

- 1 **Influence of cooling rate and additives on low-temperature properties**
- 2 **of asphalt mixtures in the TSRST**
- 3 Marek Pszczola, Cezary Szydłowski, Mariusz Jaczewski
- 4 *Highway and Transportation Engineering Department, Faculty of Civil and*
- 5 *Environmental Engineering, Gdansk University of Technology, Gdansk, Poland*
- 6 Gdansk University of Technology, Faculty of Civil and Environmental Engineering
- 7 Narutowicza Street 11/12
- 8 Gdansk, PL 80-233
- 9 tel.:+48 58 347 27 82
- 10 e-mail: [marek.pszczola@pg.edu.pl](mailto:marek.pszczola@pg.edu.pl)

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,

## 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



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

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

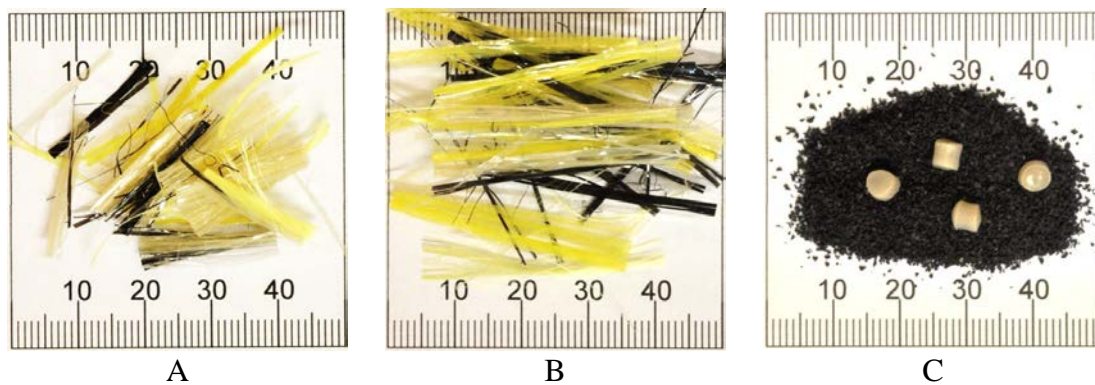
79 Asphalt concrete for wearing courses was investigated. Asphalt mixture AC 11S with  
 80 50/70 neat bitumen was chosen as a reference and designed according to EN 13108-1  
 81 standard [31] and the Polish technical guidelines WT-2 2014 [32]. Six types of bitumen  
 82 were selected for low-temperature 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.

|   |          | Type of bitumen |       |         |          |          |          |
|---|----------|-----------------|-------|---------|----------|----------|----------|
| Property  |          | 50/70           | 35/50 | 35/50 R | 45/80-55 | 25/55-60 | 25/55-80 |
| Penetration<br>at 25°C, 0.1 mm,<br>acc. to PN-EN 1426 | Original | 54              | 45    | 39      | 60       | 34       | 50       |
|   | RTFOT    | 40              | 28    | 24      | 40       | 25       | 41       |
| R&B Temperature,<br>°C,<br>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,<br>acc. to AASHTO M 320            |          | 64-22           | 70-16 | 82-16   | 70-22    | 76-22    | 82-22    |

87  
 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

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.



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 $0.50 \times 10^6$ to $7.3 \times 10^6$ of 100 kN standard axle loads |
| Aggregate type  | crushed granite  |

|  |           |      |    |     |       |    |       |       |
|--|-----------|------|----|-----|-------|----|-------|-------|
| 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   |

111

112

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  $135^{\circ}\text{C} \pm 5^{\circ}\text{C}$ , whereas for

123

asphalt mixtures containing SBS-modified bitumens it was  $145^{\circ}\text{C} \pm 5^{\circ}\text{C}$  [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  $T_0 = +20^{\circ}\text{C}$ . For the standard test method, the cooling

