1 **Influence of cooling rate and additives on low-temperature properties**

2 **of asphalt mixtures in the TSRST**

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11   **Abstract**

12   The paper presents the results and analysis of low-temperature properties of asphalt

13   mixtures according to Thermal Stress Restrained Specimen Test (TSRST) method. Different

14   groups of bitumen were investigated: neat, SBS-modified and highly SBS-modified. Influence of

15   cooling rates (1°C/h, 3°C/h, 5°C/h and 10°C/h) and additives (aramid fibres and crumb rubber)

16   was identified as well. Moreover, for each factor stiffness moduli were back-calculated from

17   the TSRST results and analysed. The greatest impact on the TSRST results had type of

18   bitumen, followed by the cooling rate and additives. Application of longer fibres improved low-

19   temperature properties of the asphalt mixtures.

20   **Keywords:** low-temperature cracking, cooling rate, asphalt mixture, bitumen

21   type, aramid fibres, crumb rubber, TSRST,

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22   **1. Introduction**

23   1.1. Background

24   Despite the increase in mean value of global temperature, many areas of northern

25   countries still experience extreme daily low temperatures during severe winters. These

26   conditions may cause transverse cracking distress in asphalt pavements. A decrease in

27   temperature creates tensile stresses in a constrained pavement that cannot be relieved if

28   the temperature is extremely low and the material is stiff. In the literature this type of

29   cracking results from a single drop in temperature to an extremely low value and cracks

30   occur when thermal tensile stresses exceed the fracture strength of an asphalt pavement

31   layer [1-6]. One of the most common laboratory methods to evaluate low-temperature

32   properties of asphalt mixtures is the Thermal Stress Restrained Specimen Test (TSRST),

33   presented for the first time in 1965 by Monismith et al. [7]. The method was then applied

34   by other researchers such as Stock and Arand [8], Jung and Vinson [9]. TSRST method

35   was evaluated and stress measurement was improved due to the phenomenon of specimen

36   bending during the test. The method estimates the bending stress from the angle of

37   rotation of the specimen by assuming the location of the axis of rotation in the centre of

38   the specimen and perpendicular to the line that connects the two displacement transducers

39   of the TSRST system [10]. The modified TSRST procedure using notched samples was

40   later proposed by Mandal and Bahia [11]. The comparison of calculated and TSRST

41   thermal stresses was also presented [12, 13].

42   Cooling rate is one of the most important factors that could influence low-

43   temperature cracking in asphalt pavements at winter conditions. It has been proved that

44   the cooling rate significantly affects the experimental measurements in the TSRST

45   method [14-16]. The field cooling rates reported in the literature vary from 0.5°C/h to

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46   3°C/h [17]. Although among laboratory tests the TSRST allows the closest simulation of

47   the field conditions (uniaxial tension test), the cooling rate of 10°C/h used in the

48   procedure is much higher (more extreme) than in real conditions. The main reason behind

49   this choice is very long duration (more than 24 hours) of the test conducted at more

50   realistic cooling rates. Nevertheless, it should be noted that when the cooling rate

51   decreases, the fracture temperature also decreases [18-20].

52   According to the literature [21], usage of softer asphalt binders and aggregates

53   with a more angular shape results in higher fracture strength values and lower fracture

54   temperatures of asphalt mixtures. It has been recommended that the fracture temperature

55   should be used to rank the low-temperature cracking resistance of asphalt mixtures. The

56   positive effect of an SBS-modified bitumen on low-temperature properties in the TSRST

57   has been proved in the literature [22, 23]. The addition of additives such as sulphur [24],

58   crumb rubber [25], rubber-bitumen granulate [26] or composition of polymer-rubber

59   modified bitumen [27] can improve the low-temperature performance of asphalt

60   mixtures. Positive effects of bio-based rejuvenating agents [28] and warm-mix additives

61   [29] on TSRST results have been observed as well.

62   The effects of polymer and fibre modification on low-temperature properties of

63   bituminous mixtures using TSRST were studied [30]. It has been concluded that while

64   polymer modification improves the low-temperature cracking resistance, cellulose or

65   synthetic fibres do not improve the low-temperature performance of asphalt mixtures.

66   Moreover, changes in asphalt binder content, within a reasonable range around the

67   optimum value, do not have a significant effect on fracture temperature and fracture

68   strength of the asphalt mixture.

69   1.2. Objectives

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70   The main objective of the research was to evaluate the influence of cooling rate,

71 type of bitumen and various additives on low-temperature properties of asphalt mixtures

72 using the TSRST procedure. The cooling rates of 1°C/h, 3°C/h, 5°C/h and 10°C/h during

73 the TSRST test were chosen and their impact on the results was discussed. Three groups

74 of bitumen were investigated: neat road bitumen, polymer SBS-modified and highly SBS-

75 modified bitumen. The influence of additives – aramid fibres of different length and

76 crumb rubber modification – on low-temperature behaviour was analysed as well.

77 **2. Materials and methods**
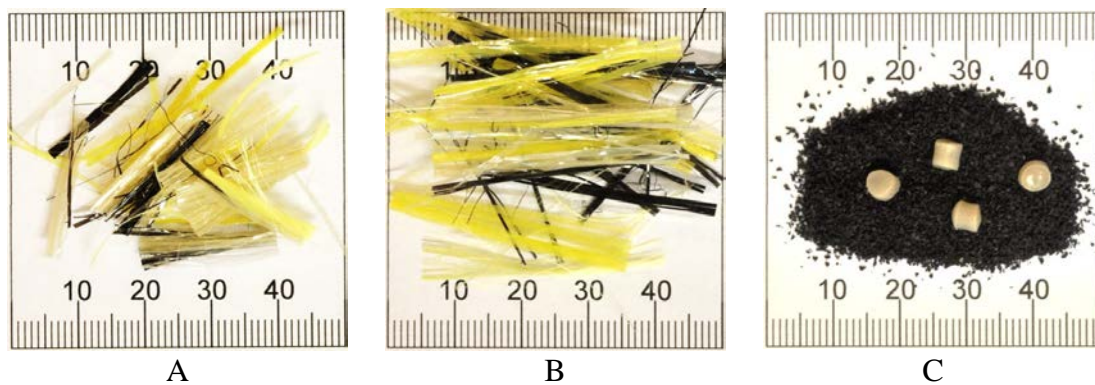
78 2.1. Materials and preparation

