GDAŃSK UNIVERSITY OF TECHNOLOGY
FACULTY OF CIVIL AND ENVIRONMENTAL ENGINEERING

EVALUATION OF ASPHALT MIXTURES WITH FORTA FI FIBERS

FINAL REPORT

Ordered by:

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Spis treści

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1. BASIS OF THE WORK

This report was prepared by the Road Construction Division, Faculty of Civil and Environmental Engineering, Gdańsk University of Technology, based on contract no WILiŚ/F/031499/002/2015 signed on 23 June 2015. The contract was ordered by Wegarten Construction Sp. z o.o. for carrying out laboratory tests and analysis of asphalt mixtures with addition of FORTA-FI fibers.

2. OBJECTIVES

The objective of the research is to determine the influence of FORTA FI fibers on selected properties of asphalt mixtures for wearing and binder course of pavement structures. The research program was defined to identify eventual differences between asphalt mixtures with and without reinforcing fibers. The program includes evaluation of parameters responsible for pavement behavior both in low and high temperatures. Additionally, the influence of different methods of fibers application on selected properties of asphalt mixtures was also evaluated.

This report is the final stage of the entire research program and presents final results of laboratory tests and their analysis.

3. SCOPES

Scopes of the work included following laboratory tests and analysis:

1. Assessment of stiffness modulus and indirect tensile strength of asphalt mixtures in the following temperatures: 0°C, +13°C, +25°C; and -20°C, 0°C, +20°C.
2. Assessment of asphalt mixtures sensitivity to water and frost action according to the standard PN-EN 12697-12[1] and procedures included in the document WT-2:2014[2].
3. Assessment of asphalt mixtures resistance to permanent deformations according to the standard PN-EN 12697-22[3], method B conditioning in air.
4. Assessment of asphalt mixtures resistance to low-temperature cracking with two research methods. The first one, developed at Gdańsk University of Technology (GUT) is based on analysis of results obtained during bending rectangular beams of asphalt mixtures with constant speed. The second one based on fracture mechanics theory.

[1] PN-EN 12697-12: 2008 Bituminous mixtures. Test methods for hot mix asphalt. Part 12. Determination of the water sensitivity of bituminous specimens

[2] Asphalt Pavements on National Roads. WT-2:2014 – Part I, Bituminous mixtures. Technical Recommendations.

[3] PN-EN 12697-22:2008 Bituminous mixtures. Test methods for hot mix asphalt. Part 22: Wheel tracking.

The influence of the method of fiber application during production of asphalt mixtures was an additional element of the research. It was determined by comparison of results of selected tests, obtained for specimens of asphalt mixtures prepared in two different ways: the first one, when fibers were added to the aggregate before adding bitumen (which is recommended by the producer), and second, when fibers were added directly to the asphalt mixture just after adding bitumen to the aggregate and primary mixing stage.

4. MATERIALS

4.1. Fibers

The reinforcing fibers for asphalt mixtures FORTA-FI® HMA™ that were used during research program were provided by the Polish dealer – Wegarten Construction Sp. z o.o.

The FORTA-FI product is a mix of aramid-polyalphaolefin fibers, which are designed for use as reinforcing fibers in asphalt mixtures in pavement structures.

The FORTA-FI fibers are produced in three variants: HMA, WMA and PAT. Each variant is dedicated for different type of asphalt mixture. The FORTA-FI HMA fibers used in this research are recommended for typical asphalt mixtures, which temperature of production and compaction is in the range from 121°C to 190°C. The FORTA-FI WMA fibers are designed for warm mix asphalt and FORTA-FI PAT fibers are recommended for cold mixes used for fast potholes repairs. The length of the fibers is 19 mm in all variants of the product.

According to the producer recommendations, the fibers should be added to mixture with a dosage rate of 0,5 kg per 1000 kg of asphalt mixture. The fibers are dosed dry, ie. they are added to the hot aggregate mixture in pugmill mixer, before liquid asphalt is added.

During specimen fabrication for this research program, fibers were added to the hot aggregate before adding bitumen to the whole mixture, as recommended by the producer. Additionally, to evaluate influence of fiber application method on asphalt mixtures parameters, for selected laboratory tests specimens were fabricated with different fiber application method, when fibers were added to the mixture after bitumen was added and initial coating of aggregate by bitumen was already achieved.

4.2. Asphalt mixtures

Composition of aggregate mix and amount of asphalt cement in asphalt mixtures used in this study was based on requirements described in documentWT:2-2014[4].. Following types of asphalt mixtures were used in this study:

- Asphalt concrete for wearing course AC 11 S with neat bitumen 50/70 for medium traffic load category KR3÷4,
- Asphalt concrete for binder course AC 16 W with neat bitumen 35/50 for medium and heavy traffic load category KR3÷7,
- Asphalt concrete for binder course AC 16 W with polymer modified bitumen PmB 25/55-60 for medium and heavy traffic load category KR3÷7.

Asphalt concretes for binder course with neat bitumen 35/50 and polymer modified bitumen PmB 25/55-60 had the same aggregate mixture composition, which was originally developed for mixture with polymer modified bitumen PmB 25/55-60. The second variant of the asphalt concrete for binder course with unmodified bitumen 35/50 was adopted only by replacing the type of bitumen while keeping the volume ratios of components.

All asphalt mixtures were prepared in laboratory conditions. During the production process the reinforcing fibers were added. Mixtures with the addition of FORTA-FI fibers were marked with abbreviation symbol “FF”. The reference mixtures were prepared with the same bitumens but without reinforcing fibers.

Asphalt mixtures were prepared in two ways. For preliminary tests and assessment of volumetric properties, mixtures were mixed manually in metal pans. In later stage of the research, mixtures were prepared in laboratory mixer. For both mixing methods, no difficulties in aggregate coating or segregation occurred. There was no need to extend mixing time due to addition of fibers. It was observed that in each type of asphalt concrete the addition of fibers caused less segregation of mixture components, and the degree of coating of coarse aggregate particles by mastic was somewhat higher.

Due to the character of the research, which objective was to evaluate the influence of fibers on parameters of asphalt mixtures 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 obtained test results.

Basic parameters of asphalt cements used in tested asphalt concretes are given in table 4.1.

[4] WT:2-2014 Asphalt pavements on national roads. Bituminous Mixtures. Technical Requirements.

Table 4.1. Parameters of asphalt cements used in tested asphalt mixtures

Properties of bitumens			
Type of bitumen	35/50	50/70	PmB 25/55-60
Penetration in 25°C, 0,1 mm, PN-EN 1426	48	63	28
Softening point, °C, PN-EN 1427	53	47	62
Dynamic Viscosity, Pa•s, PN-EN 12596 in temperatures: • 60°C • 90°C • 135°C • 160°C	 659,333 15,935 0,635 nt	 238,795 7,413 0,406 nt	 nt 66,622 1,616 0,452
Properties of bitumen after TFOT aging			
Penetration in 25°C, 0,1 mm, PN-EN 1426	45	61	26
Softening point, °C, PN-EN 1427	57	51	68

nt - not tested

4.2.1. Asphalt concrete AC 11 S for wearing course

Gradation and type of aggregates used in asphalt concrete for wearing course AC 11 S is presented in table 4.2. Composition of designed asphalt concrete AC 11 S is presented in table 4.3. Gradation of designed aggregate mixture of asphalt concrete AC 11 S and its gradation curve are presented in table 4.4 and figure 4.1 respectively. Volumetric properties are shown in the table 4.5.

Table 4.2. Gradation of aggregates used in asphalt concrete AC 11 S

Sieve size #[mm]	Coarse aggregate 8/11, % retained	Coarse aggregate 5/8, % retained	Coarse aggregate 2/5, % retained	Fine aggregate 0/2, % retained	Limestone filler, % retained
22,4	0,0	0,0	0,0	0,0	0,0
16	0,0	0,0	0,0	0,0	0,0
11,2	9,0	0,0	0,0	0,0	0,0
8	76,3	4,6	0,0	0,0	0,0
5,6	11,6	80,4	6,9	0,0	0,0
2	0,9	11,2	79,1	12,7	0,0
0,125	0,7	2,4	12,4	73,7	3,4
0,063	0,5	0,4	0,7	9,8	16,1
<0,063	1,0	1,0	0,9	3,8	80,5
Aggregate source	Nordkam Eikefet	Nordkam Eikefet	Nordkam Eikefet	Yeoman Glensanda	Lafarge Wapienno
Type of stone	Granite	Granite	Granite	Granite	Limestone

Table 4.3. Composition of asphalt mixture AC 11 S

No.	Materials	Source	Aggregate mixture [%]	Asphalt mixture [%]
1	Coarse aggregate 8/11	Nordkam, Eikefet	25,0	23,6
2	Coarse aggregate 5/8	Nordkam, Eikefet	15,0	14,2
3	Coarse aggregate 2/5	Nordkam, Eikefet	23,0	21,7
4	Fine aggregate 0/2 (crushed sand)	Yeoman, Glensanda	30,0	28,3
5	Limestone filler	Lafarge, Wapienno	7,0	6,6
6	Bitumen 50/70	Lotos Asfalt		5,6

Table 4.4. Gradation of aggregate mixture of asphalt concrete AC 11 S

Sieve size # [mm]	% passing	Limits by PN-EN 13108-1:2008 and WT-2:2014 for traffic load KR3÷7	
		Minimum	Maximum
16,0	**100,0**	100	-
11,2	**97,8**	90	100
8,0	**78,0**	60	90
5,6	**61,4**	48	75
4,0	**49,8**	42	60
2,0	**37,5**	35	50
0,125	**11,8**	8	20
0,063	**7,4**	5	11

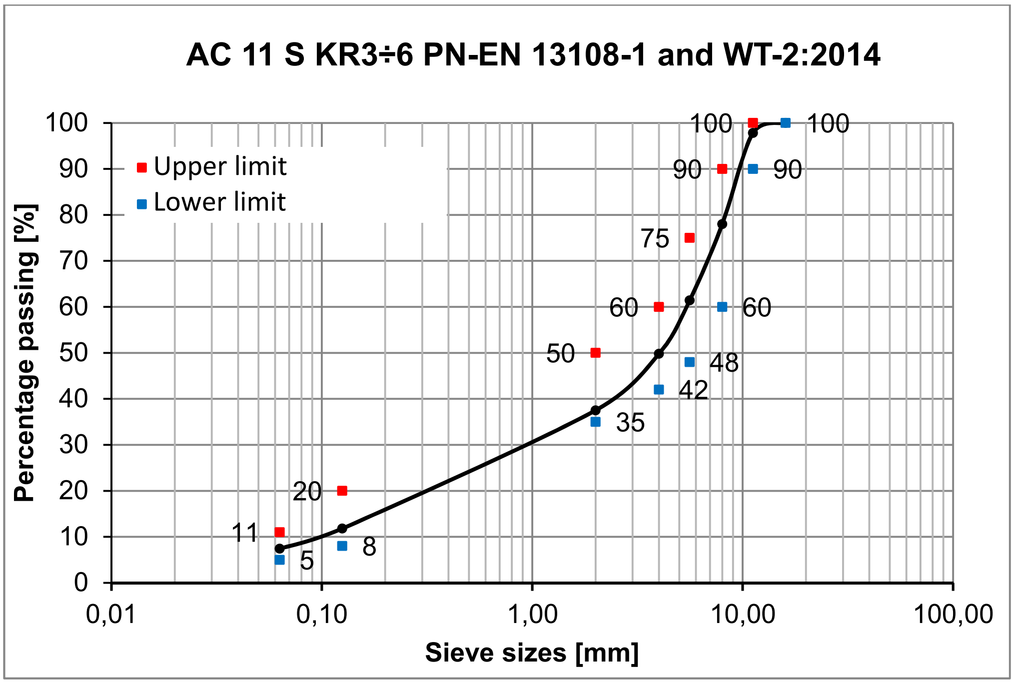

Figure 4.1. Grading curve of used asphalt concrete AC 11 S

Table 4.5. Volumetric properties of used asphalt concrete AC 11 S for wearing course

Parameter	AC 11 S 50/70	AC 11 S 50/70 FF
Binder content, %	5,6	5,6
Air voids in Marshall specimens [%]	2,6	2,8
Voids fill with bitumen VFB [%]	83,4	82,8
Voids in the mineral aggregate VMA [%]	15,9	16,0

4.2.2. Asphalt concrete AC 16 W for binder course

Gradation and type of aggregates used in asphalt concrete for wearing course AC 16 W is presented in table 4.6. Composition of designed asphalt concrete AC 16 W is presented in table 4.7. Gradation of designed aggregate mixture of asphalt concrete AC 16 W and its gradation curve are presented in table 4.8 and figure 4.2 respectively. Volumetric properties are shown in the table 4.9.

Table 4.6. Gradation of aggregates used in asphalt concrete AC 16 W

Sieve size #[mm]	Coarse aggregate 8/11, % retained	Coarse aggregate 5/8, % retained	Coarse aggregate 2/5, % retained	Aggregate with continuous grain size 0/5, % retained	Fine aggregate 0/2, % retained	Limestone filler, % retained
22,4	0,0	0,0	0,0	0,0	0,0	0,0
16	6,0	5,0	0,0	0,0	0,0	0,0
11,2	42,0	42,0	0,0	0,0	0,0	0,0
8	39,0	41,0	8,0	0,0	0,0	0,0
5,6	11,0	9,0	32,0	1,0	0,0	0,0
2	1,0	2,0	56,0	32,0	4,0	0,0
0,125	0,0	0,0	3,0	48,0	88,0	3,0
0,063	0,0	0,2	0,1	4,1	4,8	12,3
<0,063	1,0	0,8	0,9	14,9	3,2	84,7
Aggregate source	Cemex Mirowo	KG Gniewków	KG Gniewków	Lafarge Wapienno	Kruszywa Polskie Rybaki	Lafarge Wapienno
Type of stone	Granite	Granite	Granite	Limestone	Granite	Limestone

Table 4.7. Composition of asphalt mixture AC 16 W

No.	Materials	Source	Mineral aggregate [%]	Asphalt mixture [%]
1	Coarse aggregate 8/16	Cemex Mirowo	15,0	14,3
2	Coarse aggregate 8/16	KG Gniewków	23,0	21,9
3	Coarse aggregate 2/8	KG Gniewków	20,0	19,1
4	Aggregate with continuous grain size 0/5 (crushed stone)	Lafarge Wapienno	22,0	21,0
5	Fine aggregate 0/2 (crushed sand)	Kruszywa Polskie Rybaki	15,0	14,3
6	Limestone filler	Lafarge, Wapienno	5,0	4,8
7	Binder 35/50 or PmB 25/55-60	Lotos Asfalt		4,6

Table 4.8. Gradation of aggregate mixture of asphalt concrete AC 16 W

Sieve size # [mm]	[%] passing	Limits by PN-EN 13108-1:2008 and WT-2:2014	
		Minimum	Maximum
31,5	**100**	-	-
22,4	**100**	100	-
16,0	**98**	90	100
11,2	**82**	70	90
8,0	**65**	55	80
2,0	**35**	25	50
0,125	**9**	4	12
0,063	**6,4**	4	10

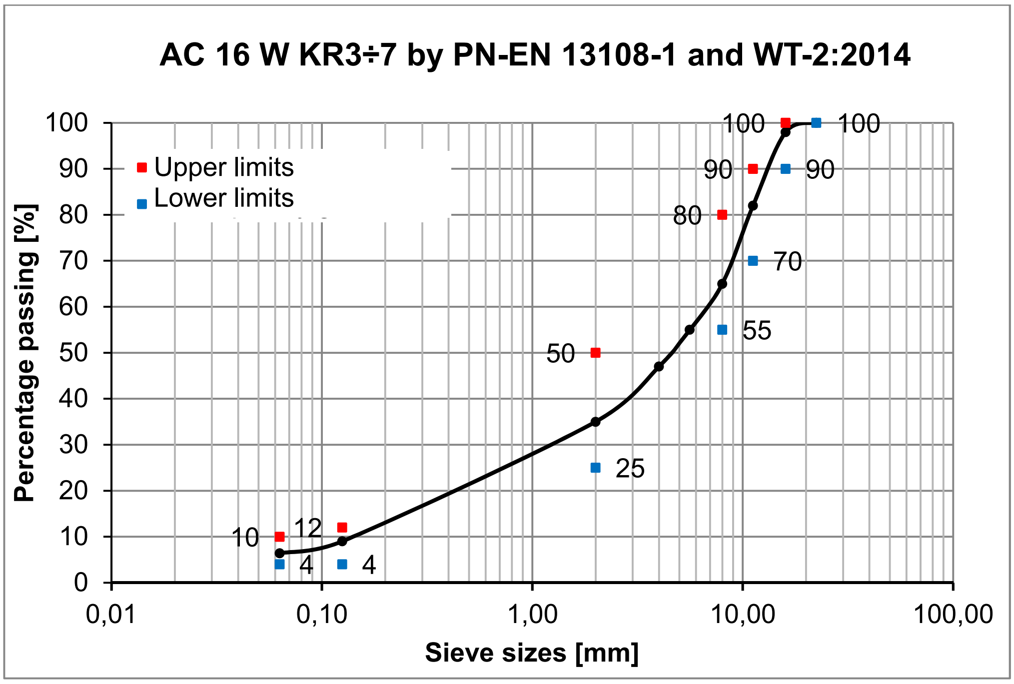

Figure 4.2. Grading curve of used asphalt concrete AC 16 W

Table 4.9. Volumetric properties of used asphalt concrete AC 16 W for binder course

Parameter	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, %	4,6	4,6	4,6	4,6
Air voids in Marshall specimens [%]	5,5	6,2	6,8	7,0
Voids fill with bitumen VFB [%]	65,8	62,6	60,5	59,7
Voids in the mineral aggregate VMA [%]	16,0	16,7	17,1	17,3

5. PREPARATION OF SPECIMENS

In accordance with recommendations of the producer, fibers were added to hot aggregate with a dosage rate of 0,05% by weight of asphalt mixture (0,5 kg of fibers for 1000 kg of asphalt mixture) before adding liquid bitumen. For this reason the mixing process was divided into two stages. At first stage the aggregate was mixed with fibers, then the bitumen was added and entire asphalt mixture was uniformly mixed.

In order to test the effect of a different method of fibers adding an additional set of specimens was prepared for selected tests. Fibers were then added in different way. In the first step, hot mineral aggregate and bitumen were mixed together. In the second step fibers were added to the initially coated asphalt mixture, and then entire mixture was remixed again.

Asphalt mixtures for tests were prepared in laboratory mixer in accordance with standard PN-EN 12697-35[5]. 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 document. The conditioning process consisted of holding the loose material at 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[6] by applying 75 blows on each side of the specimen.
- Specimens for assessment of stiffness modulus, indirect tensile strength and resistance to low temperature cracking were compacted with the use of

[5] PN-EN 12697-35+A1:2008 Bituminous mixtures - Test methods for hot mix asphalt. Part 35: Laboratory mixing.
[6] PN-EN 12697-30:2012 Bituminous mixtures - Test methods for hot mix asphalt. Part 30: Specimen preparation by impact compactor.

gyratory compactor according to standard to PN-EN 12697-31[7]. 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 water and frost action were compacted with the use of Marshall hammers according to standard PN-EN 12697-30[8] by applying 35 blows on each side of the specimen.
- Specimens for assessment of resistance to permanent deformations and low temperature cracking by Gdansk University of Technology method (GUT method) were compacted with the use of roller compactor according to standard PN-EN 12697-33[9]. Parameters of the compaction process were also set to obtain target density of 98-100% of Marshall density.