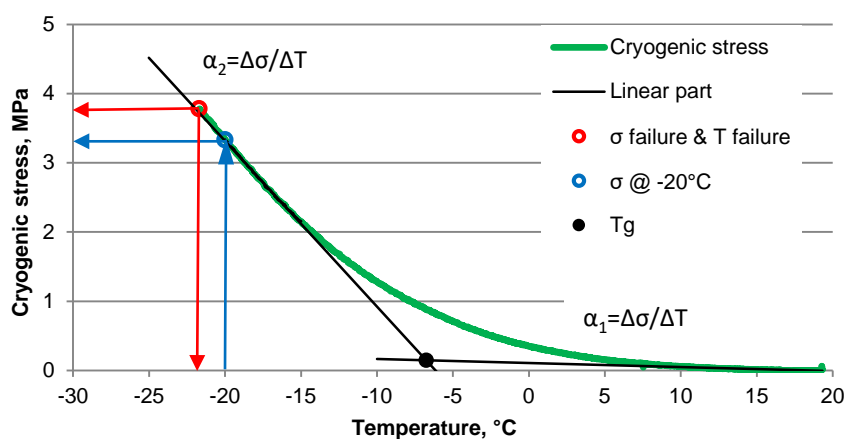
131

rate is set to  $10^{\circ}\text{C}/\text{h}$ . The thermally-induced (cryogenic) stress in specimen gradually

132

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

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.

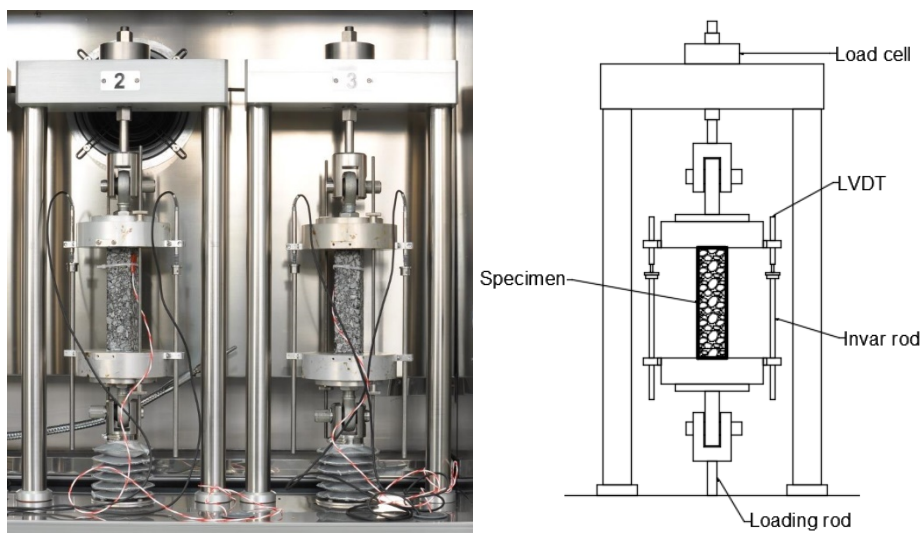


137

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.





149

150 **Fig 3.** Thermal Stress Restrained Specimen Test (TSRST) setup; on the right – schematic view; on  
 151 the left – photograph of the specimens during the test.  
 152

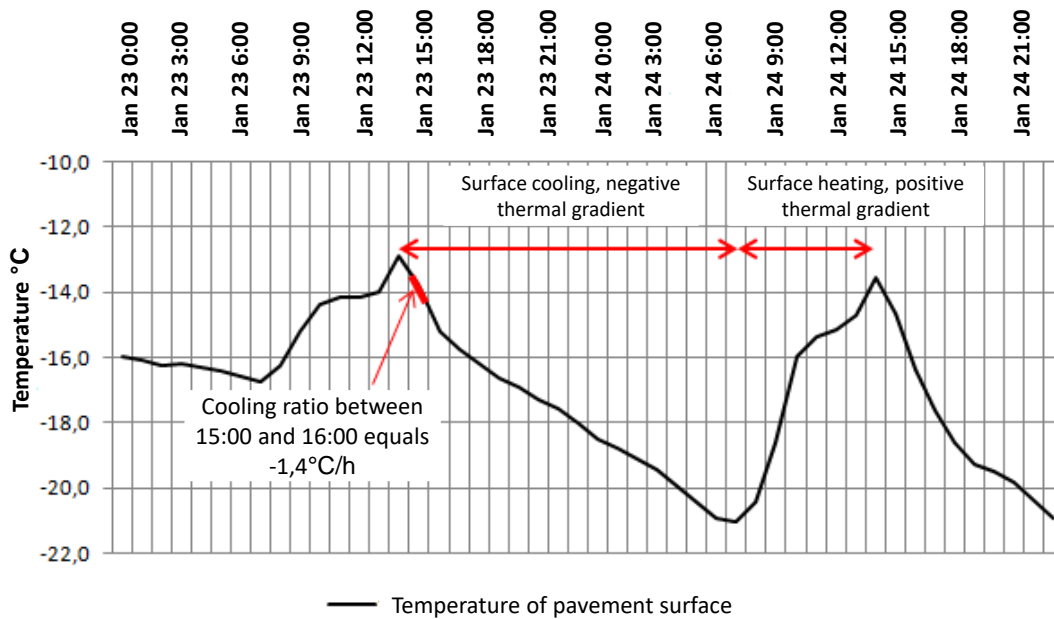
153 To assess the influence of cooling rate on stiffness modulus, the Indirect Tensile Test  
 154 (IT-CY) method according to EN 12697-26 [39] and a programmable thermostatic  
 155 chamber were used. Gyratory compacted samples (100 mm in diameter and 50 mm in  
 156 height) were prepared using 50/70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