79   Asphalt concrete for wearing courses was investigated. Asphalt mixture AC 11S with

80 50/70 neat bitumen was chosen as a reference and designed according to EN 13108-1

81 standard [31] and the Polish technical guidelines WT-2 2014 [32]. Six types of bitumen

82 were selected for low-temperature tests: two neat road bitumens 50/70 and 35/50, one

83 crumb rubber modified bitumen 35/50 R, two polymer SBS-modified bitumens 45/80-55

84 and 25/55-60, as well as one highly SBS-modified bitumen 25/55-80. The properties of

85 bitumens are shown in Table 1.

86 **Table 1.** Properties of bitumens.

Property		Type of bitumen					
		50/70	**35/50**	**35/50 R**	**45/80-55**	**25/55-60**	**25/55-80**
Penetration at 25°C, 0.1 mm, acc. to PN-EN 1426	Original	54	45	39	60	34	50
	RTFOT	40	28	24	40	25	41
R&B Temperature, °C, acc. to PN-EN 1427	Original	50.8	53.0	60.7	68.6	62.6	87.5
	RTFOT	57.8	60.1	69.9	67.4	68.2	89.1
Performance Grade, acc. to AASHTO M 320		64-22	70-16	82-16	70-22	76-22	82-22

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88   Asphalt concrete for wearing courses with 35/50 neat road bitumen was chosen

89 as a reference for evaluation of the impact of different lengths of fibres and crumb rubber

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90 modification on low-temperature properties of mixtures. The fibres used in the research

91 were aramid-polyalphaolefin fibres, which are produced for use as reinforcement in

92 asphalt mixtures. In this research two lengths of fibres were used: 19 mm (F19) and 38

93 mm (F38). The fibres were added with a dosage of 0.05% by weight of asphalt mixture.

94 According to the literature, an addition of aramid fibres improves asphalt mixture

95 resistance to low-temperature cracking [33, 34]. Crumb rubber modification method was

96 conducted in the laboratory by mixing the proportion of 191 grams of ground tyre rubber

97 (0.2/0.8mm), 9 grams of a specific polymer (polyoctynamer) and 2000 grams of asphalt

98 binder. The mixing process was performed using laboratory mixer at 200 RPM for 120

99 minutes. Temperature during the mixing process was kept within the range of 170–180°C.

100 It has been shown that crumb rubber modification improves asphalt mixture properties,

101 especially the resistance to low-temperature cracking [27]. Different additives used in the

102 tests are shown in Fig. 1.

A	B	C

103
104 **Fig 1**. The additives used in the tests: A) 19-mm-long aramid fibres (F19); B) 38-mm-long aramid
105 fibres (F38); C) crumb rubber and polyoctynamer polymer modification applied to bitumen (R)
106

107 The composition and volumetric properties of the reference asphalt mixtures are

108 presented in Table 2.

109 **Table 2.** Composition and volumetric properties of the reference asphalt mixtures: AC 11 S
110 50/70 (for cooling rate assessment) and AC 11 S 35/50 (for additive assessment)

Type of layer	wearing course
Type of traffic	medium, design life from 0.50×10^6 to 7.3×10^6 of 100 kN standard axle loads
Aggregate type	crushed granite

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Filler type				limestone			
Binder content (% by mass)				5.6			
Binder type				50/70		35/50	
Air voids in Marshall samples (2 x 75 blows) [%]				3.1		3.3	
Voids filled with bitumen VFB [%]				81.5		80.4	
Voids in the mineral aggregate VMA [%]				16.7		16.6	
Sieve size (mm)	16	11.2	8	5.6	4	2	0.125	0.063
% Passing (by mass)	100	99	83	65	54	43	12	7.4

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113   Asphalt mixtures were prepared using laboratory mixer equipment in accordance with

114   EN 12697-35 standard [35]. Prior to compaction of specimens, asphalt mixtures were

115   subjected to ageing in accordance with the procedure given in the Appendix 2 of WT-

116   2:2014 [32]. Specimens were compacted with the use of a roller compactor according to

117   EN 12697-33 standard [36]. At the first stage, slabs with dimensions of 305 x 305 x 80

118   mm were compacted. At the second stage, six prismatic beams with dimensions of 40 x

119   40 x 160 mm were cut from each slab. Parameters of the compaction process were set so

120   as to ensure that the final bulk density would reach 98-100% of the Marshall bulk density.

121   Temperature during compaction varied according to the type of bitumen: for asphalt

122   mixtures containing neat road bitumens 35/50 and 50/70 it was 135°C ± 5°C, whereas for

123   asphalt mixtures containing SBS-modified bitumens it was 145°C ± 5°C [37].

124   2.2. Methods

125   The resistance of asphalt mixtures to low-temperature cracking was assessed by

126   means of the TSRST method according to EN 12697-46 standard [38]. In the TSRST

127   procedure the specimen is held at a constant length, while temperature is decreased at a

128   uniform rate. In accordance with EN 12697-46, the thermal stress is defined as cryogenic

129   stress induced during tension due to prohibited thermal shrinkage, at the temperature T.