According to the requirements of WT-2:2014 document specimens of asphalt concrete with bitumen 35/50 and 50/70 were compacted in the temperature of 135°C ± 5°C. For specimens of asphalt concrete with polymer modified bitumen PmB 25/55-60 compaction temperature of 145°C ± 5°C was used.

In both cases no difficulties in mixing or compacting of asphalt concretes were observed. Also there was no need to prolong the process of mixing due to added fibers. It could be observed for each of asphalt concrete that reinforcing fibers caused less mixture segregation and better coating of coarse aggregate particles by mastic.

[7] PN-EN 12697-31:2005 Bituminous mixtures - Test methods for hot mix asphalt. Part 31: Specimen prepared by gyratory compactor

[8] PN-EN 12697-30:2012 Bituminous mixtures - Test methods for hot mix asphalt. Part 30: Specimen preparation by impact compactor.

[9] PN-EN 12697-33+A1: Bituminous mixtures - Test methods for hot mix asphalt. Part 33: Specimen prepared by roller compactor.

6. STIFFNESS MODULUS AND INDIRECT TENSILE STRENGTH

6.1. Stiffness modulus test method

Stiffness modulus test was conducted with the use of Nottingham Asphalt Tester (NAT) device that allows applying load to the specimen in the IT-CY scheme, which is described in appendix C of standard PN-EN 12697-26[10]. Stiffness modulus tests were performed in the scheme of indirect tensile with the vertical force applied along the peripheral surface of the cylindrical sample. The scheme of fixing of specimen in loading frame is shown in the figure 6.1.

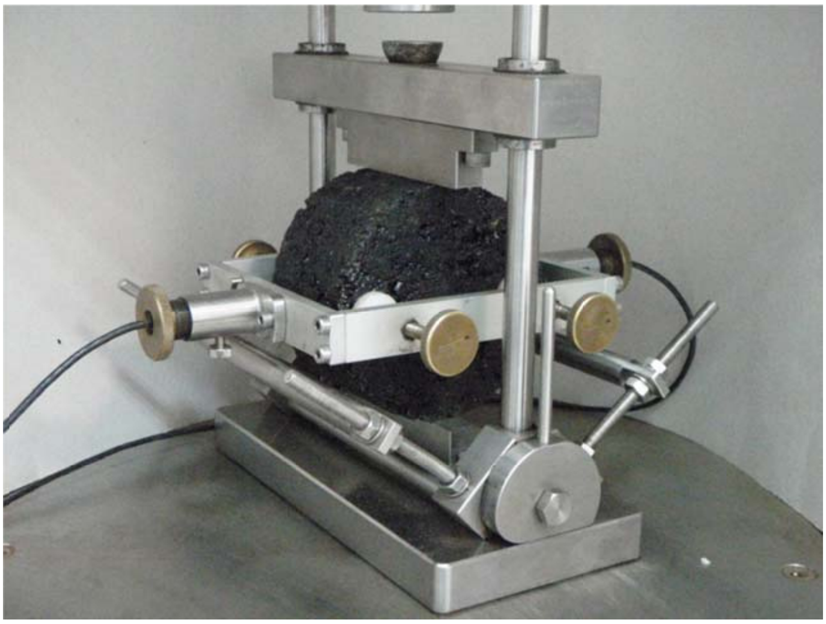

Figure 6.1. Specimen fixed in loading frame during stiffness modulus test in IT-CY scheme

During IT-CY stiffness modulus test load was applied to the specimen in a pulsed manner. Time of the increase of the load equaled 120±4 ms, and time length of one cycle was 3 s. Pulse value was determined by the software on the base of 10 conditioning cycles conducted for horizontal deformation of specimen. The test was conducted in the strain control mode with the horizontal strain set to 5 µm.

The test was conducted for two perpendicular planes. In each plane, the specimen was subjected to 5 pulse loads. On the base of 5 measurements of pulse loads, the stiffness modulus was calculated according to the formula (6.1):

$$S_m = \frac{F \times (\upsilon + 0,27)}{(z \times h)} \qquad (6.1)$$

where:

[10] PN-EN 12697-26:2012 Bituminous mixtures - Test methods for hot mix asphalt. Part 26: Stiffness

S_m – stiffness modulus, MPa,
F – maximum vertical force value, N,
ν – Poisson ratio, (-)
z – the amplitude of the horizontal deformation obtained during the loading cycle, mm,
h – average height of the specimen, mm.

The result for one specimen is the average value of the stiffness modulus measurements obtained in two perpendicular planes. The tests of stiffness modulus were conducted in three temperatures: 0°C, 13°C and 25°C.

6.2. Indirect tensile strength test method

Indirect tensile strength test was conducted on the same specimens which were used previously for stiffness modulus test. The test was conducted with the use of laboratory press with constant speed of deformation equal to 50 mm/min. Load was applied through loading frame equipped with spacers 12 mm wide and with inner curvature of 50,5 mm. The indirect tensile strength was calculated with the use of measured maximum force that occurred at failure point. The indirect tensile strength test was performed in accordance with the standard PN-EN 12697-23[11].

The view of specimen fixed in loading frame is shown in figure 6.2.

Figure 6.2. Specimen fixed in loading frame for indirect tensile strength test

The indirect tensile strength was calculated using the following formula (6.2):

[11] PN-EN 12697-23:2009 Bituminous mixtures. Test methods for hot mix asphalt. Part 23. Determination of the indirect tensile strength of bituminous specimens

$$R = \frac{2 \times P}{\pi \times D \times h} \tag{6.2}$$

where:

R – indirect tensile strength, MPa,
P – destructive force, kN,
D – diameter of specimen, m,
h – height of specimen, m.

The indirect tensile strength test was conducted in three temperatures: -20°C, 0°C and 20°C.

Both in stiffness modulus test and indirect tensile strength test, three specimens of each asphalt mixture were tested in each temperature.

6.3. Test results

The results of stiffness modulus test are presented in tables 6.1, 6.2 and 6.3. The average values of stiffness modulus are summarized in table 6.4 and presented in figures 6.3, 6.4, and 6.5. The results of indirect tensile strength are presented in tables 6.5, 6.6, 6.7. The average values of indirect tensile strength are summarized in table 6.8 and presented in figures 6.6, 6.7 and 6.8.

Table 6.1. Stiffness modulus of asphalt concrete AC 11 S with neat bitumen 50/70

	Specimen No.	Temperature [°C]	Stiffness modulus [MPa]	Average stiffness modulus [MPa]	Standard deviation [MPa]	Coefficient of variation [%]
AC 11 S 50/70 FF	440/1	0	15800	15546	2299	14,8
	440/2		17707			
	440/3		13131			
	440/4	13	7389	7484	91	1,2
	440/5		7571			
	440/6		7492			
	440/7	25	3089	3055	29	1,0
	440/8		3037			
	440/9		3040			
AC 11 S 50/70	441/1	0	12807	13669	1206	8,8
	441/2		13152			
	441/3		15047			
	441/4	13	8269	7777	443	5,7
	441/5		7655			
	441/6		7409			
	441/7	25	2784	2904	127	4,4
	441/8		3036			
	441/9		2893			

Table 6.2. Stiffness modulus of asphalt concrete AC 16 W with neat bitumen 35/50

	Specimen No.	Temperature [°C]	Stiffness modulus [MPa]	Average stiffness modulus [MPa]	Standard deviation [MPa]	Coefficient of variation [%]
AC 16 W 35/50 FF	436/1	0	15012	13772	1142	8,3
	436/2		12762			
	436/3		13543			
	436/4	13	9338	10249	1195	11,7
	436/5		9807			
	436/6		11602			
	436/7	25	4968	4739	202	4,3
	436/8		4664			
	436/9		4585			
AC 16 W 35/50	437/1	0	15164	15708	472	3,0
	437/2		15970			
	437/3		15991			
	437/4	13	10790	10405	411	3,9
	437/5		10455			
	437/6		9972			
	437/7	25	5854	5896	249	4,2
	437/8		6164			
	437/9		5671			

Table 6.3. Stiffness modulus of asphalt concrete AC 16W with polymer modified bitumen PmB 25/55-60

	Specimen No.	Temperature [°C]	Stiffness modulus [MPa]	Average stiffness modulus [MPa]	Standard deviation [MPa]	Coefficient of variation [%]
AC 16 W 25/55-60 FF	438/1	0	12277	13336	2015	15,1
	438/2		15660			
	438/3		12071			
	438/4	13	9613	9054	864	9,5
	438/5		9489			
	438/6		8059			
	438/7	25	4925	5180	229	4,4
	438/8		5252			
	438/9		5365			
AC 16 W 25/55-60	439/1	0	14809	15015	616	4,1
	439/2		14528			
	439/3		15707			
	439/4	13	9429	9422	36	0,4
	439/5		9454			
	439/6		9383			
	439/7	25	5181	4945	321	6,5
	439/8		5075			
	439/9		4580			

Table 6.4. Summary of results of stiffness modulus test

	Stiffness modulus [MPa] in temperature [°C]:		
	0	13	25
AC 11 S 50/70 FF	15 546	7 484	3 055
AC 11 S 50/70	13 669	7 777	2 904
AC 16 W 35/50 FF	13 772	10 249	4 739
AC 16 W 35/50	15 708	10 405	5 896
AC 16 W PmB 25-55-60 FF	13 336	9 054	5 180
AC 16 W PmB 25/55-60	15 015	9 422	4 945

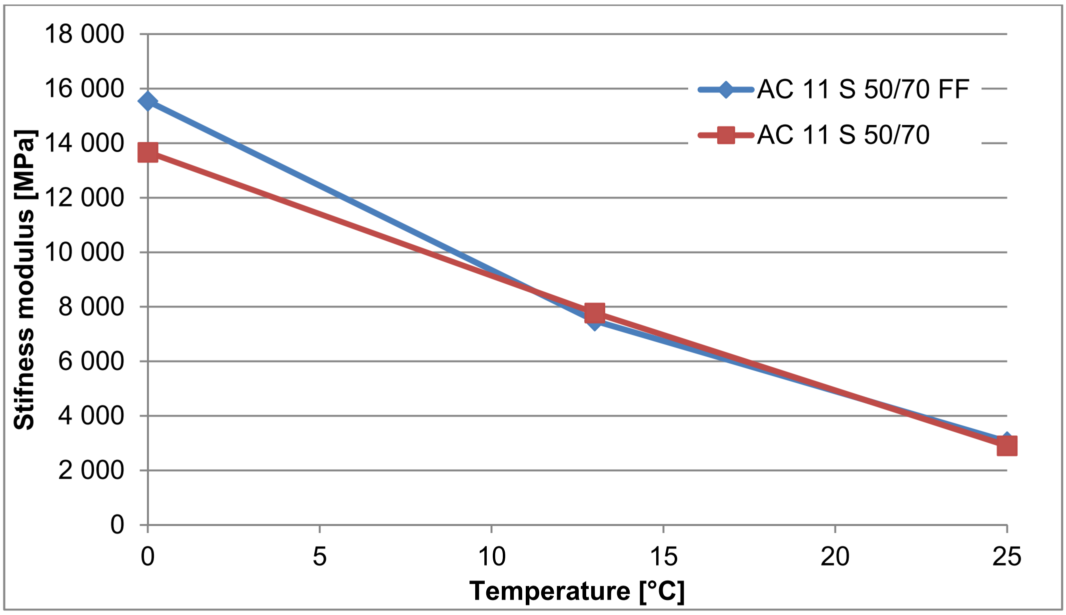

Figure 6.3. Stiffness modulus of asphalt concrete AC 11 S with neat bitumen 50/70

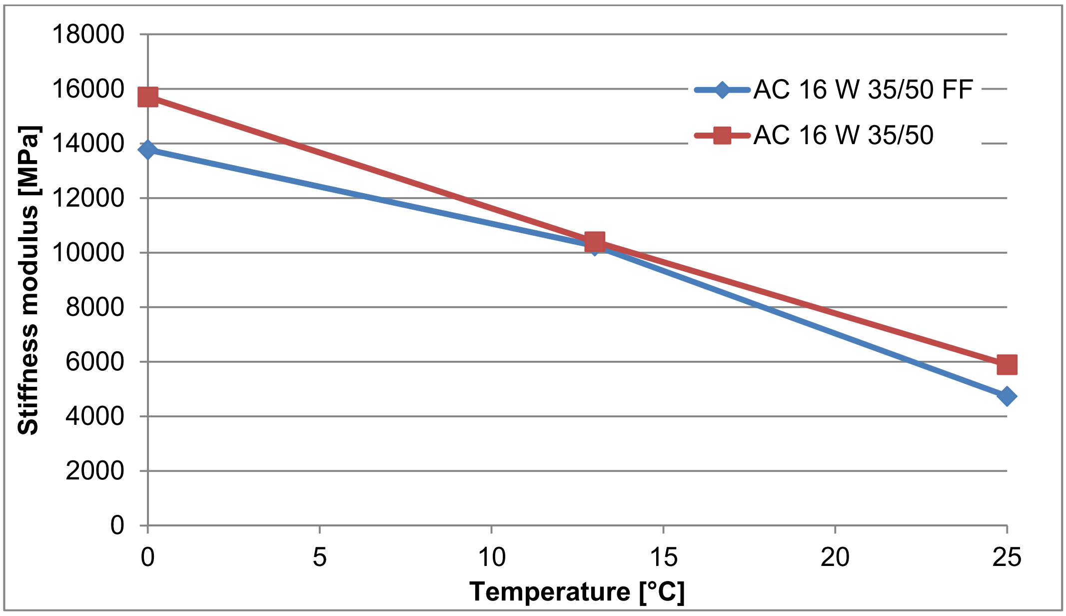

Figure 6.4. Stiffness modulus of asphalt concrete AC 16W with neat bitumen 35/50

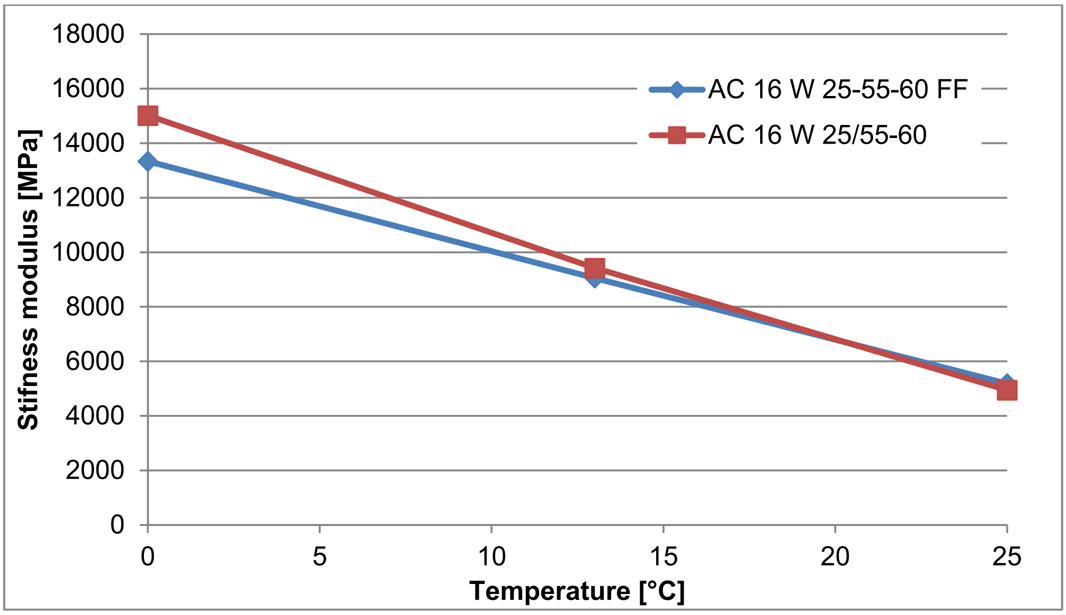

Figure 6.5. Stiffness modulus of asphalt concrete AC 16W with polymer modified bitumen PmB 25/55-60

Table 6.5. Indirect tensile strength of asphalt concrete AC 11S with neat bitumen 50/70

	Specimen No.	Temperature [°C]	Stiffness modulus [MPa]	Average stiffness modulus [MPa]	Standard deviation [MPa]	Coefficient of variation [%]
AC 11 S 50/70 FF	440/1	-20	4,39	4,58	0,26	5,6
	440/2		4,87			
	440/3		4,49			
	440/4	0	5,04	4,85	0,17	3,4
	440/5		4,78			
	440/6		4,73			
	440/7	20	1,98	1,90	0,07	3,9
	440/8		1,84			
	440/9		1,88			
AC 11 S 50/70	441/1	-20	4,80	4,63	0,54	11,6
	441/2		5,07			
	441/3		4,03			
	441/4	0	4,76	4,88	0,13	2,7
	441/5		5,02			
	441/6		4,87			
	441/7	20	1,79	1,83	0,05	2,5
	441/8		1,88			
	441/9		1,84			

Table 6.6. Indirect tensile strength of asphalt concrete AC 16W with neat bitumen 35/50

	Specimen No.	Temperature [°C]	Stiffness modulus [MPa]	Average stiffness modulus [MPa]	Standard deviation [MPa]	Coefficient of variation [%]
AC 16 W 35/50 FF	436/1	-20	3,77	3,77	0,02	0,6
	436/2		3,75			
	436/3		3,79			
	436/4	0	3,32	3,51	0,17	4,9
	436/5		3,54			
	436/6		3,66			
	436/7	20	1,99	1,93	0,11	5,9
	436/8		2,00			
	436/9		1,80			
AC 16 W 35/50	437/1	-20	3,40	3,75	0,43	11,4
	437/2		3,63			
	437/3		4,23			
	437/4	0	4,09	4,06	0,02	0,6
	437/5		4,04			
	437/6		4,06			
	437/7	20	2,35	2,28	0,10	4,2
	437/8		2,32			
	437/9		2,17			

Table 6.7. Indirect tensile strength of asphalt concrete AC 16W with polymer modified bitumen PmB 25/55-60

	Specimen No.	Temperature [°C]	Stiffness modulus [MPa]	Average stiffness modulus [MPa]	Standard deviation [MPa]	Coefficient of variation [%]
AC 16 W 25/55-60 FF	438/1	-20	3,98	4,01	0,26	6,4
	438/2		3,77			
	438/3		4,28			
	438/4	0	3,65	3,73	0,08	2,1
	438/5		3,81			
	438/6		3,75			
	438/7	20	2,13	2,01	0,11	5,3
	438/8		1,97			
	438/9		1,93			
AC 16 W 25/55-60	439/1	-20	4,56	4,58	0,01	0,3
	439/2		4,59			
	439/3		4,58			
	439/4	0	4,01	4,05	0,09	2,1
	439/5		3,98			
	439/6		4,14			
	439/7	20	1,98	1,90	0,07	3,9
	439/8		1,83			
	439/9		1,89			