164 **3. Analysis of cooling rate in real conditions**

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

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].



184

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

186 The probability of occurrence of the maximum pavement surface cooling rate

187 obtained from the analysis is presented in Table 3 after [17].

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

| Probability of cooling rate value<br>less than $V_T$ | Cooling rate<br>$V_T$ (°C/h) |
|--|------------------------------|
| 99.9%  | $\geq 3.7$                   |
| 99%  | $\geq 2.1$                   |
| 95%  | $\geq 1.2$                   |
| 90%  | $\geq 0.8$                   |
| 85%  | $\geq 0.6$                   |

190

191 The results of analysis indicate that the probability of cooling rate of pavement surface

192 being greater than 3°C/h is less than 1%. It has also been proved that the probability of

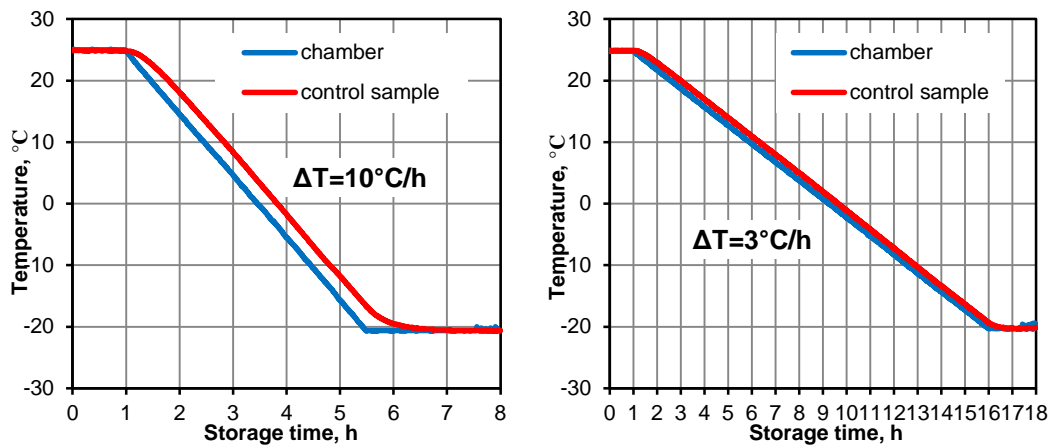
193 cooling rate being less than 1.2°C/h is 95%, which means that only 5% of the results

194 indicate a cooling rate higher than 1.2°C/h.