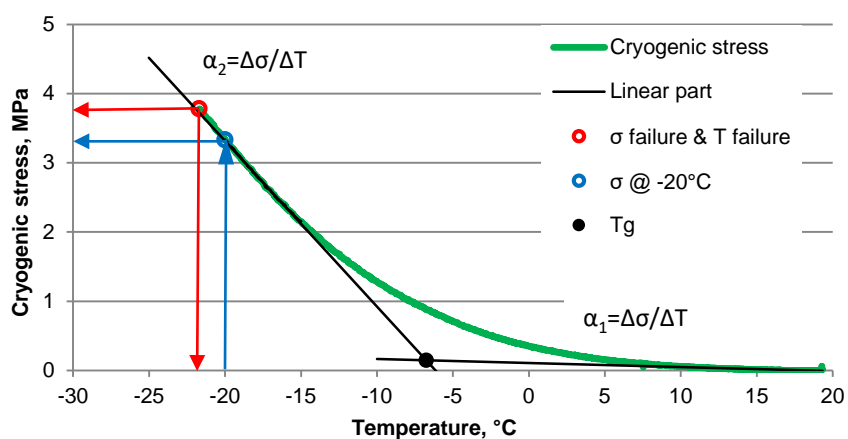130   The test starts at the temperature of $T_0 = +20°C$. For the standard test method, the cooling

131   rate is set to 10°C/h. The thermally-induced (cryogenic) stress in specimen gradually

132   increases as temperature decreases, until the specimen fractures. The temperature-

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133 dependent thermal (cryogenic) stress $\sigma_{cry}(T)$ is recorded. At the break point the stress

134 reaches its maximum value and is defined as the failure stress $\sigma_{cry,\ failure}$ and the

135 temperature at the break point is defined as the failure temperature $T_{failure}$. The graphical

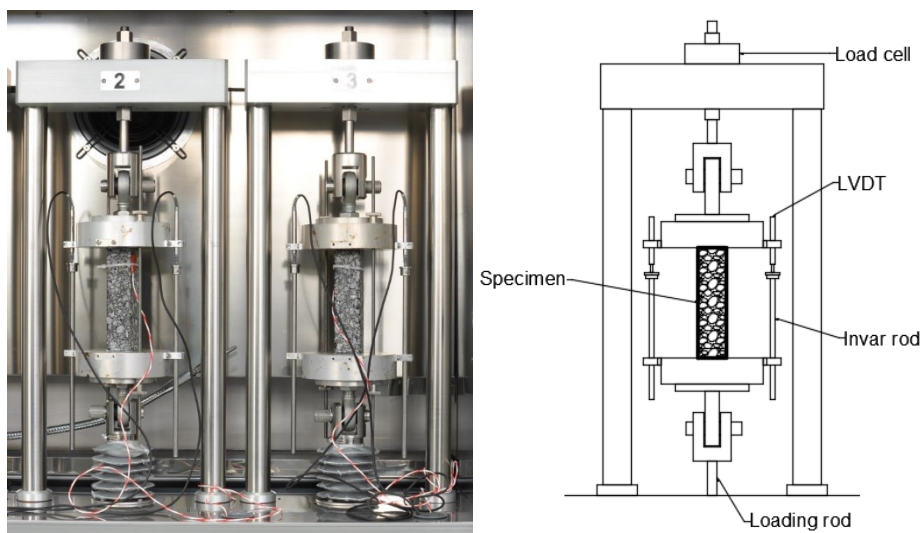136 explanation of data obtained from the TSRST is shown in Fig. 2.

137

138 **Fig 2**. The graphical explanation of data assessment.
139
140 At lower temperatures the slope of the stress-temperature curve $\Delta\sigma/\Delta T$ becomes

141 linear (constant), which means the asphalt mixture behaves like an elastic material. The

142 temperature at tangent point (T_g) is defined by the intersection between the two tangents

143 of the stress-temperature curve: at the aforementioned elastic zone and at the stress

144 relaxation zone, which occurs around the start point of the test at temperature of +20°C.

145 The specimens were tested using PAVETEST servo electric equipment. For every type

146 of asphalt mixture, 3 specimens were tested. To investigate the effect of cooling rate on

147 low-temperature cracking, additional tests were conducted with cooling rate set to: 1°C/h,

148 3°C/h and 5°C/h. The TSRST equipment and test setup are presented in Fig. 3.

Fig 3. Thermal Stress Restrained Specimen Test (TSRST) setup; on the right – schematic view; on the left – photograph of the specimens during the test.
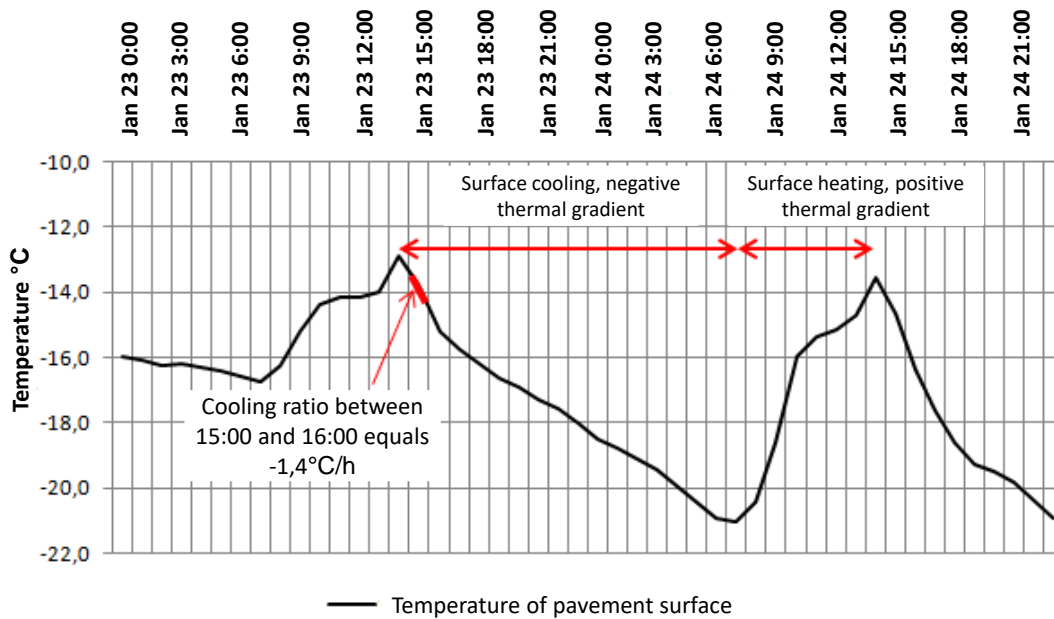
To assess the influence of cooling rate on stiffness modulus, the Indirect Tensile Test (IT-CY) method according to EN 12697-26 [39] and a programmable thermostatic chamber were used. Gyratory compacted samples (100 mm in diameter and 50 mm in height) were prepared using 50/70 neat road bitumen. Stiffness modulus was analysed at two cooling rates: 3°C/h and 10°C/h. Samples were placed in the thermostatic chamber set to +25°C and, after one hour, temperature inside the chamber started to decrease at a set cooling rate, until it reached -20°C. Isothermal storage time was counted after temperature inside the dummy samples stabilized (8 hours from the start of the test for cooling rate of 10°C/h and 18 hours for cooling rate of 3°C/h). Stiffness modulus was assessed at -20°C and was then measured after 1, 24 and 72 hours of isothermal storage. Temperature inside the dummy sample was recorded during the conditioning process.