Table 6.8. Summary of the results of indirect tensile strength test

	Indirect tensile strength [MPa] in temperature [°C]:		
	-20	0	+20
AC 11 S 50/70 FF	4,58	4,85	1,90
AC 11 S 50/70	4,63	4,88	1,83
AC 16 W 35/50 FF	3,77	3,51	1,93
AC 16 W 35/50	3,75	4,06	2,28
AC 16 W PmB 25-55-60 FF	4,01	3,73	2,01
AC 16 W PmB 25/55-60	4,58	4,05	1,90

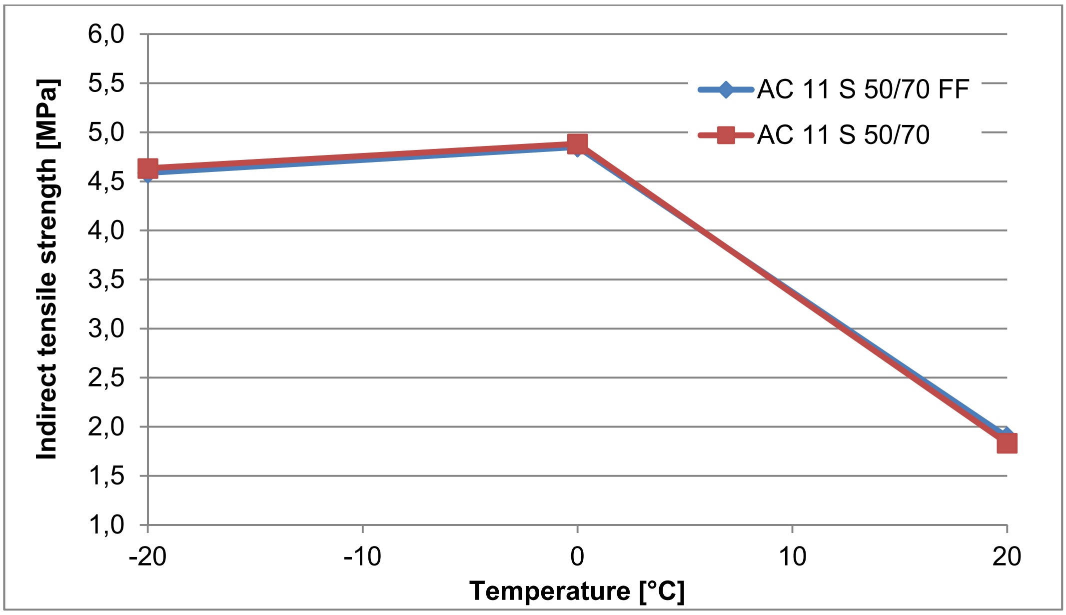

Figure 6.6. Indirect tensile strength of asphalt concrete AC 11S with neat bitumen 50/70

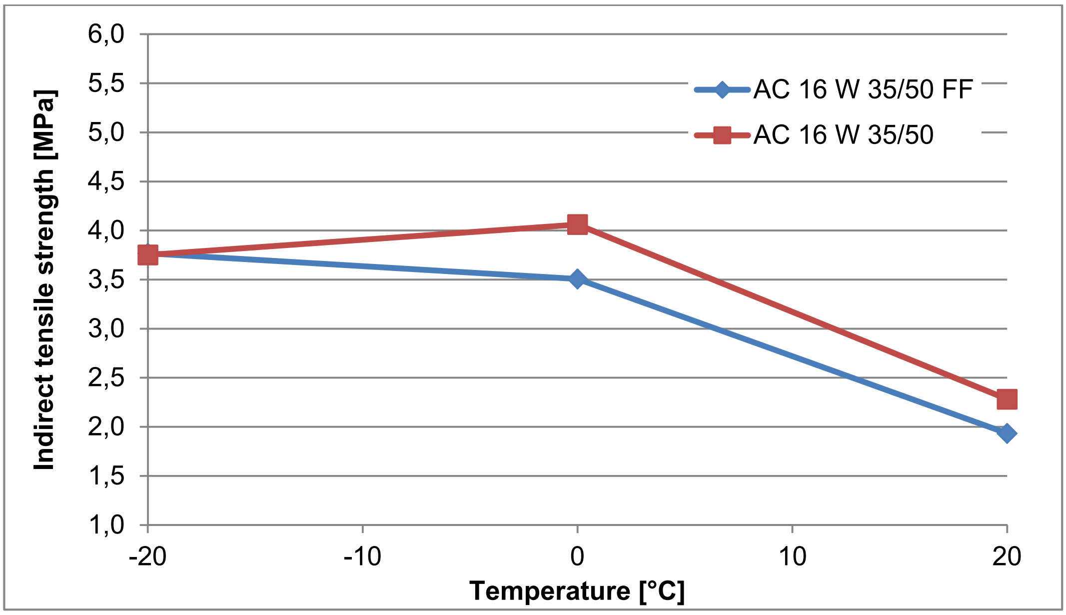

Figure 6.7. Indirect tensile strength of asphalt concrete AC 16W with neat bitumen 35/50

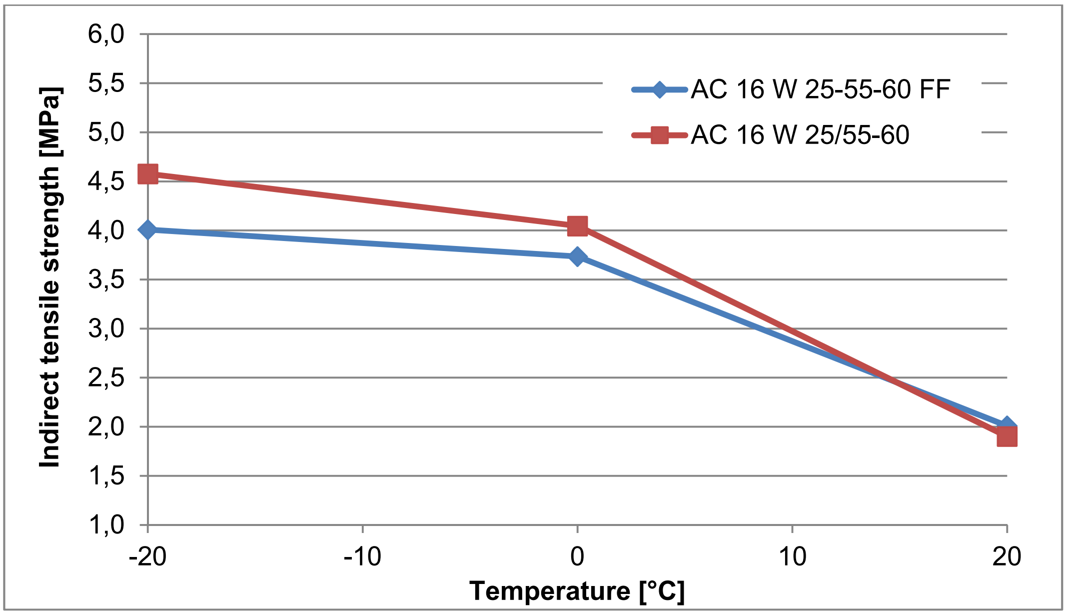

Figure 6.8. Indirect tensile strength of asphalt concrete AC 16 W with polymer modified bitumen PmB 25/55-60

In the case of indirect tensile strength an additional test of the impact of the method of fibers dosing on test results were conducted. For asphalt concrete AC 11S the additional specimens were prepared, in which the fibers were added after initial mixing of aggregate with bitumen. The results are given in table 6.9 and in figure 6.9.

Table 6.9. Indirect tensile strength of asphalt concrete AC 16 W with polymer modified bitumen PmB 25/55-60

	Specimen No.	Temperature [°C]	Indirect tensile strength [MPa]	Average indirect tensile strength [MPa]	Standard deviation [MPa]	Coefficient of variation [%]
AC 16 W 25/55-60 FF 2	503/1	-20	4,26	4,60	0,58	12,5
	503/2		5,27			
	503/3		4,28			
	503/4	0	4,46	4,66	0,17	3,7
	503/5		4,78			
	503/6		4,73			
	503/7	20	1,78	1,78	0,01	0,5
	503/8		1,76			
	503/9		1,78			

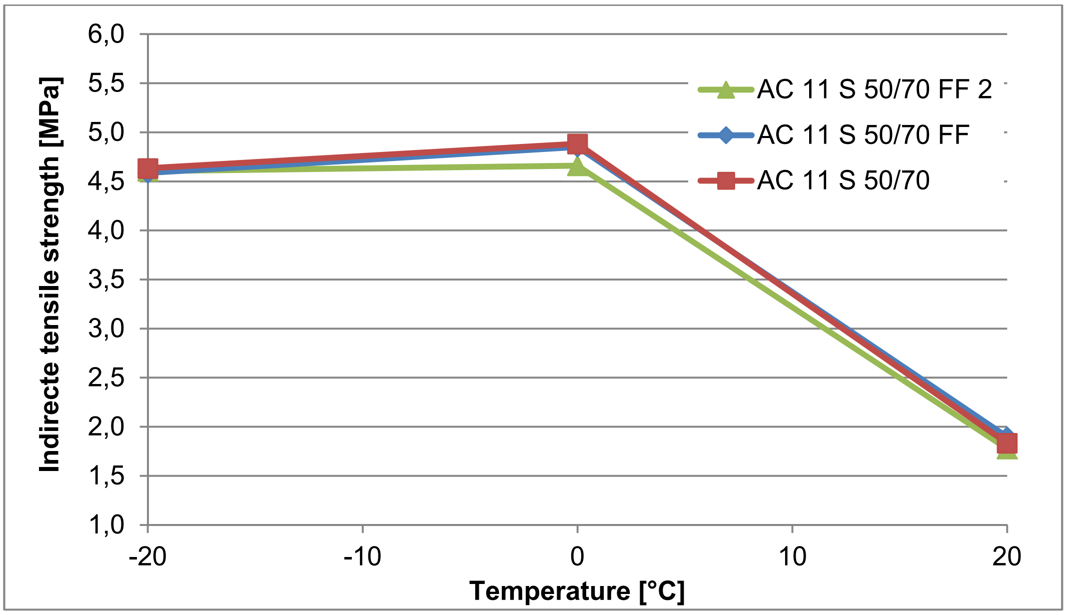

Figure 6.9. Indirect tensile strength of asphalt concrete AC 11S with bitumen 50/70

6.4. Analysis of test results

The following conclusions could be drawn from the research:

1. The addition of fibers did not influence significantly on values of stiffness modulus of analyzed asphalt concretes. In temperatures above 0°C results for asphalt concrete with and without addition of fibers were similar. Slight differences could be observed at 0°C, but these differences are within the range of 15%. In the case of asphalt concrete for wearing course the addition of fibers increased stiffness of asphalt concrete which is a negative effect in terms of low-temperature cracking. In the case of binder course the addition of fibers decreased stiffness, which can be regarded as positive effect.

2. The addition of fibers did not influence significantly on values of indirect tensile strength of all analyzed asphalt concretes, particularly in the case of asphalt concrete for wearing course, where the values of indirect tensile strength are almost identical for mixtures with and without fibers. In temperatures above 0°C results for asphalt concrete with and without addition of fibers were similar. Slight differences could be observed at 0°C and -20°C, but these differences are within the range of 10. In the case of asphalt concrete for binder course the addition of fibers decreased indirect tensile strength but the analysis of statistical differences of significance has shown that this decrease is not significant from the statistical point of view.

3. Conducted tests indicate that the addition of fibers had no impact on stiffness modulus and indirect tensile strength of tested asphalt mixtures.

4. Additional series of tests of indirect tensile strength on specimens of asphalt concrete AC 11 S, have shown that different method of specimens preparation, where fibers were added to the mixture after adding bitumen and initial coating, had no impact on tested parameters. There was a slightly lower value of the indirect tensile strength at 0°C, but these differences are not important from the statistical point of view. At temperatures -20 and +20°C values of indirect tensile strength were almost the same as for normal fiber dosing method, recommended by the producer.

7. RESISTANCE TO WATER AND FROST ACTION

7.1. Test method

Resistance of asphalt mixtures to water and frost action was evaluated according to the standard PN-EN 12697-12[12] and Appendix 1 of the document WT-2 2014.

To assess the resistance of asphalt mixtures to water and frost action 10 cylindrical specimens of each asphalt mixture were prepared. Each set of 10 specimens was divided into two groups of 5 specimens with similar average height, volumetric density and air voids content.

The first group (5 „wet" specimens) was conditioned according to the instruction given in WT-2 2014 while the second group (5 „dry" specimens) was a reference group and was kept in temperature +20±5°C.

In the first stage of conditioning process, specimens from of the „wet" set were saturated with water in temperature 20°C in vacuum chamber. In the next stage saturated specimens were held for 72 hours in water bath in temperature 40°C. Then specimens were taken out from water, wrapped in foil, inserted into plastic bags containing 10 ml of water and then finally placed for 16 hours in freezing chamber at temperature of -18°C.

Resistance of asphalt mixtures to water and frost action is measured by a ratio of indirect tensile strength of reference specimens from "dry set" compared to indirect tensile strength of conditioned specimens from "wet set". The indirect tensile strength test was performed in accordance with standard PN-EN 12697-23[13] at the temperature of +25±2°C.

12 PN-EN 12697-12: 2008 Bituminous mixtures. Test methods for hot mix asphalt. Part 12: Determination of the water sensitivity of bituminous specimens.

13 PN-EN 12697-23:2009 Bituminous mixtures. Test methods for hot mix asphalt. Part 23. Determination of the indirect tensile strength of bituminous specimens

7.2. Test results

The test results of resistance of asphalt concrete to water and frost action are presented in tables from 7.1 to 7.3 and are summarized in table 7.4 and in figures 7.1 and 7.2.

Table 7.1. Test results of resistance to water and frost action of asphalt concrete AC 11 S 50/70, performed according to the standard PN-EN12697-12 and procedure described in WT-2:2014 document, test temperature +25°C

		Specimen No.	Air voids [%]	Saturation level [%]	Force to failure [kN]	Indirect tensile strength [kPa]	Average strength [kPa]	ITSR [%]
AC 11 S 50/70 FF	**Unconditioned set**	411/1	3,0	-	12,1	1 228	1206	99,8
		411/2	3,3	-	11,6	1 170		
		411/3	3,4	-	11,9	1 187		
		411/4	3,2	-	12,1	1 212		
		411/5	3,2	-	12,3	1 232		
	Conditioned set	411/6	3,0	58	11,8	1 187	1204	
		411/7	3,1	56	11,9	1 192		
		411/8	3,1	56	11,9	1 202		
		411/9	3,2	60	11,5	1 159		
		411/10	3,1	59	12,6	1 279		
AC 11 S 50/70	**Unconditioned set**	412/1	3,0	-	11,9	1 198	1148	90,9
		412/2	3,2	-	11,5	1 148		
		412/3	2,8	-	11,2	1 124		
		412/4	3,0	-	11,3	1 099		
		412/5	3,4	-	11,7	1 172		
	Conditioned set	412/6	3,0	56	10,7	1 073	1043	
		412/7	3,0	62	10,1	1 012		
		412/8	3,2	59	10,3	1 026		
		412/9	3,2	63	10,3	1 030		
		412/10	3,1	56	10,7	1 076		

Table 7.2. Test results of resistance to water and frost action of asphalt concrete AC 16 W 35/50, performed according to the standard PN-EN12697-12 and procedure given in the WT-2:2014 document, test temperature +25°C

		Speci-men No.	Air voids [%]	Saturation level [%]	Force to failure [kN]	Indirect tensile strength [kPa]	Average strength [kPa]	ITSR [%]
AC 16 W 35/50 FF	**Unconditioned set**	405/1	6,1	-	17,1	1 638	1601	70,9
		405/2	6,3	-	16,3	1 571		
		405/3	6,1	-	16,9	1 634		
		405/4	6,5	-	16,3	1 563		
		405/5	6,5	-	16,6	1 600		
	Conditioned set	405/6	6,3	84	12,2	1 183	1135	
		405/7	6,4	80	12,1	1 149		
		405/8	6,7	62	9,6	906		
		405/9	6,7	80	11,9	1 149		
		405/10	6,6	61	13,3	1 290		
AC 16 W 35/50	**Unconditioned set**	406/1	7,2	-	16,4	1 558	1489	64,5
		406/2	7,5	-	15,4	1 444		
		406/3	7,4	-	14,3	1 352		
		406/4	7,0	-	16,8	1 604		
		406/5	6,9	-	15,5	1 485		
	Conditioned set	406/6	7,3	84	11,3	1 067	960	
		406/7	7,3	60	9,5	907		
		406/8	7,3	74	11,3	1 066		
		406/9	7,4	68	8,4	792		
		406/10	7,7	84	10,2	966		

Table 7.3. Test results of resistance to water and frost action of asphalt concrete AC 16 W with PmB 25/55-60, performed according to the standard PN-EN12697-12 and procedure given in the WT-2:2014 document, test temperature +25°C

		No	Air voids [%]	Saturation level [%]	Force to failure [kN]	Indirect tensile strength [kPa]	Average strength [kPa]	ITSR [%]
AC 16 W PmB 25/55-60 FF	**Unconditioned set**	409/1	6,5	-	17,9	1 721	1715	87,8
		409/2	6,6	-	17,4	1 664		
		409/3	6,5	-	17,9	1 708		
		409/4	6,5	-	18,3	1 750		
		409/5	6,5	-	18,0	1 733		
	Conditioned set	409/6	6,4	87	15,8	1 501	1505	
		409/7	6,7	87	15,6	1 458		
		409/8	6,4	83	16,1	1 534		
		409/9	6,8	77	16,5	1 577		
		409/10	6,2	80	15,4	1 457		
AC 16 W PmB 25/55-60	**Unconditioned set**	410/1	7,5	-	15,6	1 471	1528	89,9
		410/2	7,7	-	15,8	1 488		
		410/3	7,5	-	16,2	1 548		
		410/4	7,7	-	16,7	1 579		
		410/5	8,0	-	16,6	1 556		
	Conditioned set	410/6	7,6	84	14,9	1 422	1375	
		410/7	7,8	82	13,8	1 310		
		410/8	7,6	83	15,8	1 481		
		410/9	8,2	82	14,3	1 347		
		410/10	8,3	87	14,0	1 313		

Table 7.4. Summary of the test results of resistance to water and frost action

Type of asphalt mixture	ITSR [%]
AC 11 S 50/70 FF	100
AC 11 S 50/70	91
AC 16 W 35/50 FF	71
AC 16 W 35/50	64
AC 16 W 25/55-60 FF	88
AC 16W 25/55-60	90