## 195 4. Results and discussion

### 196 4.1. Influence of cooling rate on stiffness modulus

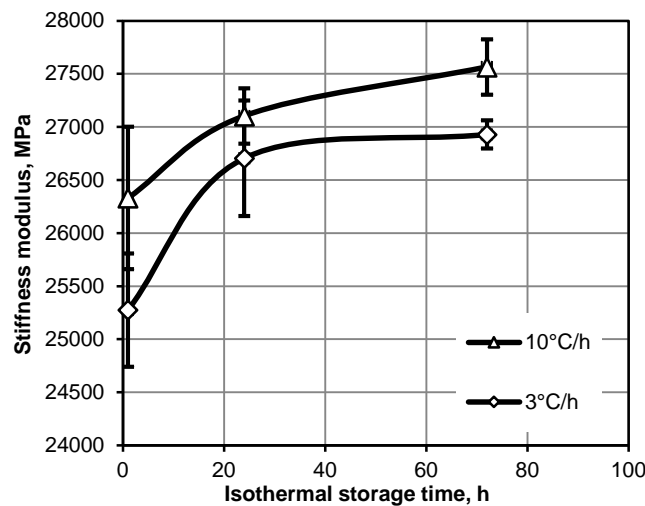
197 It was observed that asphalt mixture stiffness modulus depended on the cooling  
 198 rate during conditioning prior to the test. Temperature values recorded during the  
 199 decrease in temperature with time are presented in Fig. 5. The relationship between  
 200 stiffness modulus values for cooling 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.



204

205

206

**Fig. 6.** Results of stiffness modulus according to Indirect Tensile Test for cooling rates 3°C/h and 10°C/h.

207

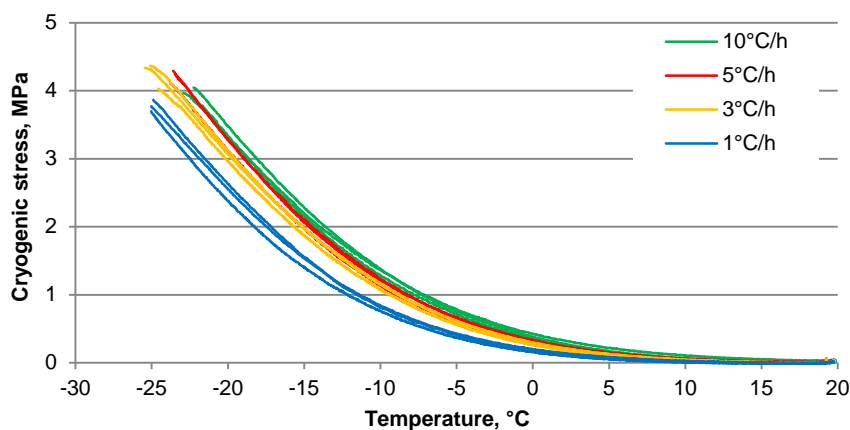
208

It was observed that cooling rate had an important impact on stiffness modulus results. With an increase in cooling rate from 3°C/h to 10°C/h, at the same isothermal

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.



221

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

226 and discussed. For comparative purposes, cryogenic stress at the temperature of  $-20^{\circ}\text{C}$   
 227 ( $\sigma_{\text{cry, @-}20^{\circ}\text{C}}$ ) was also analysed.

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

| Cooling rate, [ $^{\circ}\text{C}/\text{h}$ ] |               | $\sigma_{\text{cry, failure}}$ , [MPa] | $T_{\text{failure}}$ , [ $^{\circ}\text{C}$ ] | $\sigma_{\text{cry, @-}20^{\circ}\text{C}}$ , [MPa] | $\alpha_2$ , [ $\text{N}/\text{mm}^2/^{\circ}\text{C}$ ] | $\alpha_1$ , [ $\text{N}/\text{mm}^2/^{\circ}\text{C}$ ] | $T_g$ , [ $^{\circ}\text{C}$ ] |
|---|---------------|--|---|---|--|--|--------------------------------|
| 10 $^{\circ}\text{C}/\text{h}$                | 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 $^{\circ}\text{C}/\text{h}$                 | 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 $^{\circ}\text{C}/\text{h}$                 | 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 $^{\circ}\text{C}/\text{h}$                 | 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                            |