3. Analysis of cooling rate in real conditions

The analysis of cooling rate was performed on data comprising air and pavement temperatures obtained from 17 meteorological stations located along roads in different parts of Poland. The data, provided by the Road Administration, covered various periods

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168   for different stations. The maximum period was 10 years, from 2003 to 2013, while the

169   minimum period of measurement was 2 years. The meteorological stations were adapted

170   to measure temperature 20 cm above the pavement surface, at the road surface and at

171   depths of 5 cm and 30 cm within the pavement. In total, over 3.3 million of records were

172   analysed. Measurements were recorded at each meteorological station every 10 minutes

173   and were used to calculate an average value for each hour. The data was verified with

174   possible measurement errors in mind. Verification was performed according to the

175   following criteria: a) availability of temperature data from all measurement locations

176   (sensors in the pavement and in the air) at the moment of measurement, and b) availability

177   of temperature readings throughout the day. Detailed information regarding the

178   temperature and cooling rate analysis was presented by Pszczola et al. [17].

179   The rate of cooling of pavement surface is an important factor that significantly

180   affects the thermal stresses generated in the asphalt pavement. An example of two periods

181   of temperature action in winter – cooling of pavement surface (a decrease in pavement

182   temperature), that has negative influence on pavement structure, and heating of pavement

183   surface (an increase in pavement temperature) – are presented in Fig. 4 after [17].

Fig. 4. An example of changes in temperature at the pavement surface, after Pszczola et al. [17]

The probability of occurrence of the maximum pavement surface cooling rate obtained from the analysis is presented in Table 3 after [17].

Table 3. Probability of occurrence of pavement surface cooling rate on the basis of data from all meteorological stations [17].

Probability of cooling rate value less than V_T	Cooling rate V_T (°C/h)
99.9%	≥ 3.7
99%	≥ 2.1
95%	≥ 1.2
90%	≥ 0.8
85%	≥ 0.6

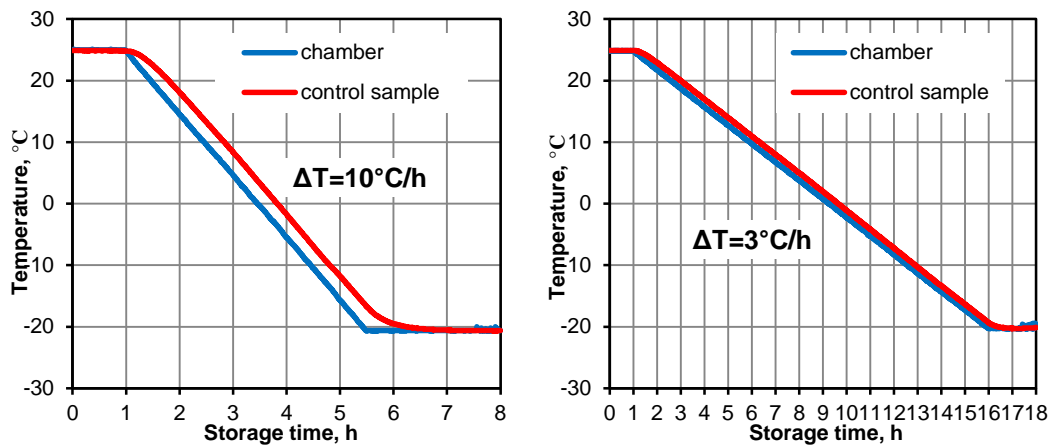The results of analysis indicate that the probability of cooling rate of pavement surface being greater than 3°C/h is less than 1%. It has also been proved that the probability of cooling rate being less than 1.2°C/h is 95%, which means that only 5% of the results indicate a cooling rate higher than 1.2°C/h.

4. Results and discussion

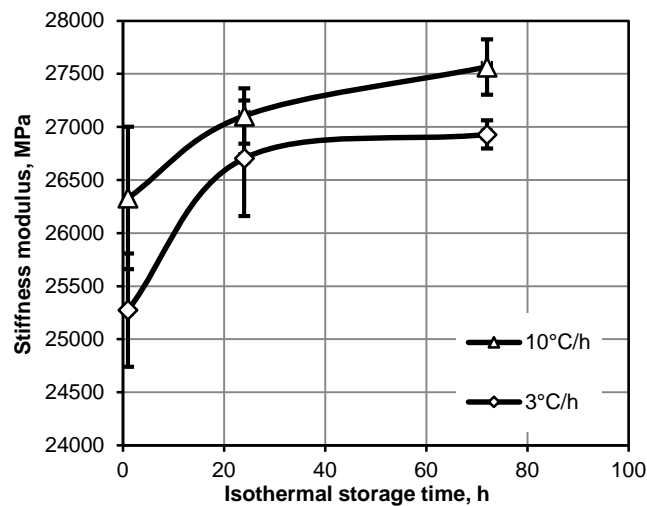4.1. Influence of cooling rate on stiffness modulus

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197   It was observed that asphalt mixture stiffness modulus depended on the cooling

198   rate during conditioning prior to the test. Temperature values recorded during the

199   decrease in temperature with time are presented in Fig. 5. The relationship between

200   stiffness modulus values for cooling rates 3°C/h and 10°C/h and isothermal storage time

201   is presented in Fig. 6.