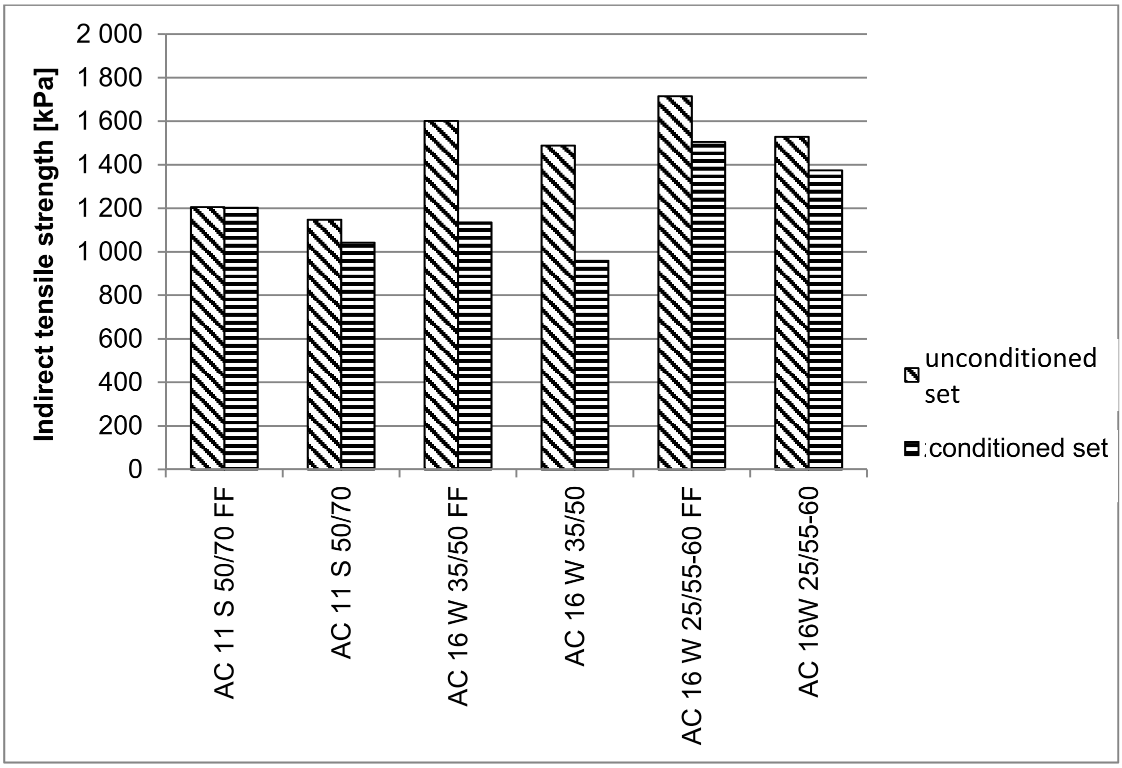

Figure 7.1. Summary of the test results of resistance to water and frost action of asphalt mixtures, indirect tensile strength

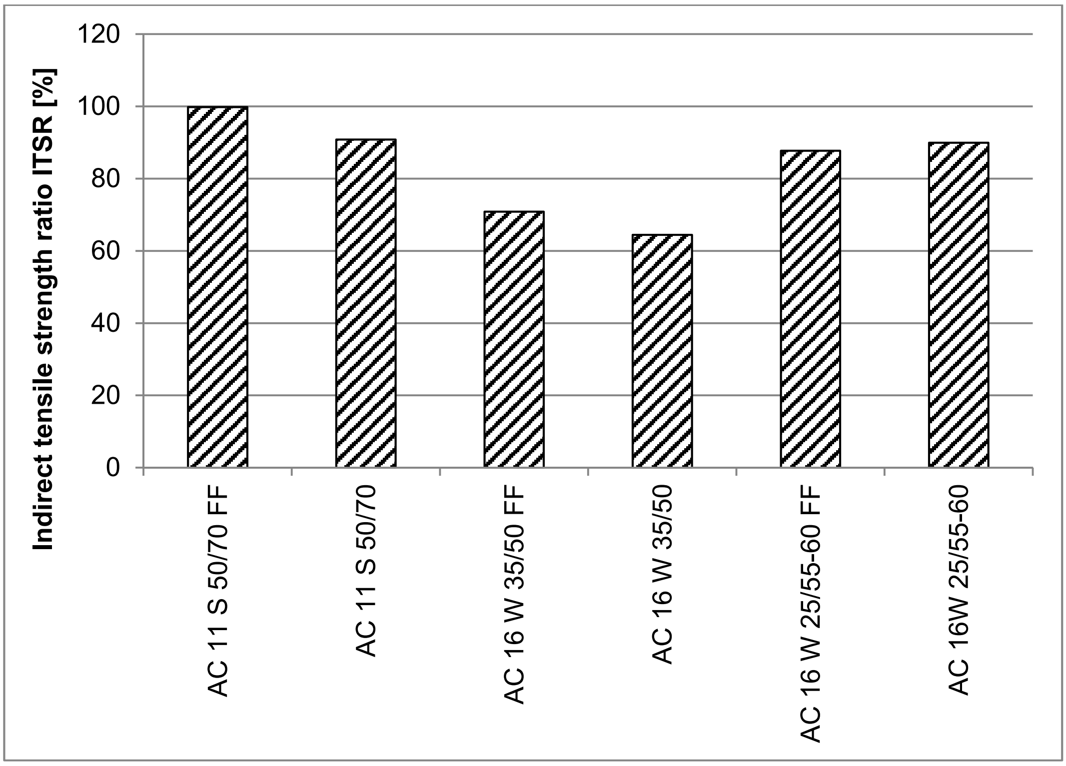

Figure 7.2. Summary of the test results of resistance to water and frost action of asphalt mixtures, indirect tensile strength ratio (ITSR)

7.3. Analysis of the test results

On the basis of performed tests of resistance to water and frost action it can be concluded that:

1. The resistance to water and frost damage was evaluated in accordance with conditioning procedure of specimens described in WT-2: 2014. Asphalt concrete AC 16W with bitumen 35/50 with and without fibers did not reach the minimum ITSR value of 80%, which is required by the document WT-2: 2014 for asphalt mixtures designed for binder course. An addition of anti-stripping agent to the asphalt mixtures would certainly increase the ITSR ratio. Due to the fact that the main purpose of the research program was to assess the influence of fibers on selected properties of asphalt concretes, the failure to achieve the minimum specified value of ITSR assumed in WT-2:2014 does not affect final conclusions.

2. The application of FORTA FI fibers increased absolute values of indirect tensile strength both in the case of reference specimens and conditioned specimens. The increase of strength varies from 5%, for reference specimens of asphalt concrete AC 11 S with bitumen 50/70, to 18% for reference specimens of asphalt concrete AC 16W with bitumen 35/50

3. For asphalt concrete AC 11 S with bitumen 50/70 and AC 16 W with bitumen 35/50 the application of FORTA FI fibers increased values of ITSR ratio. In case of asphalt concrete AC 16 W with polymer modified bitumen PmB 25/55-60 with FORTA FI fibers the ITSR ratio was slightly (2,1%) lower than ITSR ratio for reference mixture without fibers. It must be noted that the ITSR only describe the change of the value of indirect tensile strength after exposing set of specimens to destructive effect of conditioning process. ITSR does not apply to the absolute values of strength. It must be emphasized that absolute values of indirect tensile strength of conditioned samples of asphalt concrete AC 16 W with PmB 25/55-60 and FORTA FI fibers were at the same level as ITS of samples of reference mixtures (without fibers) that did not undergo conditioning process.

4. During tests of resistance to water and frost action the indirect tensile strength of specimens containing FORTA-FI fibers was higher than for specimens without FORTA-FI fibers for each case. This trend did not occur during testing indirect tensile strength in several temperatures, which results are described in chapter 6. The differences can be caused by different compaction level. For indirect tensile strength tests described in chapter 6, specimens were compacted in gyratory compactor and obtain target density close to the 100% of Marshall density. Specimens used to evaluate resistance to water and frost were compacted in Marshall hammer with 35 blows for each side. This compaction method refers to 98% of Marshall density. It suggests that the

positive effect of application of reinforcing fibers could be more visible in cases of inadequate compaction of pavement layers. During compaction of asphalt mixtures in field conditions, compaction index usually lies within the range of 98 to 99%. In such cases the positive effect of fibers application will be more evident.

8. RESISTANCE TO PERMANENT DEFORMATION

8.1. Test method

Resistance of asphalt mixtures to permanent deformation was evaluated according to standard PN-EN 12697-22, in a small device, method B, conditioning in air. The test temperature was 60° C. Specimens were prepared and compacted gradually, so as to obtain the same time period between the compaction and the test, which takes 4 days.

Resistance of asphalt mixtures to permanent deformation was evaluated on the basis of proportional rut depth PRD_{AIR} and wheel tracking rate WTS_{AIR}.

8.2. Test results

The test results of resistance to permanent deformation of asphalt concrete are shown in Table 8.1. Figure 8.1 shows the rut depth (RD_{AIR}, in mm) depending on the number of cycles.

Table 8.1. Summary of test results of resistance to permanent deformation of asphalt concrete, according to standard PN-EN12697-22 method B, conditioning in air

Specimen No	Type of asphalt mixture	Proportional rut depth PRD_{AIR} [10000 cycles, %]	Average proportional rut depth PRD_{AIR} [10000 cycles, %]	Wheel tracking slope WTS_{AIR} [mm/10^3 cycles]	Average wheel tracking slope WTS_{AIR} [mm/10^3 cycles]
411/1	AC 11 S 50/70 FF	12,0	12,1	0,21	0,20
411/2		12,3		0,19	
412/1	AC 11 S 50/70	12,3	13,6	0,21	0,23
412/2		15,0		0,24	
405/1	AC 16 W 35/50 FF	5,0	4,5	0,07	0,07
405/2		4,0		0,06	
406/1	AC 16 W 35/50	4,3	4,3	0,06	0,05
406/2		4,2		0,04	
409/1	AC 16 W 25/55-60 FF	3,0	2,9	0,04	0,04
409/2		2,8		0,03	
410/1	AC 16 W 25/55-60	3,0	3,3	0,03	0,03
410/2		3,7		0,03	

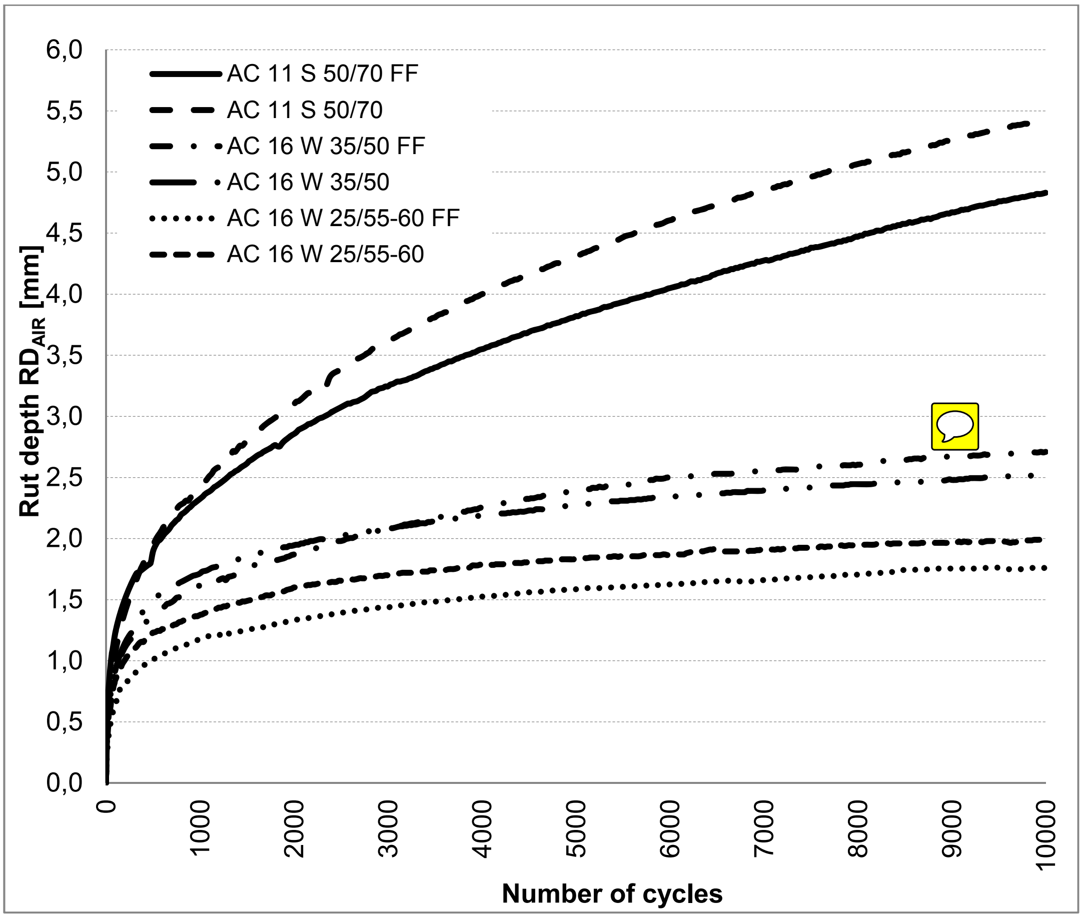

Figure 8.1. Resistance to permanent deformation according to standard PN-EN12697-22, rut depth RD_{AIR}

8.3. Analysis of test results

Based on the study of resistance to permanent deformation following conclusions could be drawn:

1. Improvement in resistance to permanent deformation was observed in the case of asphalt concrete for wearing course AC 11 S with 50/70 bitumen and asphalt concrete for binder course AC 16 W with polymer modified bitumen PmB 25-55/60.

2. In the case of asphalt concrete AC 16 W with 35/50 bitumen and addition of fibers, ruth depth results were somewhat lower than for a mixture without fibers.

3. The resulting differences between all analysed mixtures were however small and insufficient to determine a clear effect of the addition of fibers on resistance to permanent deformation.

9. RESISTANCE TO LOW TEMPERATURE CRACKING

9.1. Bending test according to GUT method

9.1.1. Test method

Resistance to low temperature cracking of asphalt mixtures was performed according to the method developed at the Gdansk University of Technology (GUT) by Judycki[14].

Following parameters were identified:
• modulus of flexural stiffness,
• ultimate strain,
• flexural strength,
• stiffening index.

During the test, a concentrated load is applied at the midspan of a simply supported beam. A constant deformation rate of 1,25 mm/min is applied by laboratory press. The specimens are rectangular beams 50×50×300 mm cut from compacted slabs. Test equipment records a relationship between the applied load and deformation of the sample.
Scheme and general view of specimen used for testing are shown in figure 9.1 and 9.2 respectively.

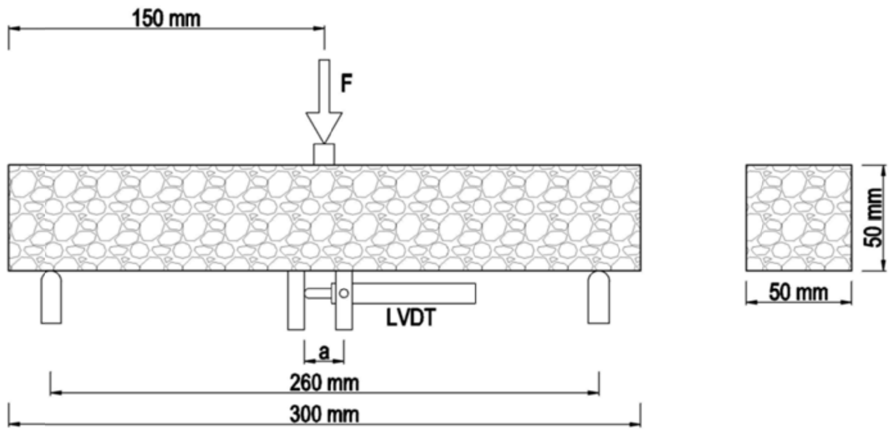

Figure 9.1. Scheme of specimen during bending test at low temperatures

[14] Judycki J. Bending test of asphaltic mixtures under statical loading. Fourth International RILEM Symposium, Mechanical Tests for Bituminous Mixes, Characterization, Design and Quality Control. Budapest; 1990. p. 207–27.

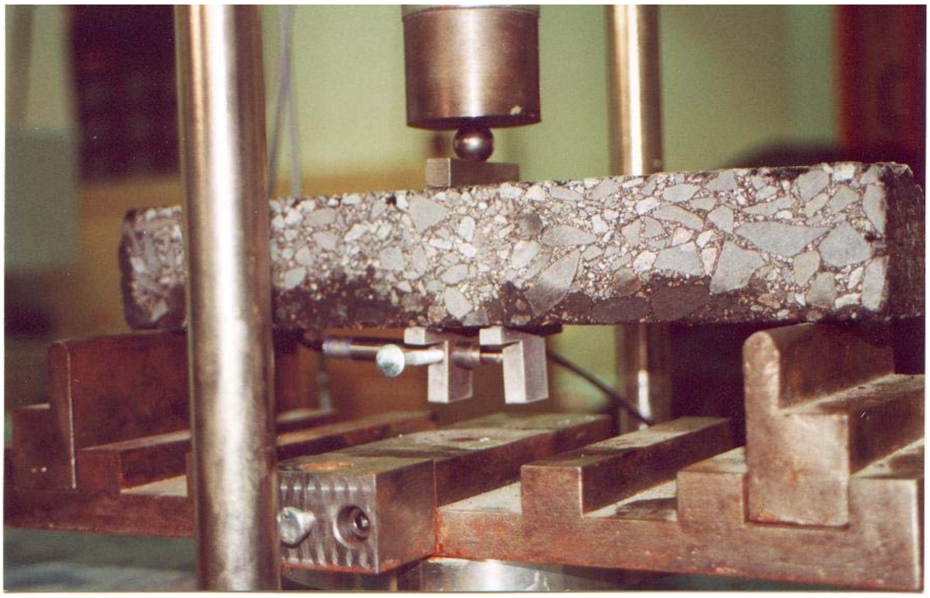

Figure 9.2. General view of the specimen during bending test at low temperatures

Described method involves following procedures:

1. The specimens were conditioned in the temperature chamber (-20°C or +10°C) for at least 18 hours before testing.
2. Each specimen was placed in special support frame and then vertical load was applied in the midspan of the beam.
3. Constant deformation applied to specimen was 1,25 mm/min.
4. During test strain was recorded at the bottom of specimen with use of LVDT transducer and at the same time force was recorded every 0,125 s.
5. Test was finished at the moment of specimen failure (test in temperature -20°C) or at the moment when maximum force was recorded (test in temperature +10°C).

A test series consisted of five identical specimens tested in the same conditions. Final result is a mean value of five measurements.

Ultimate strain and flexural strength were determined from the following equations:

$$\varepsilon_{ultimate} = \frac{p_{max}}{e} \times \frac{c}{c+a} \tag{9.1}$$

$$R_{rz} = \frac{3 \times F_{max} \times l}{2 \times b \times h^2} \tag{9.2}$$

where:

$\varepsilon_{ultimate}$ - average strain along measurement base "*e*" at the bottom of tested specimen,

p_{max} - displacement of the LVDT transducer during bending at maximum load F_{max} [mm],

e - measurement base – axial distance between steel plates, [mm],

a - distance between bottom area of specimen and axis of LVDT transducer [mm],
c - half of the specimen height [mm],
R_{rz} - flexural strength [MPa],
F_{max} - maximum force [kN],
h - height of specimen [mm],
l - specimen span between supports [mm],
b - weight of specimen [mm],
σ - stresses at the bottom of specimen in the midspan area [MPa].