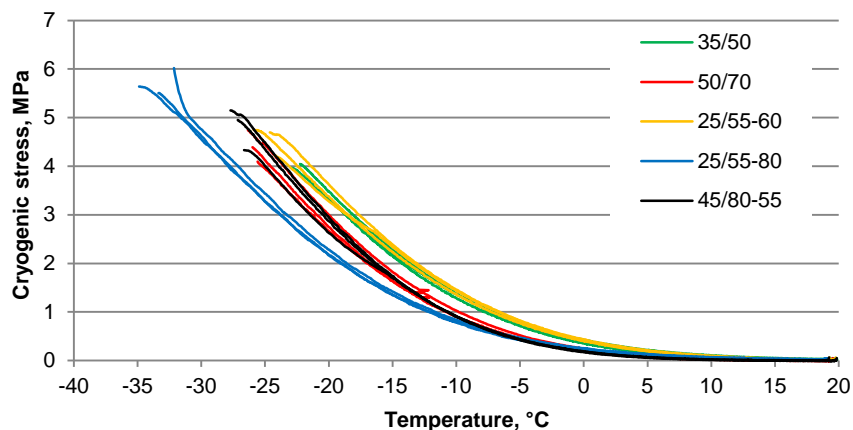
229 The conducted research confirmed that cooling rate has a significant impact on  
 230 failure temperature in the TSRST test. The higher the cooling rate, the higher the  
 231 temperature at which the low-temperature cracks were noticed. At the cooling rate of  
 232 10 $^{\circ}\text{C}/\text{h}$ , the measured fracture temperature was  $-22.4^{\circ}\text{C}$ , while at the cooling rate of 3 $^{\circ}\text{C}/\text{h}$   
 233 it was equal to  $-25.0^{\circ}\text{C}$ . 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 $^{\circ}\text{C}/\text{h}$  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

243 comparative temperature of  $-20^{\circ}\text{C}$  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  $1^{\circ}\text{C}/\text{h}$  to  $5^{\circ}\text{C}/\text{h}$  resulted in an significant  
 246 increase of cryogenic stresses. A further increase in cooling rate from  $5^{\circ}\text{C}/\text{h}$  to  $10^{\circ}\text{C}/\text{h}$   
 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  $T_{\text{failure}}$  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  $10^{\circ}\text{C}/\text{h}$  was used, in  
 252 accordance with the standard TSRST method.



253

254 **Fig. 7.** The results of failure temperature  $T_{\text{failure}}$  and cryogenic stresses  $\sigma_{\text{cry}}(T)$  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 |               | $\sigma_{\text{cry, failure}}$ , [MPa] | $T_{\text{failure}}$ , [ $^{\circ}\text{C}$ ] | $\sigma_{\text{cry, @-20}^{\circ}\text{C}}$ , [MPa] | $\alpha_2$ , [N/mm $^2$ / $^{\circ}\text{C}$ ] | $\alpha_1$ , [N/mm $^2$ / $^{\circ}\text{C}$ ] | $T_g$ , [ $^{\circ}\text{C}$ ] |
|--------------|---------------|--|---|---|--|--|--------------------------------|
| 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                         |

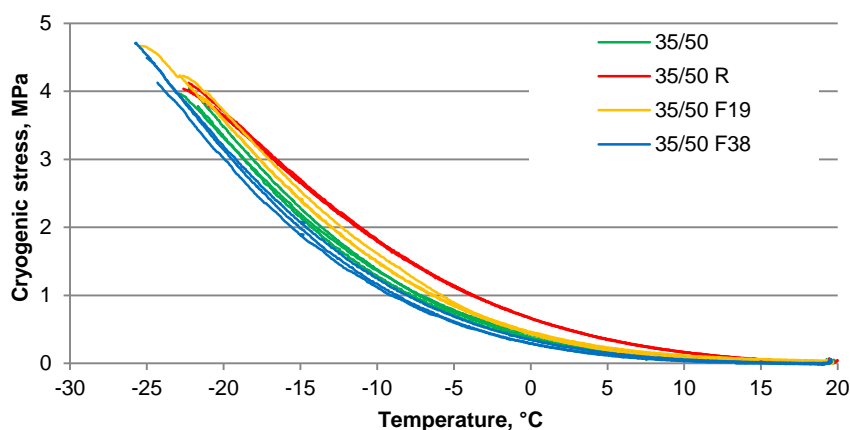
|          |               |       |       |       |        |        |         |
|----------|---------------|-------|-------|-------|--------|--------|---------|
|          | st. deviation | 0.292 | 0.9   | 0.177 | 0.033  | 0.000  | 1.543   |
|          | CV, [%]       | 6.4   | 3.6   | 5.2   | 13.9   | 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  $-20^{\circ}\text{C}$ , the tangent point ( $T_g$ ) and slopes of  
260 curves  $\alpha_1$  and  $\alpha_2$ . Use of the neat road bitumen 30/50 resulted in the highest mean value  
261 of failure temperature equal to  $T_{\text{failure}} = -22.3^{\circ}\text{C}$ . For the SBS-modified bitumen 25/55-60  
262 an improvement of failure temperature to  $-24.9^{\circ}\text{C}$  was observed, but the values of  
263 cryogenic stress at  $-20^{\circ}\text{C}$  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  $T_{\text{failure}}$  and cryogenic stresses  $\sigma_{\text{cry}}(T)$  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.





