_R}\right]\right\}}} \tag{2}$$

where: |E*| – dynamic modulus, psi; Max – limiting maximum modulus, psi; f – frequency, Hz; TR – reference temperature, K; T – test temperature, K; δ, β, γ – fitting parameters; ΔEa – activation energy (treated as fitting parameter).

The reference temperature value of +20°C was selected. Master Curves developed for tested mixtures are shown on figure 6.

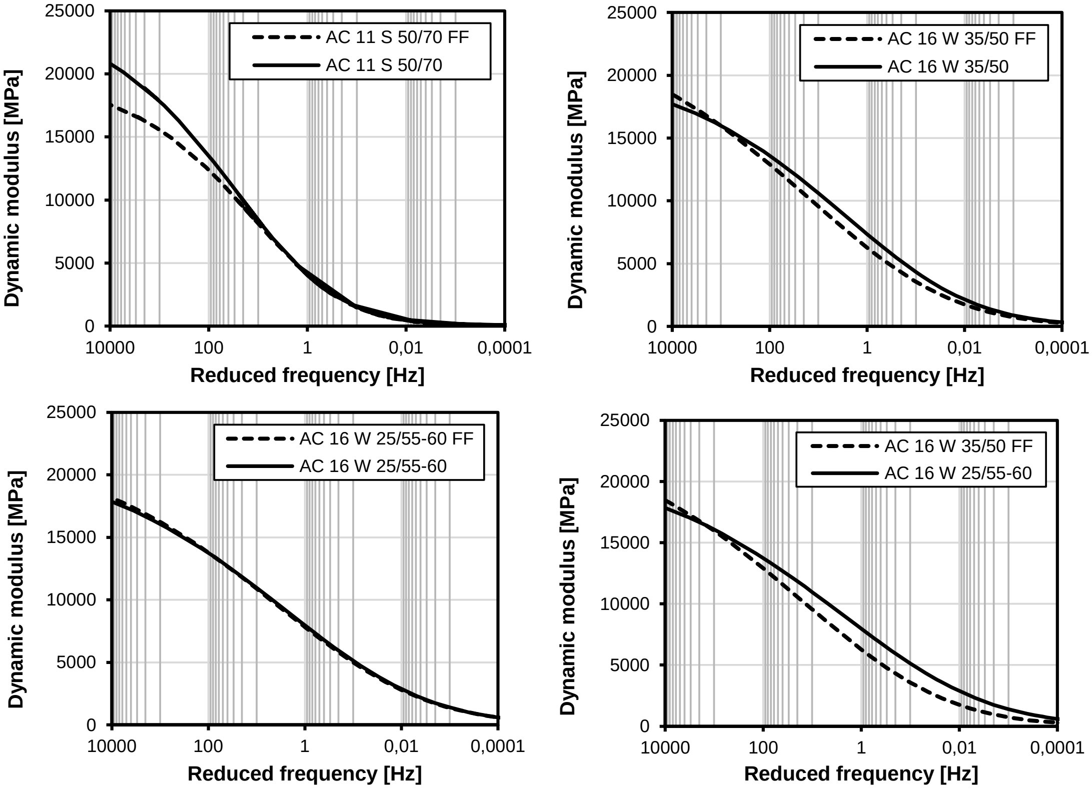

Fig. 6. Master curves of dynamic modulus determined for tested asphalt mixtures, reference temperature T=20°C.

4. Discussion and Conclusions

The addition of polymer (aramid-polyalphaolefin) fibres improved performance characteristics of asphalt concretes such as resistance to low-temperature cracking. In particular, positive effect of fibres was observed in the case of asphalt concretes with neat bitumen and softer bitumen 50/70. Positive effect in asphalt concrete with polymer modified bitumen (PmB) 25/55-60 and harder neat bitumen 35/50 was not so distinctive.

Obtained results indicate that using evaluated fibres in asphalt mixtures can improve their performance, especially in terms of resistance to low temperature cracking. For every tested asphalt concrete, increase of flexural strength, critical strain and reduction of flexural stiffness modulus in -20°C was observed during bending beam test. All tested asphalt concretes with application of fibres had higher fracture energy compared to asphalt concretes without fibres. The same trend was observed in the analysis of the stress intensity factor, but the differences were not so significant.

Study of the dynamic modulus (E*) of asphalt concrete for wearing course with application of fibres confirmed the capability to improve properties at low temperatures. Values of dynamic modulus of this mixture for high reduced frequencies were significantly lower than similar values for reference mixture, without fibres. Dynamic modulus of asphalt concrete for binder course with neat bitumen 35/50 and addition of fibres was in general slightly higher for most frequencies than for reference mixture. For asphalt concrete for binder course with polymer modified bitumen 25/55-60 there was no clear differences between mixtures with and without fibres. Moreover, dynamic modulus of mixtures for binder course with neat bitumen 35/50 and addition of fibres was in general lower than modulus of similar mixture with polymer modified bitumen 25/55-60 without fibres. On the other hand, behaviour of all three asphalt mixtures with fibres in low reduced frequencies was similar to reference samples, thus it can be concluded that their response to permanent deformations in high temperatures will not be improved over the traditional mixtures.

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