202

203   **Fig. 5.** Temperature charts during conditioning process.

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205   **Fig. 6.** Results of stiffness modulus according to Indirect Tensile Test for cooling rates 3°C/h
206   and 10°C/h.
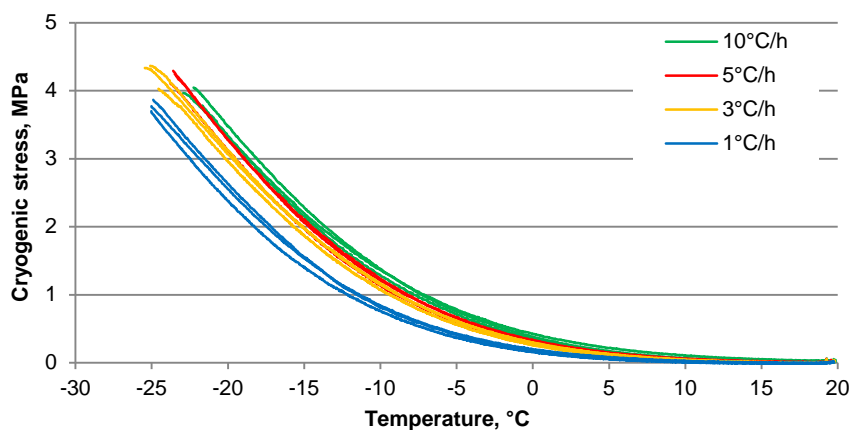
207   It was observed that cooling rate had an important impact on stiffness modulus

208   results. With an increase in cooling rate from 3°C/h to 10°C/h, at the same isothermal

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209   storage time, the values of stiffness moduli increased. Isothermal storage time influenced

210   stiffness modulus as well. Modulus of asphalt concrete increased with time. It should be

211   noted that both cooling rate and isothermal storage time could affect the TSRST result.

212   Cooling rate of 10°C/h results in higher modulus, which could lead to inferior crack

213   resistance at low temperatures. Physical hardening phenomena during isothermal storage

214   time can also increase stiffness of the asphalt concrete [40, 41]. Cooling rate has a more

215   significant impact on stiffness modulus than isothermal storage time.

216   4.2.Influence of cooling rate on the TSRST results

217   The influence of cooling rate was investigated for the asphalt concrete AC 11S

218   mixture for wearing courses with 35/50 neat bitumen. Four different cooling rates were

219   investigated: 1°C/h, 3°C/h, 5°C/h and 10°C/h. The results of thermal (cryogenic) stresses

220   recorded during TSRST test at different cooling rates are presented in Fig. 7.

222   **Fig. 7.** The results of thermal (cryogenic) stresses recorded during TSRST test at different cooling rates.

223   Table 4 shows the analysis of TSRST test results, taking into consideration different

224   cooling rates. Besides the cryogenic stress and temperature values at failure ($\sigma_{cry,\ failure}$ and

225     $T_{failure}$), slopes of curve tangents for elastic and stress relaxation zones were determined

13

226 and discussed. For comparative purposes, cryogenic stress at the temperature of -20°C

227 ($\sigma_{cry, @-20°C}$) was also analysed.

228 **Table 4.** TSRST test results for AC 11 S 35/50 with different cooling rates.

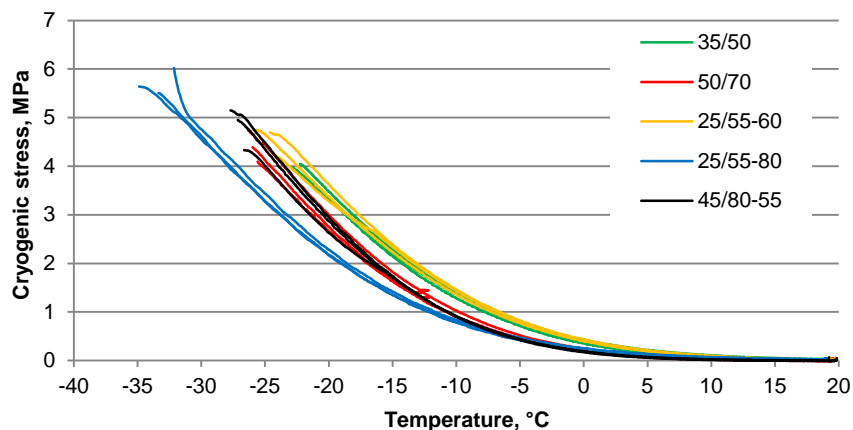| Cooling rate, [°C/h]		$\sigma_{cry, failure}$, [MPa]	$T_{failure}$, [°C]	$\sigma_{cry, @-20°C}$, [MPa]	α_2, [N/mm²/°C]	α_1, [N/mm²/°C]	T_g, [°C]
10°C/h	mean value	3.931	-22.3	3.376	-0.235	-0.006	-6.380
	st. deviation	0.136	0.6	0.090	0.008	0.001	0.332
	CV, [%]	3.5	2.7	2.7	3.5	13.1	5.2
5°C/h	mean value	4.217	-23.6	3.224	-0.260	-0.004	-7.970
	st. deviation	0.092	0.2	0.094	0.006	0.001	0.101
	CV, [%]	2.2	0.6	2.9	2.3	14.5	1.3
3°C/h	mean value	4.242	-25.0	3.054	-0.243	-0.007	-8.120
	st. deviation	0.186	0.4	0.081	0.007	0.000	0.243
	CV, [%]	4.4	1.6	2.6	2.8	6.4	3.0
1°C/h	mean value	3.779	-25.1	2.515	-0.227	-0.004	-9.360
	st. deviation	0.084	0.1	0.127	0.004	0.001	0.324
	CV, [%]	2.2	0.2	5.1	1.9	11.5	3.5

229   The conducted research confirmed that cooling rate has a significant impact on

230 failure temperature in the TSRST test. The higher the cooling rate, the higher the

231 temperature at which the low-temperature cracks were noticed. At the cooling rate of

232 10°C/h, the measured fracture temperature was -22.4°C, while at the cooling rate of 3°C/h

233 it was equal to -25.0°C. The results of pavement temperature measurements from

234 meteorological stations located along the roads proved that under real conditions cooling

235 rate was no higher than 3°C/h for 99% of the records. This conclusion could pose a basis

236 for a decrease in cooling rate in the TSRST method. On the other hand, such a decision

237 would extend the duration of test procedure. From the analysis of slopes of curve tangents

238 for elastic and stress relaxation zones, it was concluded that cooling rate has minor

239 influence on slopes, both for elastic and relaxation zones.