277

278  
279  
280  
281

**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] | $\sigma_{cry, @-20^{\circ}C}$ , [MPa] | $\alpha_2$ , [N/mm <sup>2</sup> /°C] | $\alpha_1$ , [N/mm <sup>2</sup> /°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          |

282

283

284

285

286

287

288

289

290

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.

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

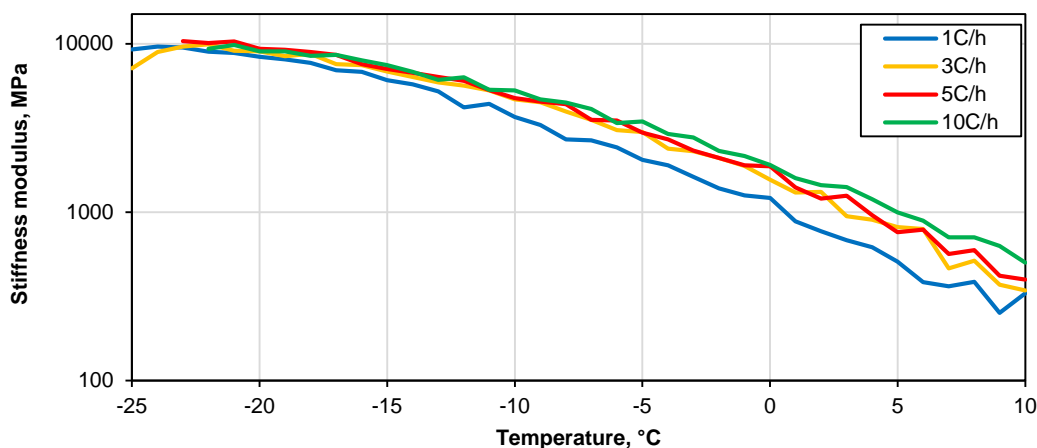
304 The influence of cooling rate, additives and bitumen types on the stiffness  
305 modulus obtained from the TSRST results was analysed and discussed. Stiffness moduli  
306 were back-calculated from all the tested specimens. For this purpose, Hills and Brian  
307 method [42] was adapted. While very 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

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:

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

318 where:  $\sigma(T_i)$  – calculated thermal stresses for the temperature  $T_i$ , MPa,  $\alpha_L$ - linear  
 319 coefficient of thermal contraction, assumed as  $\alpha_L = 2.7 \times 10^{-5} \text{ 1/}^\circ\text{C}$  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,  $\Delta T$  – temperature increment, assumed as  $\Delta T = 1^\circ\text{C}$ .

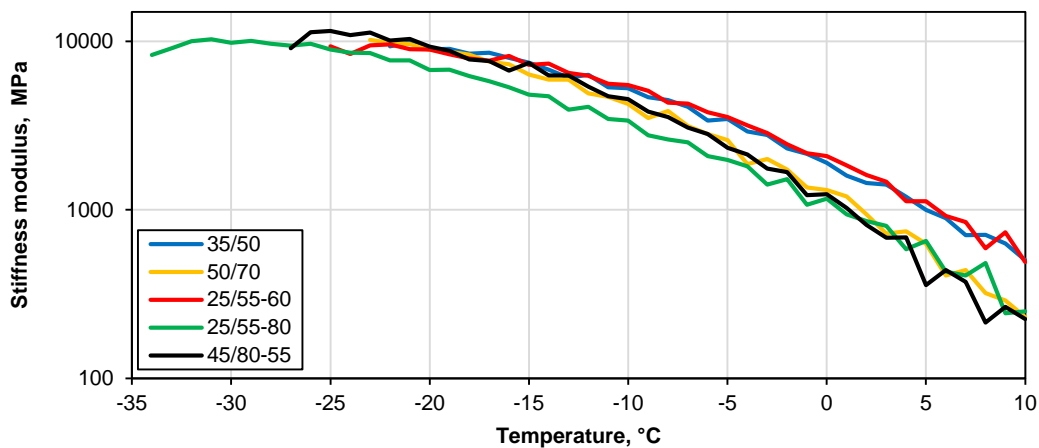
322 For each specimen, stiffness moduli for all temperatures were calculated using the  
 323 least squares method and SOLVER expansion tool. The results obtained for all specimens  
 324 in a given test batch were then averaged. Back-calculated values for different cooling  
 325 rates, types of bitumen 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].