Modulus of flexural stiffness was determined on the basis of relationship between stress and strain during bending of specimen. Values of strain were determined from the displacements of LVDT transducer at the bottom of tested specimen. Values of stress were determined from the force measurements and geometrical sizes of specimens. Modulus of flexural stiffness was determined from the following equation:

$$S = \frac{\Delta\sigma}{\Delta\varepsilon} \tag{9.3}$$

where:
S - modulus of flexural stiffness,
$\Delta\sigma$ - change in stress values ,
$\Delta\varepsilon$ - change in strain values.

Evaluation of tested asphalt concretes was carried out on the basis of: ultimate strain, flexural strength, modulus of flexural stiffness and stiffening index as an additional parameter , which is defined as follows:

$$SI = \frac{\Delta S}{\Delta T} \tag{9.4}$$

where:
SI - stiffening index,
ΔS - change in modulus of flexural stiffness during bending at different temperatures (+10° i -20°C),
ΔT - change in temperatures (between +10°C i -20°C).

On the basis of stiffening index behavior of asphalt concrete during cooling can be evaluated.

There are no criteria for evaluating resistance to low-temperature cracking of asphalt mixtures. One can only conclude that more favorable characteristics of asphalt mixtures at low temperatures are:

1. Higher flexural strength R_{rz} at low temperatures because it can withstand higher thermal stresses during cooling.
2. Higher ultimate strain $\varepsilon_{ulttimate}$ at low temperatures because of less brittle state and more flexibility of asphalt mixture.

3. Lower modulus of flexural stiffness S at low temperatures because values of thermal stresses occurring during cooling of mixture are directly proportional to values of that modulus.
4. Lower stiffening index SI, because in that case asphalt mixture is less thermal sensitive.

9.1.2. Test results

Test results of resistance to low temperature cracking of tested asphalt mixtures are presented in tables from 9.1 to 9.6 and figures from 9.3 to 9.6.

Table 9.1. Results of resistance to low temperature cracking of tested mixture AC 11 S 50/70 FF

<table>
<tr><th rowspan="2"></th><th rowspan="2">Test temperature [°C]</th><th colspan="3">Flexural strength R_{rz} [MPa]</th><th colspan="3">Ultimate strain ε_{gran} [‰]</th><th colspan="3">Modulus of flexural stiffness S [GPa]</th><th rowspan="2">Stiffening index SI [-]</th></tr>
<tr><th>Single sample</th><th>$\bar{X}$</th><th>S</th><th>Single sample</th><th>$\bar{X}$</th><th>S</th><th>Single sample</th><th>$\bar{X}$</th><th>S</th></tr>
<tr><td rowspan="10">AC 11 S 50/70 FF</td><td rowspan="5">-20</td><td>8,57</td><td rowspan="5">8,36</td><td rowspan="5">0,272</td><td>0,89</td><td rowspan="5">0,74</td><td rowspan="5">0,126</td><td>9,73</td><td rowspan="5">11,54</td><td rowspan="5">1,793</td><td rowspan="10">0,38</td></tr>
<tr><td>8,42</td><td>sd</td><td>sd</td></tr>
<tr><td>7,89</td><td>0,61</td><td>13,88</td></tr>
<tr><td>8,53</td><td>0,79</td><td>10,66</td></tr>
<tr><td>8,40</td><td>0,68</td><td>11,91</td></tr>
<tr><td rowspan="5">10</td><td>sd</td><td rowspan="5">2,88</td><td rowspan="5">0,080</td><td>sd</td><td rowspan="5">12,41</td><td rowspan="5">1,404</td><td>sd</td><td rowspan="5">0,23</td><td rowspan="5">0,026</td></tr>
<tr><td>2,93</td><td>11,53</td><td>0,25</td></tr>
<tr><td>2,77</td><td>11,93</td><td>0,23</td></tr>
<tr><td>2,94</td><td>11,68</td><td>0,25</td></tr>
<tr><td>2,87</td><td>14,50</td><td>0,19</td></tr>
</table>

$\bar{X}$ – average value
S – standard deviation
sd - the specimen was damaged during the test

Table 9.2. Results of resistance to low temperature cracking of tested mixture AC 11 S 50/70

Mixture	Test temperature [°C]	Flexural strength R_{rz} [MPa] – Single sample	$\bar{X}$	S	Ultimate strain ε_{gran} [‰] – Single sample	$\bar{X}$	S	Modulus of flexural stiffness S [GPa] – Single sample	$\bar{X}$	S	Stiffening index SI [-]
AC 11 S 50/70	-20	7,74	8,10	0,303	0,66	0,68	0,032	12,11	12,50	0,415	0,41
		7,92			0,65			12,45			
		8,32			0,69			12,36			
		8,05			sd			sd			
		8,49			0,72			13,09			
	10	3,16	3,23	0,054	11,63	12,25	1,195	0,26	0,26	0,022	
		3,23			10,73			0,30			
		3,32			13,96			0,23			
		3,24			12,53			0,25			
		3,23			12,40			0,26			

$\bar{X}$ – average value
S – standard deviation
sd - the specimen was damaged during the test

Table 9.3. Results of resistance to low temperature cracking of tested mixture AC 16 W 35/50 FF

Mixture	Test temperature [°C]	Flexural strength R_{rz} [MPa] – Single sample	$\bar{X}$	S	Ultimate strain ε_{gran} [‰] – Single sample	$\bar{X}$	S	Modulus of flexural stiffness S [GPa] – Single sample	$\bar{X}$	S	Stiffening index SI [-]
AC 16 W 35/50 FF	-20	6,18	6,32	0,158	0,58	0,52	0,065	10,70	12,10	1,363	0,38
		6,19			0,49			12,31			
		sd			sd			sd			
		6,46			0,56			11,49			
		6,46			0,44			13,89			
	10	4,80	4,63	0,352	6,53	5,75	0,750	0,72	0,81	0,110	
		4,20			5,12			0,81			
		4,67			4,90			0,94			
		5,10			5,72			0,88			
		4,39			6,47			0,68			

$\bar{X}$ – average value
S – standard deviation
sd - the specimen was damaged during the test

Table 9.4. Results of resistance to low temperature cracking of tested mixture AC 16 W 35/50

	Test temperature [°C]	Flexural strength R_{rz} [MPa]			Ultimate strain ε_{gran} [‰]			Modulus of flexural stiffness S [GPa]			Stiffening index SI [-]
		Single sample	$\bar{X}$	S	Single sample	$\bar{X}$	S	Single sample	$\bar{X}$	S	
AC 16 W 35/50	-20	sd	6,29	0,196	sd	0,47	0,048	sd	13,74	0,899	0,43
		6,48			0,45			14,61			
		6,42			0,53			13,23			
		6,08			0,48			12,75			
		6,16			0,42			14,39			
	10	4,61	4,53	0,182	5,08	5,54	0,502	0,89	0,81	0,068	
		4,70			5,91			0,79			
		4,25			4,97			0,84			
		4,44			6,12			0,71			
		4,63			5,61			0,81			

$\bar{X}$ – average value
S – standard deviation
sd - the specimen was damaged during the test

Table 9.5. Results of resistance to low temperature cracking of tested mixture AC 16 W 25/55-60 FF

	Test temperature [°C]	Flexural strength R_{rz} [MPa]			Ultimate strain ε_{gran} [‰]			Modulus of flexural stiffness S [GPa]			Stiffening index SI [-]
		Single sample	$\bar{X}$	S	Single sample	$\bar{X}$	S	Single sample	$\bar{X}$	S	
AC 16 W 25/55-60 FF	-20	7,18	7,00	0,545	0,81	0,71	0,100	9,12	10,16	1,917	0,31
		6,37			0,72			8,97			
		7,42			0,61			12,37			
		6,48			sd			sd			
		7,56			sd			sd			
	10	4,21	4,63	0,243	3,57	4,46	0,786	1,15	0,84	0,357	
		4,63			5,38			0,84			
		4,75			3,79			0,23			
		4,81			5,08			0,93			
		4,74			4,51			1,03			

$\bar{X}$ – average value
S – standard deviation
sd - the specimen was damaged during the test

Table 9.6. Results of resistance to low temperature cracking of tested mixture AC 16 W 25/55-60

Mixture	Test temperature [°C]	Flexural strength R_{rz} [MPa] Single sample	$\bar{X}$	S	Ultimate strain ε_{gran} [‰] Single sample	$\bar{X}$	S	Modulus of flexural stiffness S [GPa] Single sample	$\bar{X}$	S	Stiffening index SI [-]
AC 16 W 25/55-60	-20	6,03	6,51	0,381	0,65	0,66	0,093	9,35	10,02	1,336	0,30
		6,50			0,57			11,62			
		6,74			0,78			8,41			
		6,28			0,58			11,17			
		7,01			0,73			9,56			
	10	sd	4,57	0,236	sd	4,90	0,724	sd	0,93	0,145	
		4,44			4,15			1,04			
		4,74			4,75			0,98			
		4,31			5,89			0,72			
		4,80			4,81			0,98			

$\bar{X}$ – average value
S – standard deviation
sd - the specimen was damaged during the test

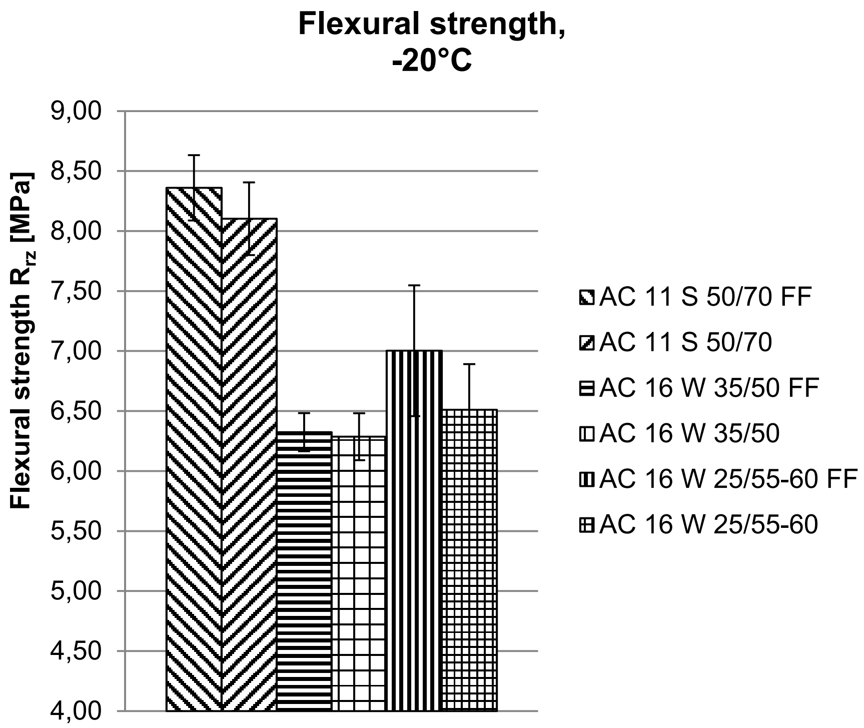

Figure 9.3. Flexural strength

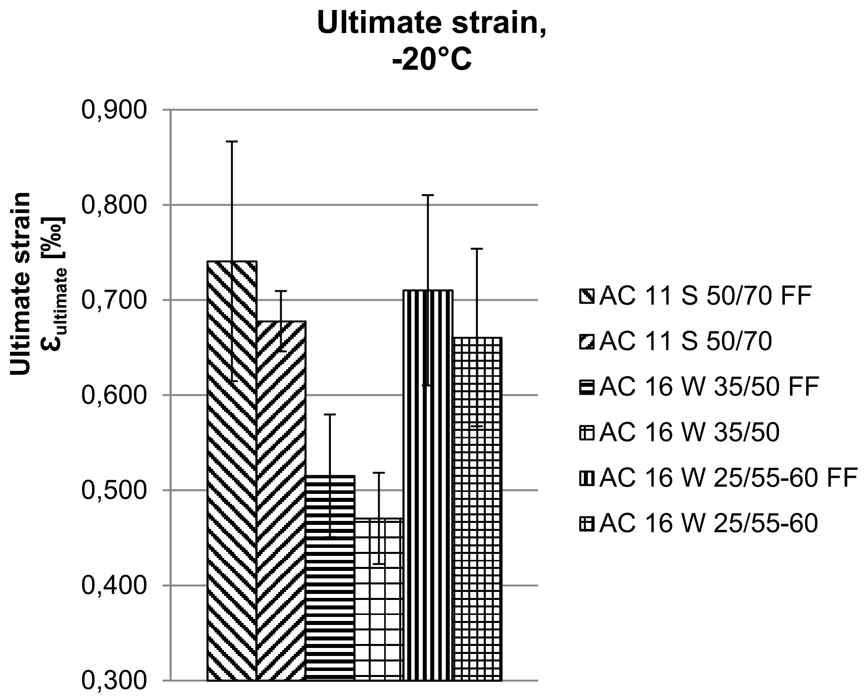

Figure 9.4. Ultimate strain

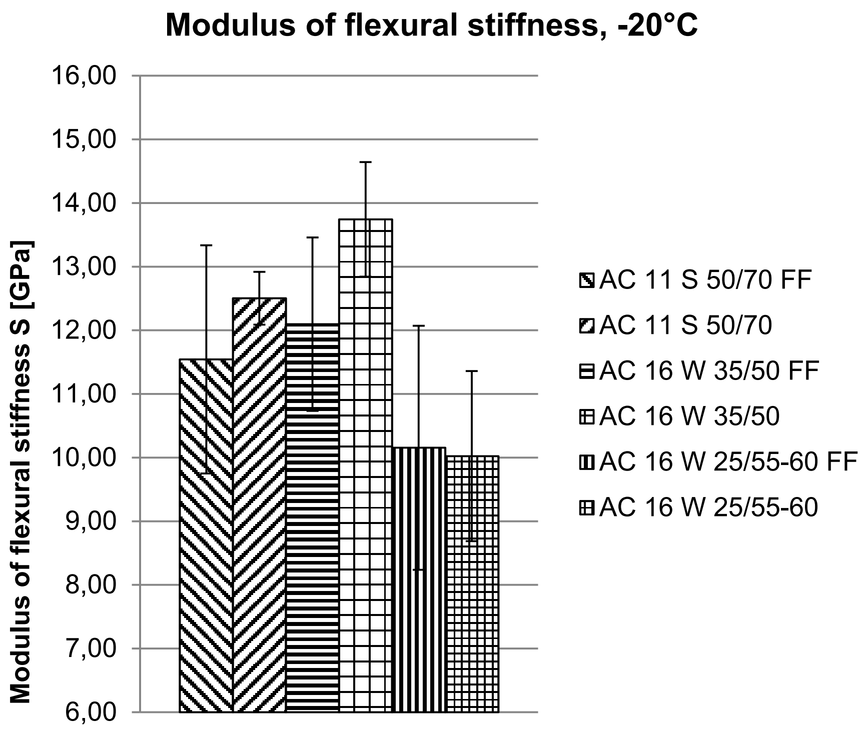

Figure 9.5. Modulus of flexural stiffness

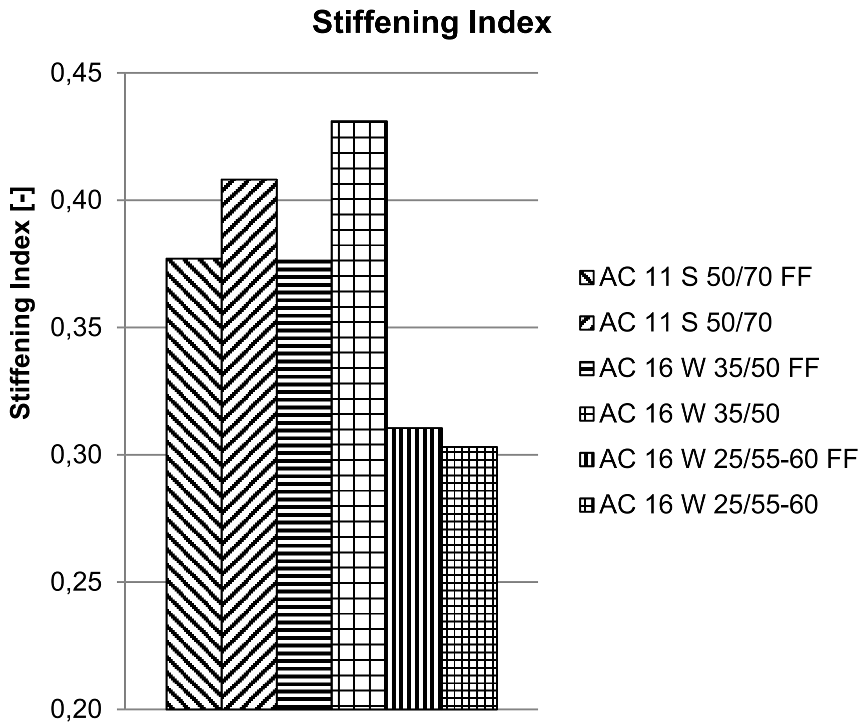

Figure 9.6. Stiffening Index

9.1.3. Analysis of test results

Based on the test results it can be concluded that:

1. The addition of fibers to the asphalt mixture had a positive effect on flexural strength. For each mixture this parameter was increased. The highest increase was the for asphalt concrete AC 16 with modified bitumen PmB 25/55-60, then for asphalt concrete AC 11 S with bitumen 50/70, and the lowest increase was observed for asphalt concrete AC 16 with bitumen 35/50.

2. The positive effect of the fibers addition was also highlighted in the case of ultimate strain, which for mixtures with fibers was always greater than for the reference mixtures without fibers.

3. It was observed that the modulus of flexural stiffness of asphalt mixtures with fibers was lower in the case of mixtures: AC 11 S with bitumen 50/70 and AC 16 W with bitumen 35/50 compared with reference mixtures without fibers. Modulus of flexural stiffness of asphalt concrete AC 16W with modified bitumen PmB 25/55-60 was slightly higher for samples with fibers.

4. The addition of fibers decreased stiffening index of asphalt concrete AC 11 S with bitumen 50/70 and AC 16 W with bitumen 35/50, which is a positive effect in terms of resistance to low temperature cracking. Stiffening index of asphalt

concrete AC 16 W with modified bitumen PmB 25/55-60 was slightly higher for the specimens with fibers.

5. The addition of fibers to the asphalt mixture AC 16 W with bitumen 35/50 had positive effect on parameters tested at low temperatures, however this increase was not high enough to reach the level of similar parameters obtained for asphalt concrete with modified bitumen PmB 25/55-60, even without the addition of fibers. This means that the type of bitumen (modified or unmodified) is more important in terms of resistance to low temperature cracking than addition of fibers.