240   Cryogenic stress at failure temperature is not a parameter that would enable

241 reliable comparison of mixtures in terms of the impact of cooling rate. It was observed

242 that, in order to assess the influence of cooling rate on cryogenic stresses, a set

14

243 comparative temperature of -20°C was needed, which distinguished the results of

244 cryogenic stresses according to the TSRST method better than the temperature at failure

245 of specimens. An increase in cooling rate from 1°C/h to 5°C/h resulted in an significant

246 increase of cryogenic stresses. A further increase in cooling rate from 5°C/h to 10°C/h

247 did not significantly affect the results of cryogenic stresses.

248 4.3. The influence of bitumen type on the TSRST results

249 The results of failure temperature $T_{failure}$ and cryogenic stresses for asphalt

250 mixtures containing different types of bitumen are presented in Fig. 7. The analysis of

251 additional parameters is shown in Table 5. The cooling rate of 10°C/h was used, in

252 accordance with the standard TSRST method.

253

254 **Fig. 7.** The results of failure temperature $T_{failure}$ and cryogenic stresses $\sigma_{cry}(T)$ from the TSRST
255 method for asphalt mixtures with different types of bitumen.
256
257 **Table 5.** TSRST test results for asphalt mixtures with different types of bitumen

Bitumen type		$\sigma_{cry, failure}$, [MPa]	$T_{failure}$, [°C]	$\sigma_{cry, @-20°C}$, [MPa]	α_2, [N/mm²/°C]	α_1, [N/mm²/°C]	T_g, [°C]
35/50	mean value	3.931	-22.3	3.376	-0.235	-0.006	-6.380
	st. deviation	0.136	0.6	0.090	0.008	0.001	0.332
	CV, [%]	3.5	2.7	2.7	3.5	13.1	5.2
50/70	mean value	4.409	-26.0	2.803	-0.275	-0.004	-10.243
	st. deviation	0.325	0.4	0.177	0.016	0.001	0.127
	CV, [%]	7.4	1.4	6.3	5.7	13.0	1.2
25/55-60	mean value	4.556	-24.9	3.426	-0.238	-0.006	-6.090

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	st. deviation	0.292	0.9	0.177	0.033	0.000	1.543
	CV, [%]	6.4	3.6	5.2	13.9	6.5	25.3
25/55-80	mean value	5.722	-33.5	2.210	-0.263	-0.005	-13.047
	st. deviation	0.267	1.4	0.062	0.007	0.001	0.371
	CV, [%]	4.7	4.2	2.8	2.7	32.3	2.8
45/80-55	mean value	4.811	-27.1	2.816	-0.252	-0.003	-9.017
	st. deviation	0.426	0.6	0.171	0.026	0.000	0.553
	CV, [%]	8.9	2.0	6.1	10.4	3.4	6.1

258 The conducted research confirmed that type of bitumen has an important influence

259 on failure temperature, cryogenic stress at -20°C, the tangent point (T_g) and slopes of

260 curves α_1 and α_2. Use of the neat road bitumen 30/50 resulted in the highest mean value

261 of failure temperature equal to $T_{failure} = -22.3°C$. For the SBS-modified bitumen 25/55-60

262 an improvement of failure temperature to -24.9°C was observed, but the values of

263 cryogenic stress at -20°C and temperature at tangent point (T_g) were even more

264 disadvantageous than for the neat road bitumen 35/50. Very low value of temperature at

265 tangent point (T_g) for the SBS-modified bitumen 25/55-60 in comparison with neat road

266 bitumens 35/50 and – especially – 50/70, indicated that at higher temperatures this

267 bitumen quickly started performing within the elastic zone, whereas stress relaxation

268 diminished, and, as a consequence, the bitumen became more susceptible to thermal

269 cracking. The best low-temperature properties according to the TSRST method were

270 observed for the asphalt mixture with highly SBS-modified bitumen 25/55-80. This

271 suggests that the level of SBS-modification is an important factor that influences the low-

272 temperature properties of asphalt mixtures.

273 4.4.The influence of additive type on the TSRST results

274 The results of failure temperature $T_{failure}$ and cryogenic stresses $\sigma_{cry}(T)$ for asphalt

275 mixtures with different types of additives are presented in Fig. 8. The analysis of

276 additional parameters is shown in Table 6.

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Fig. 8. The results of failure temperature $T_{failure}$ and cryogenic stresses $\sigma_{cry}(T)$ from the TSRST for asphalt mixtures with different types of additives.

Table 6. TSRST test results for asphalt mixtures with different types of additives

Additive type		$\sigma_{cry,\ failure}$, [MPa]	$T_{failure}$, [°C]	$\sigma_{cry,\ @-20°C}$, [MPa]	α_2, [N/mm²/°C]	α_1, [N/mm²/°C]	T_g, [°C]
35/50	mean value	3.931	-22.3	3.376	-0.235	-0.006	-6.380
	st. deviation	0.136	0.6	0.090	0.008	0.001	0.332
	CV, [%]	3.5	2.7	2.7	3.5	13.1	5.2
35/50 R	mean value	4.056	-22.4	3.661	-0.198	-0.010	-2.740
	st. deviation	0.062	0.2	0.041	0.003	0.000	0.089
	CV, [%]	1.5	0.8	1.1	1.5	4.7	3.2
35/50 F19	mean value	4.274	-23.3	3.621	-0.236	-0.007	-5.497
	st. deviation	0.378	2.1	0.080	0.001	0.000	0.438
	CV, [%]	8.8	9.1	2.2	0.5	1.4	8.0
35/50 F38	mean value	4.440	-25.0	3.117	-0.226	-0.006	-7.037
	st. deviation	0.291	0.8	0.088	0.004	0.001	0.349
	CV, [%]	6.6	3.0	2.8	1.7	14.4	5.0

The results shown in Table 6 indicate that application of crumb rubber to the bitumen can even make the asphalt mixture stiffer. Although the failure temperature results are the same (-22.3°C for the 35/50 bitumen and -22.4°C for the 35/50 R bitumen) the values of cryogenic stress at -20°C and temperature at tangent point (T_g) both indicate a reduction in low-temperature properties of the asphalt mixture containing crumb rubber modified bitumen. It is possible that a different base asphalt for rubber modification should have been used. Rubber modification of 35/50 asphalt caused a decrease in penetration from 45 to 39. It would be worthwhile to investigate asphalt 50/70 with rubber modification in future research.