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

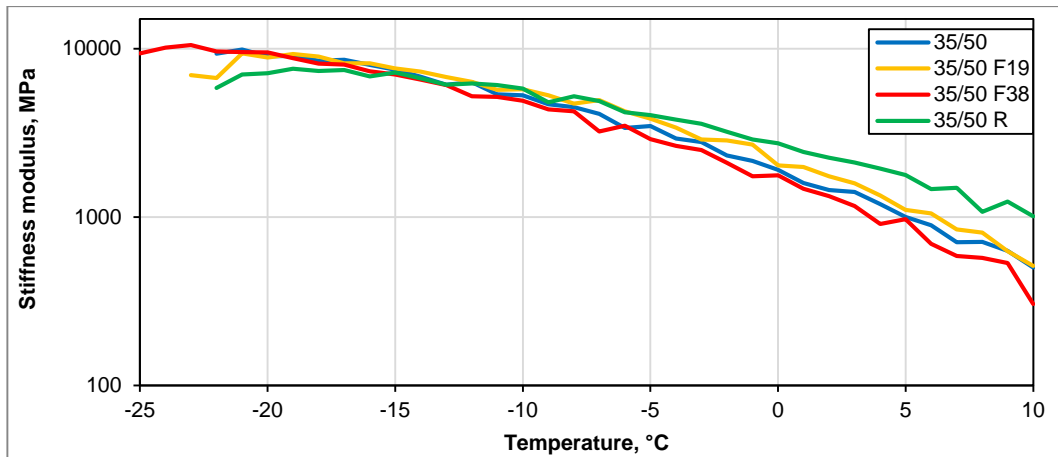
329 Cooling rate influenced stiffness modulus, as was expected. In all cases the values  
 330 of stiffness moduli ranged from 500 to 10000 MPa. The lowest values were obtained for  
 331 the cooling rate of  $1^\circ\text{C/h}$  and the highest for the cooling rate of  $10^\circ\text{C/h}$ . The increase in  
 332

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



341  
 342 **Fig. 10.** Back-calculated values of stiffness moduli for different bitumen types.

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



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

370 increases. The greatest difference in cryogenic stresses and failure temperatures  
371 occurs between the cooling rates of 1°C/h and 3°C/h.

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

375 4. The addition of 19-mm-long aramid fibres and crumb rubber does not change the  
376 failure temperature significantly. On the other hand, mixtures containing longer  
377 (38 mm) aramid fibres presented lower failure temperature in comparison to the  
378 reference AC 11S 35/50 mixture.

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

#### 384 **Acknowledgement**

385 Part of the laboratory research was completed under GRAM grant, awarded in a  
386 competitive procedure by the Dean of the Faculty of Civil and Environmental  
387 Engineering, Gdansk University of Technology, who is gratefully acknowledged for the  
388 support.

#### 389 **References**

390 [1] B.A. Burgers, O. Kopvillem, F.D. Young, Ste. Anne test – relationships between  
391 predicted fracture temperatures and low temperature field performance, Asphalt  
392 Paving Technol. 40 (1971) 148-193.