9.2. Fracture toughness test

Fracture toughness was evaluated with the use of semi-circular bending test performed according to standard PN-EN 12697-44 PN-EN 12697-44[15]. Because crack propagation test is not commonly used in Poland, the test methodology described by standard PN-EN 12697-44 was modified. Modification of the procedure was based on literature review[16,17]. Standard method included in standard PN-EN 12697-44 is based 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 measured, which characterizes the critical strain energy release rate.

9.2.1. Specimen preparation

For Semi-Circular Bending test, semi round specimens with a diameter of 150 mm ± 1 mm, height of 75 mm ± 1 mm and a thickness of 50 mm ± 1 mm were used. Specimens were cut from bigger cylindrical samples compacted in the gyratory compactor. The diameter and height of original cylindrical samples were 150 and 105 mm respectively. From each original sample four semi-circular specimens were cut. To initiate crack at the bottom of each specimen a notch was cut on bottom plane of the specimen. Three depths of notch were cut – 10 mm, 20 mm and 30 mm. The width of the notch was 2 mm.

[15] PN-EN 12697-44:2010 Bituminous mixtures. Test methods for hot mix asphalt. Part 44: Crack propagation by semi-circular bending test.

[16] Mostafa A. Elseifi, Louay N. Mohammad, Hao Ying, Samuel Cooper III, Modeling and evaluation of the cracking resistance of asphalt mixtures using the semi-circular bending test at intermediate temperatures, Road Materials and Pavement Design, Vol. 13, No. S1, June 2012, 124–139

[17] X.-J. Li & M.O. Marasteanu, Using Semi Circular Bending Test to Evaluate Low Temperature Fracture Resistance for Asphalt Concrete, Experimental Mechanics 2010, 50:867–876

9.2.2. Test method

The semi-circular specimen was subjected to vertical load 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. Specimen and loading frame during the test were placed in thermostatic chamber of the press to maintain constant desired test temperature.

Fracture toughness characterizes the behavior of asphalt mixture during propagation of the crack. To initiate a crack, each specimen was cut before the test at the mid-span of the tension zone.

It is assumed, that if a small micro crack is initiated in asphalt layer, acting forces can load sides of the crack in three modes, which are shown in figure 9.7.

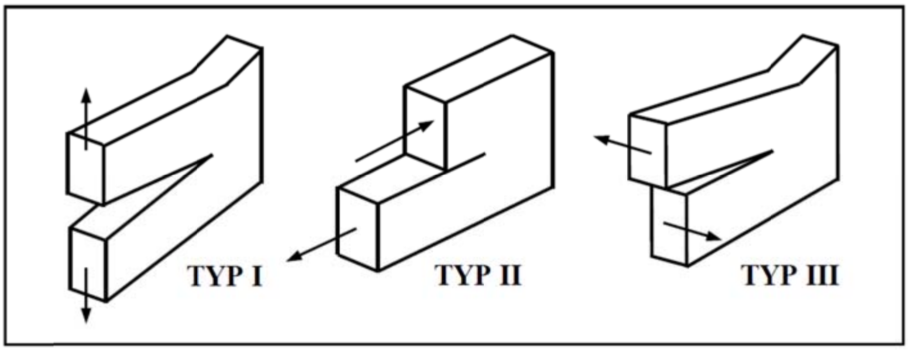

Figure 9.7. Types of crack loading[18]

From the point of view of real behavior of asphalt layers in pavement structure, mode I is recognized as mode which suits the best to real conditions. In mode I the stress acts perpendicular to the fracture area. In a critical situation, when stresses reach critical value, uncontrolled propagation of the crack occurs in the pavement. On the basis of critical stresses (critical forces) and strains at the time of their occurrence following parameters characterizing the resistance of asphalt mixtures to cracking are calculated:

- critical stress intensity factor, K_{IC}, called fracture toughness,
- critical value of the *J-integral*, J_C characterizes the energy release rate.

Fracture toughness is calculated with the use of formula (9.5) [5]:

$$K_I = \sigma_0 Y_I \sqrt{\pi a} \qquad (9.5)$$

where:

a - depth of the notch,

[18] Artamendi I., Khalid H. A., A comparison between beam and semi-circular bending fracture tests for asphalt, Road Materials and Pavement Design, volume 7, supplement 1, 2006, pages 163-180

σ_0 - maximum stress during the test,
Y_I - normalized stress intensity factor in the type I of crack loading.

The maximum bending stress in the specimen is calculated using following formula (9.6):

$$\sigma_0 = \frac{F}{2rB} \tag{9.6}$$

where:
F - maximum force during the test,
r - radius of the specimen,
B - thickness of the specimen.

The normalized stress intensity factor Y_I depends on the type and shape of the specimen. Its value can be determined using finite element method. For semi-circular samples with the ratio of the mid-span beam to the specimen diameter equal to 0.8 the normalized stress intensity factor is calculated from the following formula (9.7):

$$Y_I = 4{,}782 - 1{,}219\left(\frac{a}{r}\right) + 0{,}063exp\left(7{,}045\left(\frac{a}{r}\right)\right) \tag{9.7}$$

where:
a - depth of the notch,
r - radius of the specimen.

The critical value of the J-integral that characterize strain energy release rate during crack propagation was calculated by method used among others by Elseifi at al.[6] This method involves calculating the relationship between the change in notch length that was cut in the bottom plane of the sample, and change of strain energy measured to failure. The J-integral was calculated by formula (9.8):

$$J_C = -\left(\frac{1}{B}\right)\frac{dU}{da} \tag{9.8}$$

where:
U - strain energy to failure of the specimen,
a - depth of the notch,
B - thickness of specimen
dU/da - change of strain energy with changing of notch depth.

In order to determine the change of strain energy with the change of notch depth, tests were carried out on specimens with different depth of initial crack, which was 10 mm, 20 mm and 30 mm.

During the test specimens were subjected to bending load which was applied with constant speed. For each specimen, a value of force and vertical displacement were measured. The displacement rate was 1 mm/min. All tests were carried out at -20°C.

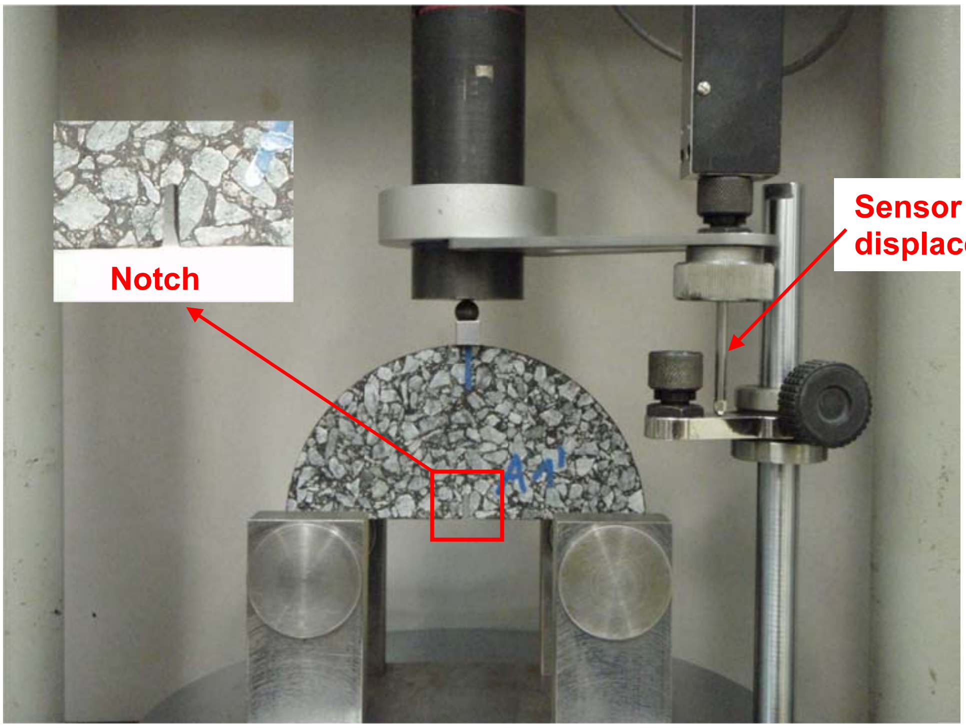

Figure 9.8. SCB specimen placed on loading frame

On the basis of the value of maximum load recorded at the corresponding vertical displacement critical stress intensity factor, K_{IC} was calculated.

Strain energy to failure was calculated as the area under the graph *F(d)* and from the analysis of the graph that illustrate relationship between deformation energy and depth of the notch. From the graph *U(a)* were determined equation of linear regression in which the slope of the function is the derivative *dU/da*.

9.2.3. Test results

Figures 9.9 to 9.14 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.

Summary of the test results of fracture toughness are shown in Table 9.7. and Figure 9.15 and 9.16. Detailed results are presented in Appendix 1.

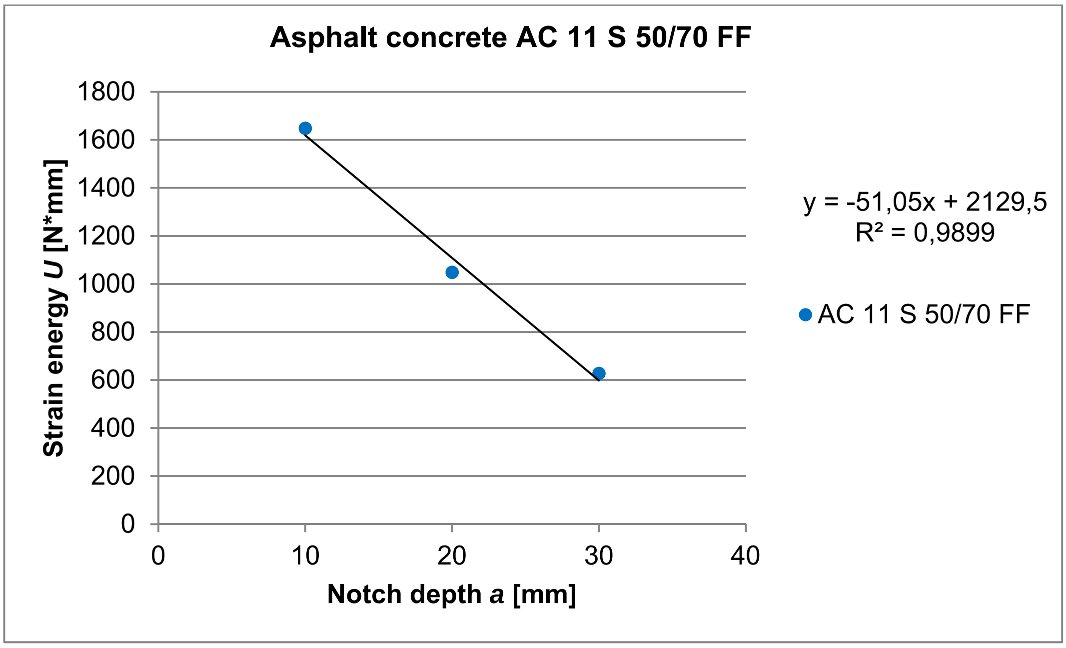

Figure 9.9. Relationship between strain energy and the notch depth, asphalt mixture AC 11 S with bitumen 50/70 FF

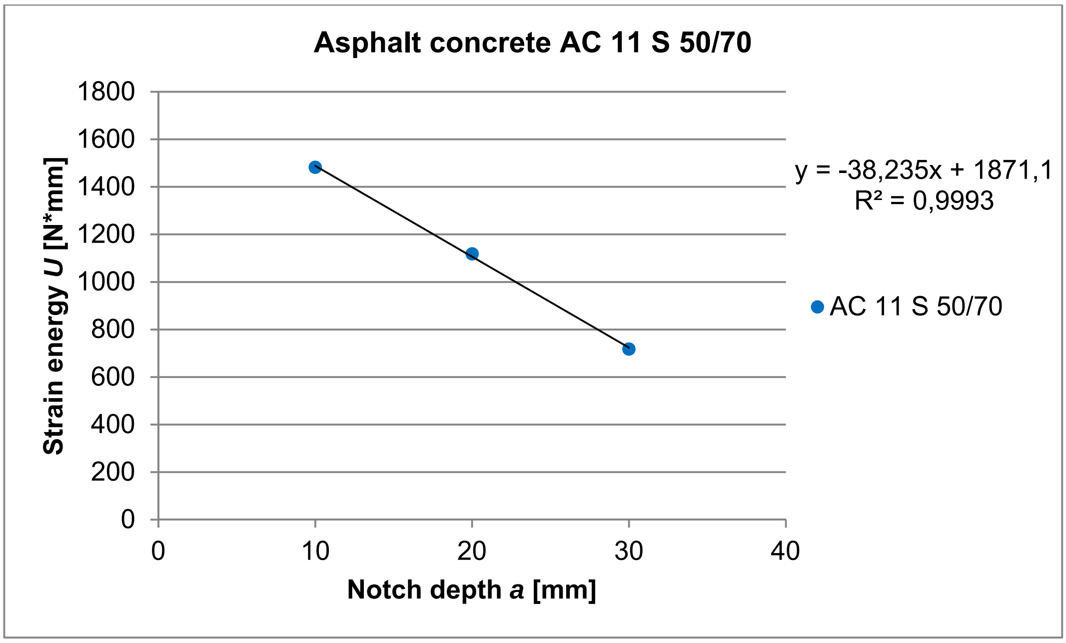

Figure 9.10. The relationship between the strain energy and the notch depth, asphalt mixture: AC 11 S with bitumen 50/70

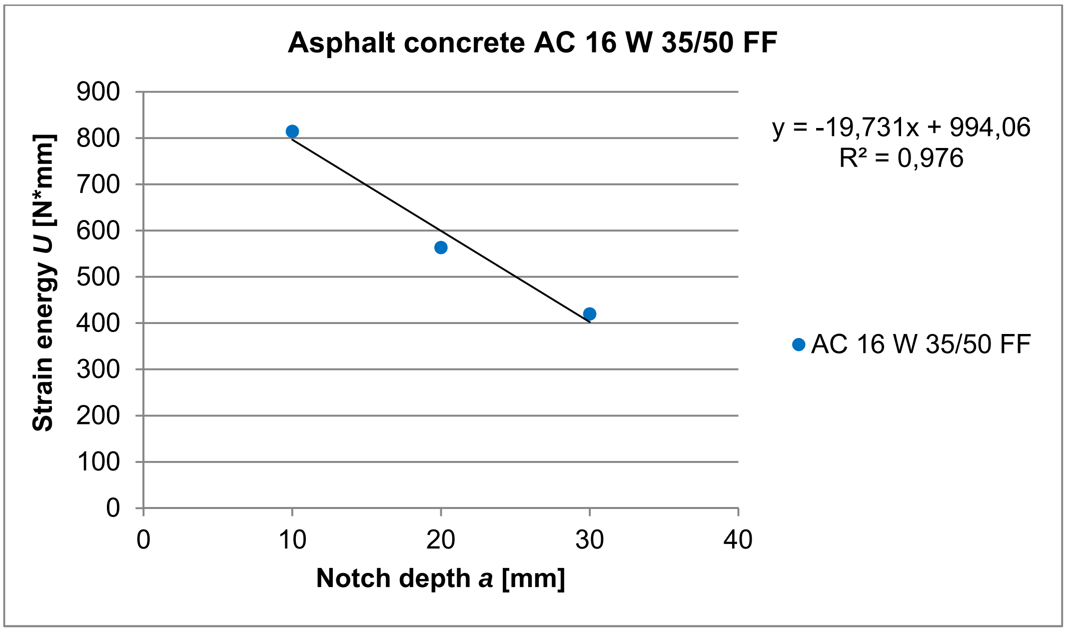

Figure 9.11. The relationship between the strain energy and the notch depth, asphalt mixture: AC 16 W with bitumen 35/50 FF

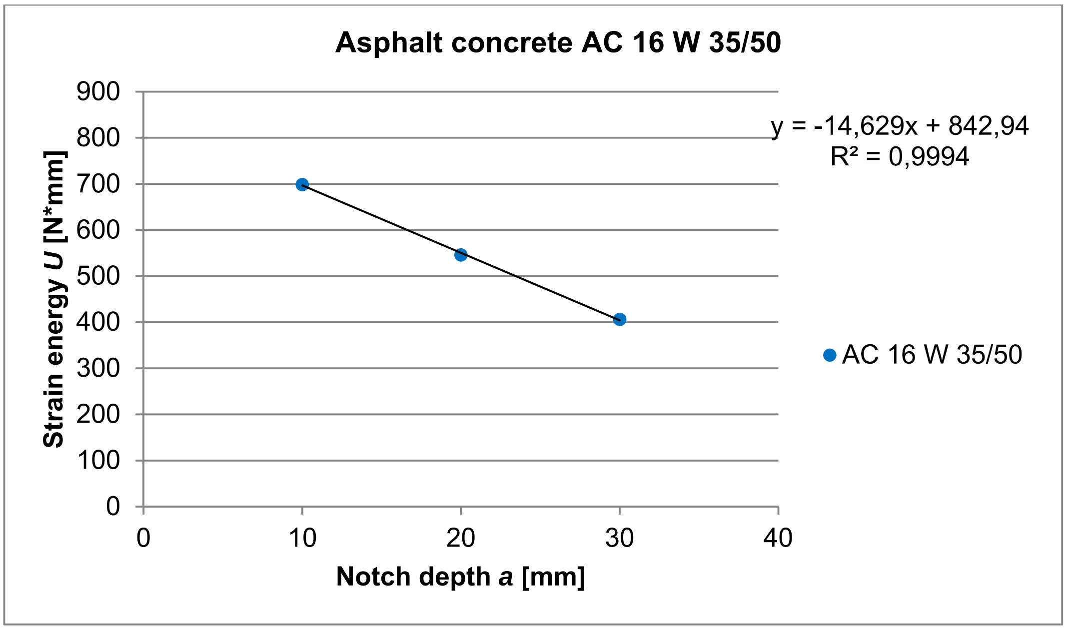

Figure 9.12. The relationship between the strain energy and the notch depth, asphalt mixture: AC 16 W with bitumen 35/50