17

291   The TSRST results of the asphalt mixtures with aramid fibres showed that the

292   length of fibres was an important factor that could influence the low-temperature

293   properties of the mixtures tested. The application of 38-mm-long aramid fibres led to

294   higher improvement in low-temperature properties of the asphalt mixture than the 19-

295   mm-long aramid fibres (-25.0°C for the 35/50 F38 bitumen and -23.3°C for the 35/50 F19

296   bitumen). It should be clearly stated that the mixing process in the laboratory may be the

297   crucial factor that influences the positive or negative effects of aramid fibre additives on

298   asphalt mixtures. Temperature at tangent point did not show significant differences after

299   the application of aramid fibres. Surprisingly, the addition of crumb rubber resulted in an

300   increase in stiffness and, as a result, an increase in temperature at tangent point. Extended

301   research effort should be invested in the assessment of aramid fibre behaviour at low

302   temperatures when asphalt mixtures are mixed and compacted in the field.

303   4.5.Stiffness modulus back-calculations from the TSRST results
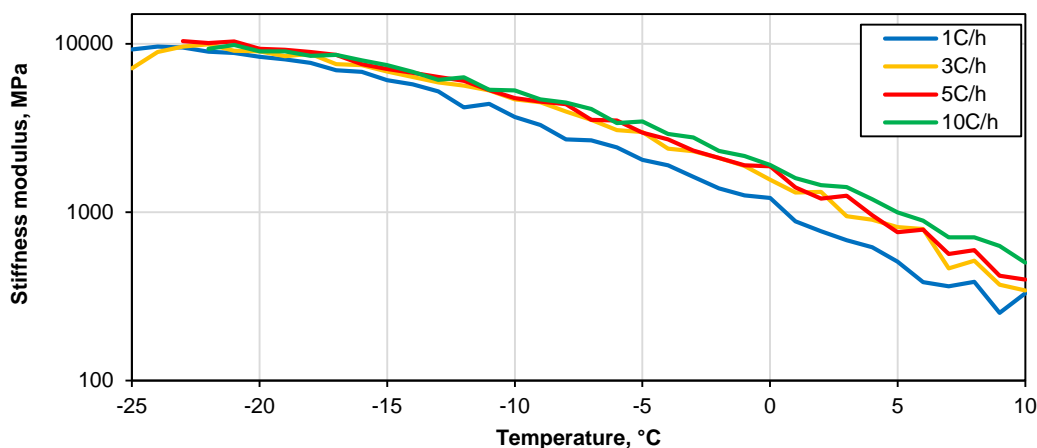
304   The influence of cooling rate, additives and bitumen types on the stiffness

305   modulus obtained from the TSRST results was analysed and discussed. Stiffness moduli

306   were back-calculated from all the tested specimens. For this purpose, Hills and Brian

307   method [42] was adapted. While very simple, it allows easy and direct calculation of

308   stiffness modulus for each temperature. It also enables minimization of the number of

309   assumed factors which are taken into consideration during calculation of thermal stresses.

310   However, the chosen calculation method has two major limitations: unlike other methods

311   [4, 7, 43], it does not take into consideration the stress relaxation effect, which is an

312   important factor in the cryogenic stress build-up. It also does not include the effect of

313   physical hardening [40, 41], which can influence the values of stiffness moduli due to

314   prolonged exposure of the specimen to low temperatures. Nevertheless, as the previous

18

315 studies have shown [13], Hills and Brien method gives relatively accurate results despite

316 its limitations. Basic equation of the Hills and Brien method for the infinite beam scheme

317 (similar as in the TSRST test) is given as follows:

$$\sigma\left(T_i\right) = \alpha_L \sum_{i=1}^{n} S\left(t, T_i\right) \Delta T \qquad (1)$$

318 where: $\sigma(T_i)$ – calculated thermal stresses for the temperature T_i, MPa, α_L- linear

319 coefficient of thermal contraction, assumed as $\alpha_L = 2.7 \times 10^{-5}$ 1/°C for all the analysed

320 mixtures, $S(t, T_i)$ – stiffness modulus for the time of loading t and the temperature T_i,

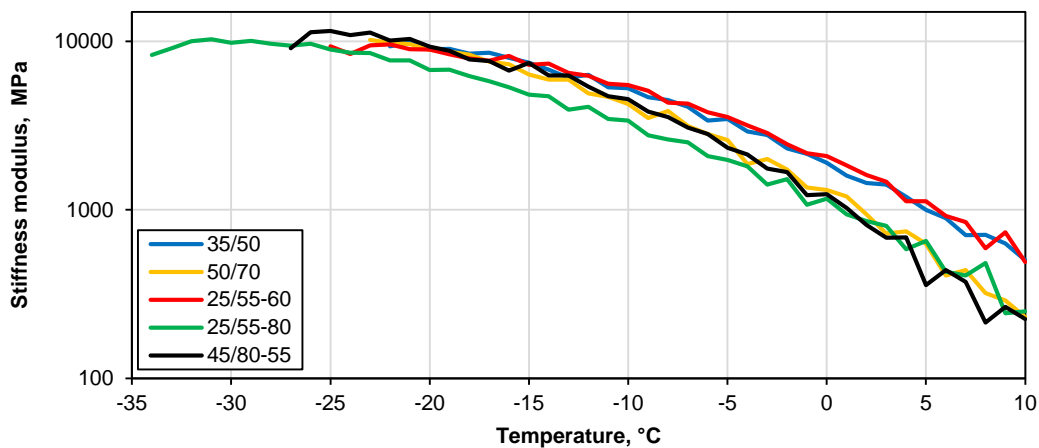321 MPa, ΔT – temperature increment, assumed as $\Delta T = 1$°C.