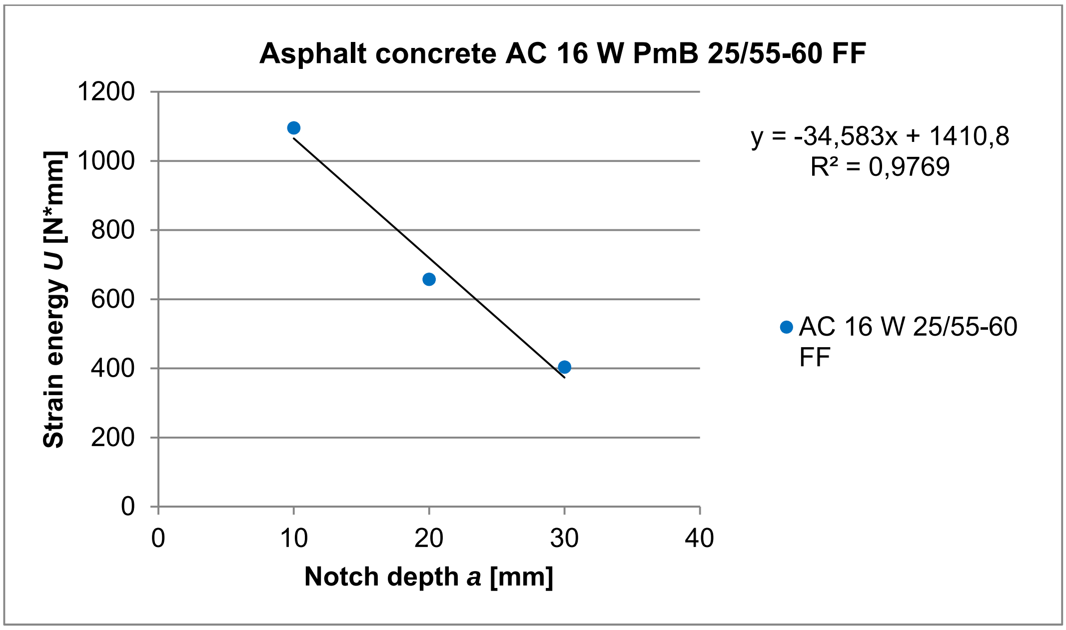

Figure 9.13. The relationship between the strain energy and the notch depth, asphalt mixture: AC 16 W with PmB 25/55-60 FF

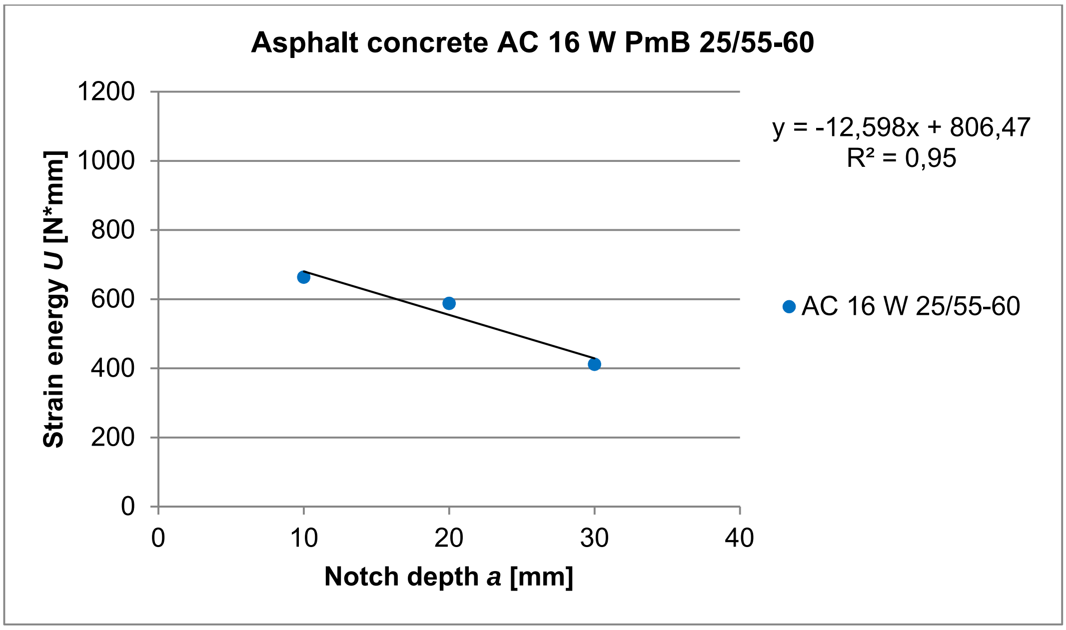

Figure 9.14. The relationship between the strain energy and the notch depth, asphalt mixture: AC 16 W with PmB 25/55-60

Table 9.7. The results of fracture toughness test at -20°C, the average values from four specimens

Type of asphalt mixture	a [mm]	F_{max} [N]	U [N*mm]	σ_0 [N/mm^2]	K_{IC} [N*mm$^{-3/2}$]	dU/da [N]	J_C [kJ/m^2]
AC 11 S 50/70 FF	10	9699	1648,8	1,3	34,7	-51,05	1,02
	20	7645	1049,0	1,0	39,3		
	30	5097	627,8	0,7	35,3		
AC 11 S 50/70	10	9082	1482,8	1,2	32,4	-38,24	0,76
	20	7562	1118,3	1,0	38,9		
	30	5005	718,1	0,7	34,7		
AC 16 W 35/50 FF	10	8154	814,6	1,1	29,1	-19,73	0,39
	20	6299	563,7	0,8	32,4		
	30	4001	420,0	0,5	27,7		
AC 16 W 35/50	10	7832	698,8	1,0	28,0	-14,63	0,29
	20	5879	546,1	0,8	30,3		
	30	3352	406,2	0,4	23,2		
AC 16 W 25/55-60 FF	10	8750	1095,7	1,2	31,3	-34,58	0,69
	20	5914	657,7	0,8	30,4		
	30	4307	404,0	0,6	29,8		
AC 16 W 25/55-60	10	8403	663,8	1,1	30,0	-12,60	0,25
	20	6268	587,9	0,8	32,3		
	30	4449	411,9	0,6	30,8		

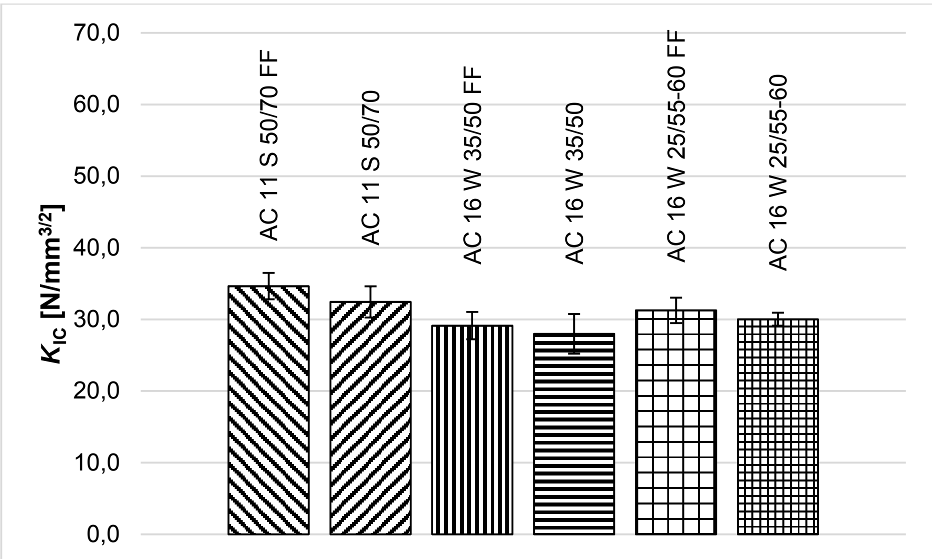

Figure 9.15. Fracture toughness K_{IC} of investigated asphalt concretes for notch depth a = 10mm

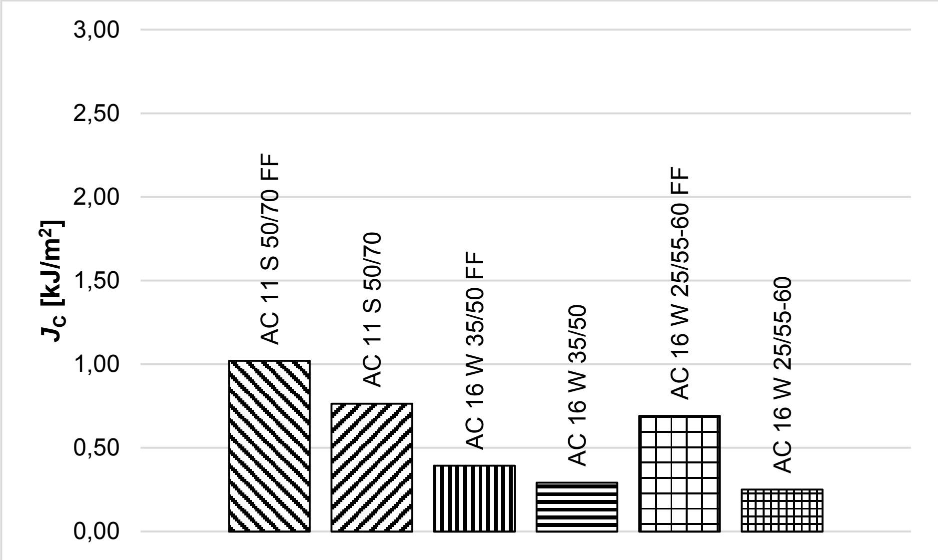

Figure 9.16. Integral J_C investigated asphalt concretes

For fracture toughness parameter, an additional series of specimens was tested to evaluate the influence of fibers dosing method on test results. Besides the method recommended by the producer according to which fibers are added to hot aggregate before bitumen is added, another method was used, where fibers were added to the mixture with already added bitumen and initially coated. Such specimens were marked as FF2.

Asphalt mixtures prepared in this manner were aged before compaction according to short term aging procedure. In addition, another asphalt mixture for binder course AC 16 W 35/50 produced in asphalt plant was also tested at this stage. The composition of this mixture was different than mixtures for binder course used through earlier stage of research. In this case, previously produced asphalt concrete was re-heated and fibers were added. Due to the fact that this mixture was produced in asphalt plant, a short term aging procedure was omitted.

Results of additional research are shown in Figure 9.17, and 9.18. The mixture that was produced in asphalt plant and reheated in laboratory to add fibers is marked as AC 16 W 35/50 WMB.

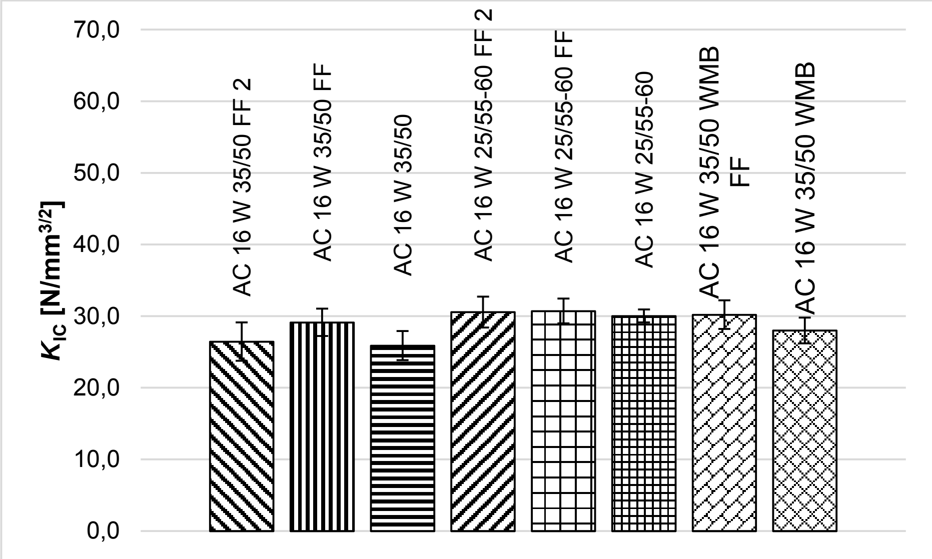

Figure 9.17. The test results of fracture toughness K_{IC} of investigated asphalt concretes for notch depth *a* = 10mm - additional research

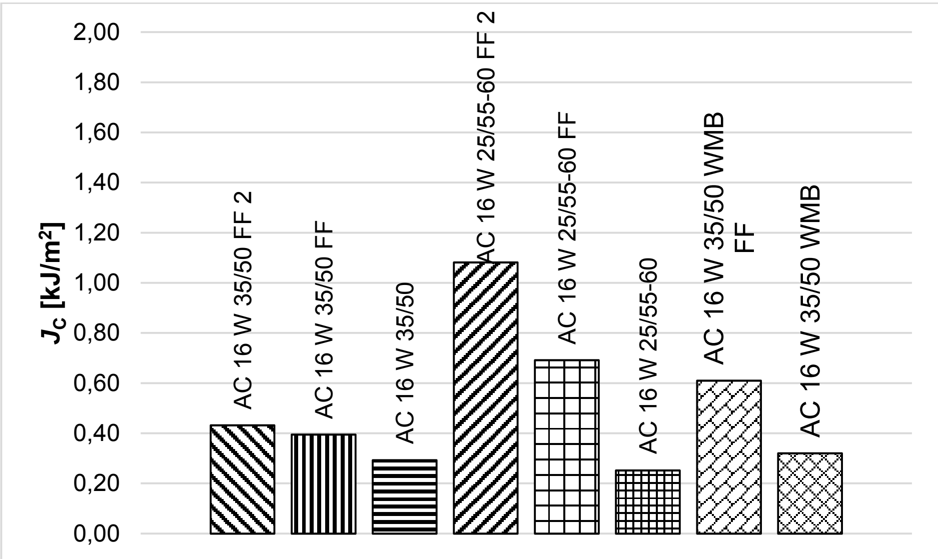

Figure 9.18. The integral J_C investigated asphalt concretes - additional research

9.2.4. Analysis of test results

Based on the study of fracture toughness it can be concluded that:

1. At the temperature of -20°C the fracture toughness measured by the stress intensity factor K_{IC} is slightly higher for mixtures containing FORTA-FI fibers in comparison with mixtures without fibers, which can be recognized as positive result.

2. The fracture toughness measured by the J-integral was significantly higher for mixtures containing FORTA-FI fibers as compared to mixtures without them. J-integral takes into account not only the maximum force but also strain at the

time of specimen failure. In terms of real conditions that occur in pavement layers this measurement can be considered as more reliable. Increased value of the J-integral means that more strain energy must be used to propagate the crack.

3. The largest increase of J-integral occurred in case of addition of fibers to the asphalt concrete for wearing course AC 11S with bitumen 50/70 and for asphalt concrete for binder course AC 16W with polymer modified bitumen PmB 25/55-60. Change of J-integral for asphalt concrete AC 16 W with bitumen 35/50 was smaller, but absolute value of J-integral for this asphalt mixture with FORTA FI fibers was higher than for specimens of asphalts concrete AC 16 W PmB 25/55-60 without fibers.

4. The additional research conducted on specimens of asphalt concretes that were prepared in a different way than recommended by the producer (fibers were added to mixture after bitumen was added and initial coating was done) showed that the method of fiber application can influence fracture properties of asphalt mixtures measured by the J-integral. In each case the value of the J-integral for additional specimens was higher than the value of the J-integral for mixtures where fibers were applied before adding the bitumen.

10. DYNAMIC MODULUS TEST IN AMPT/SPT APPARATUS

10.1. Test method

Dynamic modulus test in Asphalt Mixture Performance Tester/Simple Performance Tester (AMPT/SPT) apparatus was made on the basis of proposed American guidelines NCHRP 9-29: PP 02 as included in the NCHRP Report 614. This is a revised and simplified version of the dynamic modulus test based on AASHTO TP62.

The study was conducted on cylindrical specimens of 100 mm in diameter and height of 150 mm, which were compacted in the gyratory compactor device. Before actual testing, the upper and lower parts of the specimens were cut precisely in order to obtain two flat and parallel surfaces.

The dynamic modulus test was based on axial sinusoidal 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 10.1.

Figure 10.1. View of the AMPT/SPT apparatus

The parameters measured in the test were dynamic modulus and phase angle. The load frequencies were used as follows: 25 Hz, 20 Hz, 10 Hz, 5 Hz, 2 Hz, 1 Hz, 0.5 Hz, 0.2 Hz, 0.1 Hz, 0.01 Hz. The specimen was placed in a transparent, moveable chamber in which constant temperature was kept during the test. The sample was then loaded axially by an actuator. The measurement of the dynamic modulus and phase angle was performed at 3 temperatures according to the US Guidelines: + 4°C; + 20°C and + 40°C in the frequency range from 25 Hz to 0.01 Hz. According to the guidelines, in the frequency of 0.01 Hz test was made only for the highest temperature. For each temperature 3 cylindrical specimens were tested.

The dynamic modulus test was conducted in order to obtain the characteristics of asphalt mixtures in the form of Master Curves. In that case tests were performed to a limited extent, only for one mixture AC 11S with of bitumen 50/70.

10.2. Test results

The test results of the dynamic modulus for asphalt mixture AC 11S are shown in Table 10.1. The phase angles for the examined mixture are presented in Table 10.2. The results are presented as average values of dynamic modulus and phase angles, with coefficients of variation.

Table 10.1. The average values of dynamic modules for asphalt concrete AC 11 S with and without FORTA FI fibers

Temp. [°C]	Type of asphalt mixture	Test frequency f, Hz									
		25	20	10	5	2	1	0,5	0,2	0,1	0,01
4,0	**AC 11S FF**	**18469**	**18176**	**17085**	**15953**	**14375**	**13178**	**11952**	**10511**	**9330**	nt
	CV [%]	7,13	7,03	6,90	6,52	6,25	5,95	5,53	5,97	5,13	nt
	AC 11S	**20163**	**19768**	**18483**	**17170**	**15385**	**13997**	**12580**	**10723**	**9348**	nt
	CV [%]	5,11	5,14	5,19	5,05	4,80	4,57	4,23	3,50	2,75	nt
20,0	**AC 11S FF**	**8872**	**8551**	**7338**	**6179**	**4775**	**3833**	**2998**	**2096**	**1546**	nt
	CV [%]	3,43	3,65	4,02	4,29	4,16	3,80	3,44	4,46	4,91	nt
	AC 11S	**8965**	**8631**	**7359**	**6159**	**4730**	**3794**	**2974**	**2062**	**1513**	nt
	CV [%]	3,40	3,72	4,23	4,18	4,08	3,87	3,84	3,78	3,71	nt
40,0	**AC 11S FF**	**1525**	**1376**	**948**	**634**	**368**	**251**	**176**	**117**	**90**	**47**
	CV [%]	7,36	8,20	9,56	10,79	12,04	12,59	13,02	14,29	14,45	9,09
	AC 11S	**1897**	**1743**	**1235**	**856**	**510**	**355**	**255**	**174**	**136**	**84**
	CV [%]	2,01	2,27	2,18	0,89	1,83	1,70	2,46	3,83	5,11	2,45

CV – coefficient of variation
nt – not tested

Table 10.2. The average values of the phase angles for asphalt concrete AC 11 S with and without FORTA FI fibers

Temp. [°C]	Type of asphalt mixture	Test frequency f, Hz									
		25	20	10	5	2	1	0,5	0,2	0,1	0,01
4,0	**AC 11S FF**	**8,04**	**8,35**	**9,35**	**10,42**	**12,03**	**13,38**	**14,94**	**16,97**	**18,81**	nt
	CV [%]	3,65	2,87	2,80	2,70	2,58	2,69	2,84	0,93	0,65	nt
	AC 11S	**8,15**	**8,53**	**9,54**	**10,62**	**12,21**	**13,60**	**15,17**	**17,55**	**19,62**	nt
	CV [%]	0,55	1,05	0,90	0,68	0,54	0,85	1,18	1,67	1,63	nt
20,0	**AC 11S FF**	**21,23**	**21,71**	**24,02**	**26,32**	**29,36**	**31,43**	**33,50**	**34,87**	**35,34**	nt
	CV [%]	2,03	1,85	2,07	2,15	2,19	2,04	1,74	1,78	1,90	nt
	AC 11S	**21,24**	**21,86**	**24,18**	**26,47**	**29,52**	**31,57**	**33,30**	**35,11**	**35,71**	nt
	CV [%]	1,14	0,63	0,74	0,84	1,01	1,20	1,35	1,57	1,60	nt
40,0	**AC 11S FF**	**42,69**	**41,64**	**41,52**	**41,23**	**40,36**	**38,61**	**36,34**	**32,77**	**29,72**	**20,33**
	CV [%]	1,87	1,49	1,97	2,78	3,25	3,19	3,11	2,90	3,49	0,84
	AC 11S	**41,31**	**40,02**	**39,80**	**39,26**	**38,32**	**36,61**	**34,37**	**30,98**	**28,05**	**18,83**
	CV [%]	1,37	1,31	1,00	1,45	0,89	1,05	1,49	2,55	3,31	3,45

CV – coefficent of variation
nt – not tested

To determine the equation of the master curve for dynamic modulus the final version of the formula given in section 10.1.3 of the Guidelines NCHRP 9-29: PP 02 was used. This formula is as follows (10.1):

$$\log\left|E^*\right| = \delta + \frac{(Max - \delta)}{1 + e^{\beta + \gamma\left\{\log f + \frac{\Delta E_a}{19.14714}\left[\left(\frac{1}{T}\right) - \left(\frac{1}{T_r}\right)\right]\right\}}} \tag{10.1}$$

where:

|E*| - dynamic modulus, psi (1 MPa = 145,0377 psi)

Max	- specified limiting maximum modulus; psi
f	- frequency of loading in test temperature, Hz
Tr	- reference temperature, K
T	- test temperature, K
ΔEa	- activation energy (treated as a fitting parameter).
δ,β,γ	- fitting parameters.

To determine the reduced frequency during determining the master curve Arrhenius equation was used as described in section 10.1.2 of the guidelines NCHRP 9-29: PP 02. The formula is as follows (10.2):

$$\log f_r = \log f + \frac{\Delta E_a}{19.14714}\left(\frac{1}{T} - \frac{1}{T_r}\right) \tag{10.2}$$

To determine the master curve, average dynamic modulus values obtained from tests performed at 3 temperatures were used. The reference temperature value of +20°C was selected. Resulting master curves are shown in Figure 10.2.

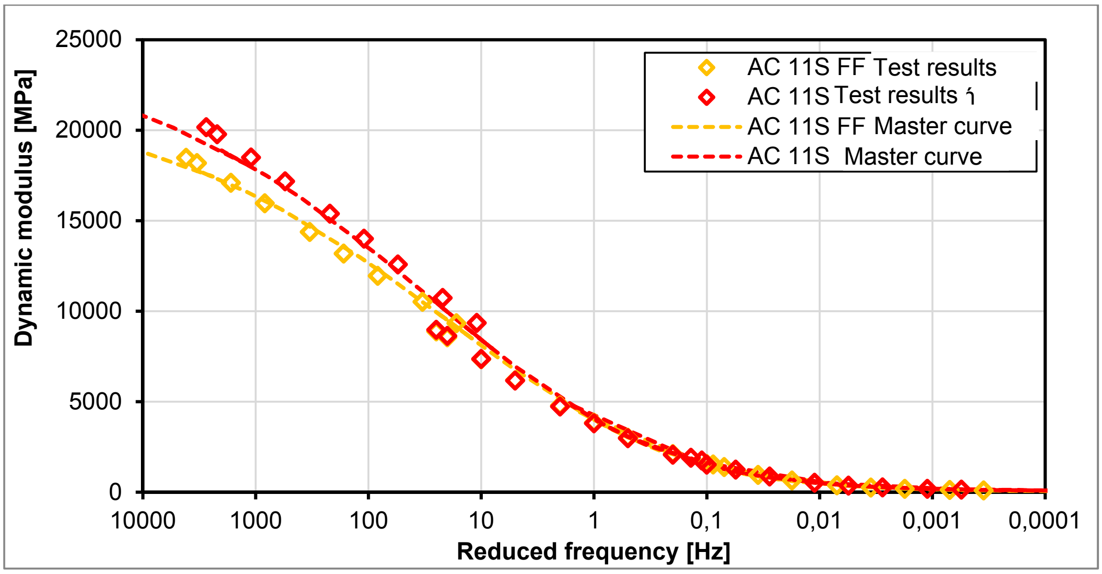

Figure 10.2. Master curves determined for asphalt mixtures of AC 11S type, reference temperature T=20°C

10.3. Analysis of test results

Results obtained in the AMPT/SPT test of dynamic modulus for most of the reduced frequencies were very similar. Differences occurred only at reduced frequencies from 100 to 10,000 Hz, which corresponds to the properties of asphalt mixtures at low temperatures. Asphalt mixture AC 11S FF obtained somewhat lower values of dynamic modulus, which is advantageous from the point of view low-temperature behavior. However, the difference between results is not too significant and it is equal to about 1 500 MPa.

Master curve analysis showed no effect of the fiber addition on the properties of asphalt mixtures in the reduced frequencies range of 0.0001 to 100 Hz, which corresponds to properties at high temperatures.

11. CONCLUSIONS

Based on the results of the research concerning selected properties of asphalt concretes with and without FOTRA-FI fibers, that fulfil Polish technical requirements of the WT-2 2014, the following conclusions can be drawn:

1. The addition of aramid FORTA-FI fibers improves performance characteristics of asphalt concretes, primarily resistance to low-temperature cracking. In particular, positive effect of fibers was observed in the case of asphalt concretes with neat bitumen and softer bitumen. Positive effect in asphalt concrete with polymer modified bitumen (PmB) and harder bitumen was not so distinctive.

2. The addition of FORTA-FI fibers does not cause problems in the design and production procedures of asphalt mixtures in the laboratory. Evaluation of full scale production of asphalt mixtures with addition of FORTA-FI in asphalt mixing plant was not the objective of this research program.

3. The application of FORTA-FI fibers did not change significantly the stiffness modulus in the temperature range from 0°C to 25°C and did not change significantly the indirect tensile strength of the asphalt concrete in a temperature range from -20°C to +20°C. However, It should be noted, that the addition of fibers for asphalt concretes with the compaction index of about 98% (specimens used in the research of resistance to water and frost action) in each case increased indirect tensile strength at temperature +25°C for 5-12%.

4. Application of FORTA-FI fibers in asphalt concrete with neat bitumens (without polymer modification) definitely improved strength indicators during test of resistance to water and frost action. However, in the case of polymer modified bitumen no effect was observed.

5. There was no significant increase of resistance to permanent deformation of asphalt concretes after FORTA FI were implemented in their composition. However, some increase of resistance to permanent deformation was observed in particular for asphalt concrete for wearing course with bitumen 50/70.

6. Application of FORTA-FI fibers in asphalt concrete clearly improves resistance to low temperature cracking. For every type of tested asphalt concrete, increase of flexural strength, ultimate strain and reduction of flexural stiffness modulus in -20°C was observed. This can indicate that asphalt concretes with the addition of FORTA FI fibers can be more resistant to low temperature cracking. The

stiffening index for asphalt concretes with FORTA-FI fibers was also lower in temperature -20°C.

7. Increased resistance to low temperature cracking of asphalt concretes with FORTA-FI fibers was clearly confirmed in tests of fracture toughness at temperature -20°C. All tested asphalt concretes with application of fibers had higher fracture energy compared to asphalt concretes without fibers. The same trend was observed in the analysis of the stress intensity factor, but conclusions were not so clear.

8. Study of the dynamic modulus (E*) of asphalt concrete for wearing course with application of fibers confirmed the capability to improve properties at low temperatures. No clear differences in frequencies that correspond to properties of asphalt mixtures at high temperature were observed.

9. Preliminary study of the effect of different application method of FORTA-FI fibers to asphalt concrete (ie. when added to the asphalt mixture, after initial coating) showed its positive effect on the mechanical properties and performance. More favorable results of low temperature cracking resistance measured by the energy to failure were achieved for specimens prepared using a method when fibers were added to mixture after bitumen was added and initial coating was done. This issue requires further research.

10. Increased capability of asphalt concretes with use of fibers in fracture toughness test was observed, so it would be advisable to carry out more research work in the area of fatigue life of asphalt mixtures, which results could further highlight benefits of FORTA-FI fibers application.

11. In summary, conducted research has shown positive potential of FORTA-FI fibers usage, mainly in the area of resistance of asphalt mixtures to low temperature cracking. This is a very important issue in Polish climatic conditions. Another possible area which could show the potential benefits of FORTA-FI fibers application is fatigue life of asphalt concrete and pavement structures. Because of the vast knowledge concerning this topic it was not analyzed at this stage of the research.

APPENDIX 1. Detailed results of the fracture toughness test

Type of asphalt mixture	Notch depth [mm]	No of sample	F_{max} [N]	Average F_{max} [N]	δ [mm]	Average δ [mm]	ε_{max} [%]	Average ε_{max} [%]	σ_0 [N/mm^2]	Average σ_0 [N/mm^2]	K_{Ic} [N/mm$^{3/2}$]	Average K_{Ic} [N/mm$^{3/2}$]	U	Average U	dU/da	J-integral
AC 11 S 50/70 FF	10	424/13	9888	9699	0,29	0,33	0,4	0,4	1,3	1,3	35,3	34,7	1547,77	1648,8	-51,05	1,02
		424/14	8935		0,26		0,3		1,2		31,9		1246,28			
		424/15	10084		0,37		0,5		1,3		36,0		1980,65			
		424/16	9890		0,40		0,5		1,3		35,3		1820,36			
	20	424/17	7411	7645	0,26	0,25	0,4	0,3	1,0	1,0	38,1	39,3	1054,83	1049,0		
		424/18	8178		0,27		0,4		1,1		42,1		1170,99			
		424/19	7796		0,23		0,3		1,0		40,1		994,07			
		424/20	7194		0,24		0,3		1,0		37,0		975,95			
	30	424/21	4647	5097	0,21	0,23	0,3	0,3	0,6	0,7	32,2	35,3	543,13	627,8		
		424/22	4887		0,23		0,3		0,7		33,8		453,16			
		424/23	6041		0,27		0,4		0,8		41,8		938,15			
		424/24	4812		0,22		0,3		0,6		33,3		576,59			
AC 11 S 50/70	10	423/13	8356	9082	0,30	0,29	0,4	0,4	1,1	1,2	29,9	32,4	1492,89	1482,8	-38,24	0,76
		423/14	9380		0,23		0,3		1,3		33,5		1238,58			
		423/15	8844		0,33		0,4		1,2		31,6		1598,95			
		423/16	9748		0,30		0,4		1,3		34,8		1600,64			
	20	423/17	7708	7562	0,23	0,27	0,3	0,4	1,0	1,0	39,7	38,9	1020,65	1118,3		
		423/18	7468		0,33		0,4		1,0		38,4		1325,01			
		423/19	7583		0,28		0,4		1,0		39,0		1156,31			
		423/20	7487		0,22		0,3		1,0		38,5		971,20			
	30	423/21	4906	5005	0,22	0,25	0,3	0,3	0,7	0,7	34,0	34,7	609,05	718,1		
		423/22	5728		0,21		0,3		0,8		39,7		799,21			
		423/23	4125		0,31		0,4		0,6		28,6		709,22			
		423/24	5260		0,25		0,3		0,7		36,4		754,81			

Type of asphalt mixture	Notch depth [mm]	No of sample	F_{max} [N]	Average F_{max} [N]	δ [mm]	Average δ [mm]	ε_{max} [%]	Average ε_{max} [%]	σ_0 [N/mm^2]	Average σ_0 [N/mm^2]	K_{Ic} [N/mm$^{3/2}$]	Average K_{Ic} [N/mm$^{3/2}$]	U	Average U	dU/da	J-integral
AC 16 W 35/50 FF	10	413/13	7473	8154	0,12	0,18	0,2	0,2	1,0	1,1	26,7	29,1	529,59	814,6	-19,73	0,39
		413/14	8657		0,22		0,3		1,2		30,9		1018,92			
		413/15	8495		0,23		0,3		1,1		30,4		1064,84			
		413/16	7991		0,15		0,2		1,1		28,5		645,10			
	20	413/17	6695	6299	0,13	0,17	0,2	0,2	0,9	0,8	34,5	32,4	505,30	563,7		
		413/18	5650		0,21		0,3		0,8		29,1		501,49			
		413/19	6778		0,20		0,3		0,9		34,9		740,54			
		413/20	6072		0,15		0,2		0,8		31,2		507,65			
	30	413/21	3821	4001	0,15	0,17	0,2	0,2	0,5	0,5	26,5	27,7	317,89	420,0		
		413/22	3702		0,14		0,2		0,5		25,6		287,26			
		413/23	4464		0,21		0,3		0,6		30,9		673,77			
		413/24	4017		0,18		0,2		0,5		27,8		401,08			
AC 16 W 35/50	10	414/13	-	7247	-	0,18	-	0,2	-	1,0	-	25,9	-	698,8	-14,63	0,29
		414/14	-		-		-		-		-		-			
		414/15	6843		0,21		0,3		0,9		24,4		783,82			
		414/16	7650		0,15		0,2		1,0		27,3		613,72			
	20	414/17	6368	5879	0,17	0,16	0,2	0,2	0,8	0,8	32,8	30,3	722,39	546,1		
		414/18	5688		0,18		0,2		0,8		29,3		573,46			
		414/19	5543		0,15		0,2		0,7		28,5		439,74			
		414/20	5915		0,13		0,2		0,8		30,4		448,86			
	30	414/21	3758	3367	0,30	0,20	0,4	0,3	0,5	0,4	26,0	23,3	592,06	406,2		
		414/22	-		-		-		-		-		-			
		414/23	3418		0,14		0,2		0,5		23,7		300,43			
		414/24	2926		0,17		0,2		0,4		20,3		326,07			

Type of asphalt mixture	Notch depth [mm]	No of sample	F_{max} [N]	Average F_{max} [N]	δ [mm]	Average δ [mm]	ε_{max} [%]	Average ε_{max} [%]	σ_0 [N/mm^2]	Average σ_0 [N/mm^2]	K_{Ic} [N/mm$^{3/2}$]	Average K_{Ic} [N/mm$^{3/2}$]	U	Average U	dU/da	J-integral
AC 16 W 25/55-60 FF	10	418/13	8323	8597	0,21	0,22	0,3	0,3	1,1	1,1	29,7	30,7	1055,52	1095,7	-34,58	0,69
		418/14	9157		0,20		0,3		1,2		32,7		1065,94			
		418/15	8312		0,26		0,3		1,1		29,7		1165,63			
		418/16	-		-		-		-		-		-			
	20	418/17	5606	6193	0,18	0,19	0,2	0,3	0,7	0,8	28,8	31,9	546,58	657,7		
		418/18	-		-		-		-		-		-			
		418/19	6780		0,21		0,3		0,9		34,9		768,76			
		418/20	-		-		-		-		-		-			
	30	418/21	4301	4307	0,11	0,16	0,1	0,2	0,6	0,6	29,8	29,8	303,93	404,0		
		418/22	4635		0,19		0,3		0,6		32,1		518,53			
		418/23	3608		0,18		0,2		0,5		25,0		379,63			
		418/24	4685		0,15		0,2		0,6		32,4		414,05			
AC 16 W 25/55-60	10	419/13	8047	8403	0,11	0,14	0,1	0,2	1,1	1,1	28,7	30,0	481,02	663,8	-12,60	0,25
		419/14	8488		0,15		0,2		1,1		30,3		685,25			
		419/15	8432		0,14		0,2		1,1		30,1		678,96			
		419/16	8645		0,17		0,2		1,2		30,9		810,00			
	20	419/17	6079	6268	0,17	0,17	0,2	0,2	0,8	0,8	31,3	32,3	533,57	587,9		
		419/18	6274		0,15		0,2		0,8		32,3		546,57			
		419/19	6212		0,15		0,2		0,8		32,0		490,47			
		419/20	6507		0,22		0,3		0,9		33,5		781,03			
	30	419/21	4320	4449	0,16	0,16	0,2	0,2	0,6	0,6	29,9	30,8	402,31	411,9		
		419/22	4800		0,19		0,3		0,6		33,2		516,36			
		419/23	4319		0,14		0,2		0,6		29,9		357,11			
		419/24	4358		0,16		0,2		0,6		30,2		371,63			

Type of asphalt mixture	Notch depth [mm]	No of sample	F_{max} [N]	Average F_{max} [N]	δ [mm]	Average δ [mm]	ε_{max} [%]	Average ε_{max} [%]	σ_0 [N/mm^2]	Average σ_0 [N/mm^2]	K_{Ic} [N/mm$^{3/2}$]	Average K_{Ic} [N/mm$^{3/2}$]	U	Average U	dU/da	J-integral

AC 16 W 35/50 FF 2	10	505-1	6559	7399	0,18	0,19	0,2	0,3	0,9	1,0	23,4	26,4	647,66	851,2	-21,59	0,43
		505-2	7636		0,25		0,3		1,0		27,3		1239,35			
		505-3	8003		0,15		0,2		1,1		28,6		666,58			
		505-4	-		-		-		-		-		-			
	20	505-5	6609	5573	0,23	0,19	0,3	0,3	0,9	0,7	34,0	28,7	782,35	738,4		
		505-6	4460		0,16		0,2		0,6		23,0		341,68			
		505-7	5650		0,19		0,3		0,8		29,1		613,16			
		505-8	-		-		-		-		-		1216,53			
	30	505-9	3974	3999	0,14	0,19	0,2	0,3	0,5	0,5	27,5	27,7	325,57	419,4		
		505-10	3943		0,20		0,3		0,5		27,3		449,32			
		505-11	4245		0,19		0,3		0,6		29,4		432,01			
		505-12	3834		0,23		0,3		0,5		26,5		470,66			
AC 16 W 25/55-60 FF 2	10	504-1	9211	8386	0,36	0,32	0,5	0,4	1,2	1,1	32,9	30,6	1852,67	1491,4	-54,08	1,08
		504-2	8027		0,24		0,3		1,1		28,7		1091,14			
		504-3	8430		0,41		0,6		1,1		30,1		1906,93			
		504-4	7875		0,26		0,4		1,1				1114,76			
	20	504-5	5921	6385	0,24	0,20	0,3	0,3	0,8	0,9	30,5	32,9	786,97	746,1		
		504-6	-		-		-		-		-		-			
		504-7	7005		0,20		0,3		0,9		36,0		863,19			
		504-8	6230		0,16		0,2		0,8		32,1		588,06			
	30	504-9	-	4326	-	0,15	-	0,2	-	0,6	-	30,0	-	409,8		
		504-10	4723		0,17		0,2		0,6		32,7		492,31			
		504-11	4011		0,16		0,2		0,5		27,8		387,77			
		504-12	4244		0,13		0,2		0,6		29,4		349,36			