322 For each specimen, stiffness moduli for all temperatures were calculated using the

323 least squares method and SOLVER expansion tool. The results obtained for all specimens

324 in a given test batch were then averaged. Back-calculated values for different cooling

325 rates, types of bitumen and types of additives are presented in Figures 9-11, respectively.

326 Despite the relative simplicity of the method, the obtained values are in agreement with

327 other studies [20].

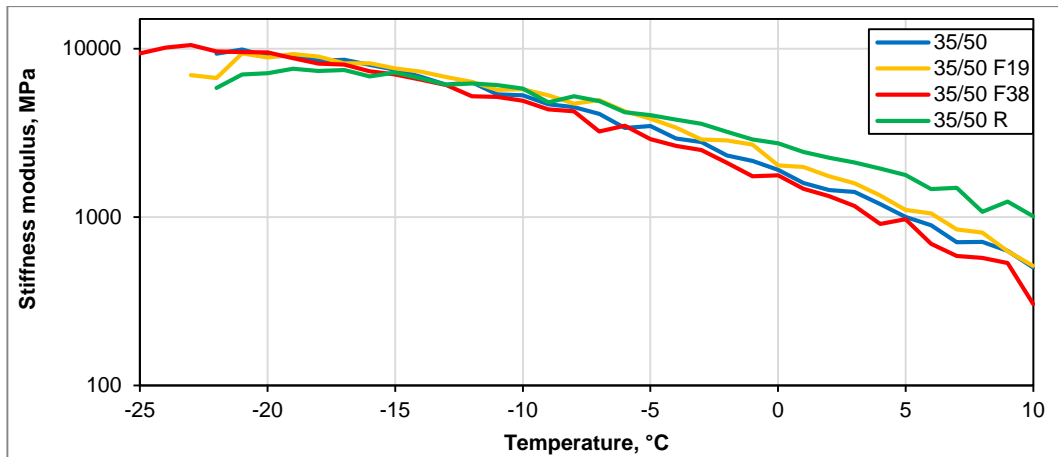329 **Fig. 9.** Back-calculated values of stiffness moduli for different cooling rates.

330 Cooling rate influenced stiffness modulus, as was expected. In all cases the values

331 of stiffness moduli ranged from 500 to 10000 MPa. The lowest values were obtained for

332 the cooling rate of 1°C/h and the highest for the cooling rate of 10°C/h. The increase in

the value of stiffness modulus was also the lowest in the case of the lowest cooling rate. Interestingly, with the increase in the cooling rate, the difference in stiffness moduli diminished, and the highest relative differences were visible for the highest temperatures. For the cooling rates of 3°C/h and higher, the moduli were even for temperatures lower than -5°C. In the case of cooling rate of 1°C/h, the tested mixture presented the same values of stiffness moduli for temperatures lower than -15°C. The decrease in the values of stiffness moduli around -25°C was associated with thermal damage of the tested specimen.

Fig. 10. Back-calculated values of stiffness moduli for different bitumen types.

In the case of different bitumen types, calculated results allowed grouping of the tested materials into three different groups. Like in the previous comparison, the biggest relative differences were visible for higher temperatures. The highest values were obtained for the bitumens 35/50 and 25/55-60. Second group, with lower calculated stiffness moduli, was in penetration grade range from 45 to 70. However, like previously, the calculated values were even for temperatures of -12°C and lower. The last group was represented by a hard grade highly-modified bitumen. While at higher temperatures it presented values of stiffness moduli similar to those of a higher penetration grade group, it maintained relatively lower stiffness for the whole temperature range, down to failure temperature.

20

353

354 **Fig. 11.** Back-calculated values of stiffness moduli for different additives.

355   As for different additive types, the calculated values of stiffness moduli indicated that

356 the addition of aramid fibre did not affect the stiffness moduli of the reference mixture.

357 The only difference was visible in the value of fracture temperature, 3°C lower for longer

358 aramid fibres in comparison to the reference mixture and the one with shorter fibres.

359 Interestingly, at temperatures higher than 0°C, addition of crumb rubber increased the

360 values of stiffness moduli. However, similarly to previous comparisons, the difference

361 diminished at temperatures lower than -10°C.

362 **5. Summary and conclusions**

363   Based on the test results and the conducted analysis, the following conclusions

364 can be drawn:

365 1. Maximum cooling rate determined from the field conditions is lower than 3.7°C/h

366   with the probability of 99.9% and lower than 2.1°C/h with the probability of 99%.

367   It is significantly lower than the cooling rate applied in the TSRST.

368 2. Laboratory tests confirmed the influence of cooling rate and bitumen type on

369   fracture temperature. With an increase in cooling rate, fracture temperature

21

increases. The greatest difference in cryogenic stresses and failure temperatures

occurs between the cooling rates of 1°C/h and 3°C/h.

3. Failure temperature for neat bitumen increases with a decrease in penetration grade. As for SBS-polymer type bitumen, failure temperature decreases with an increase in the amount of SBS polymer.

4. The addition of 19-mm-long aramid fibres and crumb rubber does not change the failure temperature significantly. On the other hand, mixtures containing longer (38 mm) aramid fibres presented lower failure temperature in comparison to the reference AC 11S 35/50 mixture.

5. Back-calculations of stiffness moduli from the TSRST results show significant differences in the stiffness moduli values due to change in the cooling rate. The lowest values were back-calculated for the cooling rate of 1°C/h and the highest for the cooling rate of 10°C/h. The lowest stiffness modulus value are presented by the mixture with hard grade highly SBS-modified bitumen.

Acknowledgement

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