- 393 [2] T. Pucci, A.G. Dumont, H. Di Benedetto, Thermomechanical and Mechanical  
394 Behaviour of Asphalt Mixtures at Cold Temperature: Road and Laboratory  
395 Investigations, *Road Mater. Pavement* 5 (2004), 45–72.
- 396 [3] M. Marasteanu, A. Zofka, M. Turos, X. Li, R. Velasquez, X. Li, W. Buttlar, G.  
397 Paulino, A. Braham, E. Dave, J. Ojo, H. Bahia, Ch. Williams, J. Bausano, A.  
398 Kvasnak, A. Gallistel, J. McGraw, Investigation of low temperature cracking in  
399 asphalt pavements – A Transportation Pooled Fund Study, Report No. MN/RC  
400 2007-43, (2007).
- 401 [4] J. Judycki, A new viscoelastic method of calculation of low-temperature thermal  
402 stresses in asphalt layers of pavements, *Int. J. Pavement Eng.* 19 (2016) 24–36.  
403 <https://doi.org/10.1080/10298436.2016.1149840>.
- 404 [5] D. Rys, J. Judycki, M. Pszczola, M. Jaczewski, L. Melun, Comparison of low-  
405 temperature cracks intensity on pavements with high modulus asphalt concrete  
406 and conventional asphalt concrete bases, *Constr. Build. Mater.* 147 (2017) 478–  
407 487. <https://doi.org/10.1016/j.conbuildmat.2017.04.179>.
- 408 [6] M. Pszczola, M. Jaczewski, D. Rys, P. Jaskula, C. Szydłowski, Evaluation of  
409 Asphalt Mixture Low-Temperature Performance in Bending Beam Creep Test,  
410 *Materials (Basel)* 11(1) (2018) 100. <https://doi.org/10.3390/ma11010100>.
- 411 [7] C.L. Monismith, G.A. Secor, K.E. Secor, Temperature induced stresses and  
412 deformations in asphalt concrete, *Asphalt Paving Technol.* 34 (1965) 248-285.
- 413 [8] A.F. Stock, W. Arand, Low temperature cracking in polymer modified binders,  
414 *Asphalt Paving Technol.* 62 (1993) 23-53.



- 415 [9] D. Jung, T.S. Vinson, Low temperature cracking resistance of asphalt concrete  
416 mixtures, *Asphalt Paving Technol.* 62 (1993) 54-92.
- 417 [10] R. Velasquez, J.F. Labuz, M.O. Marasteanu, A. Zofka, Revising thermal stresses  
418 in the TSRST for low-temperature cracking prediction, *J. Mater. Civil Eng.*  
419 21(11) (2009) 680-687. [https://doi.org/10.1061/\(ASCE\)0899-  
420 1561\(2009\)21:11\(680\)](https://doi.org/10.1061/(ASCE)0899-1561(2009)21:11(680)).
- 421 [11] T. Mandal, H. Bahia, Measuring crack propagation resistance of asphalt mixtures  
422 using notched samples in the TSRST, 62nd Annual Canadian Technical Asphalt  
423 Association Conference. (2017) 1-21.
- 424 [12] M. J. Farrar, E.Y. Hajj, J.P. Planche, M.Z. Alavi, A method to estimate the  
425 thermal stress build-up in an asphalt mixture from a single-cooling event, *Road  
426 Mater. Pavement* 14(S1) (2013) 201-211.  
427 <https://doi.org/10.1080/14680629.2013.774756>.
- 428 [13] M. Pszczoła, J. Judycki, Comparison of calculated and measured thermal stresses  
429 in asphalt concrete, *Balt. J. Road Bridge E.* 10(1) (2015) 39-45.  
430 <https://doi.org/10.3846/bjrbe.2015.05>.
- 431 [14] T.R.J.Fabb, The influence the of mix composition, binder properties and cooling  
432 rate on asphalt cracking at low temperatures, *Asphalt Paving Technol.* 43 (1974)  
433 285-331.
- 434 [15] D. Jung, T.S. Vinson, *Low-Temperature Cracking: Test Selection*, Strategic  
435 Highway Research Program, National Research Council, SHRP-A-400,  
436 Washington, DC, (1994).



- 437 [16] H.K. Kanerva, T.S. Vinson, H. Zeng, Low-Temperature Cracking: Field  
438 Validation of the Thermal Stress Restrained Specimen Test, Strategic Highway  
439 Research Program, National Research Council, SHRP-A-401, Washington, DC,  
440 (1994).
- 441 [17] M. Pszczola, J. Judycki, D. Rys, Evaluation of pavement temperatures in Poland  
442 during winter conditions. *Transp. Res. Proc.* 14 (2016) 738–747.  
443 <https://doi.org/10.1016/j.trpro.2016.05.342>.
- 444 [18] A.K. Apeageyi, E.V. Dave, W.G. Buttlar, Effect of cooling rate on thermal  
445 cracking asphalt concrete pavements, *Asphalt Paving Technol.* 77 (2008) 709-  
446 738.
- 447 [19] B. Teltayev, B. Radovskiy, Predicting thermal cracking of asphalt pavements  
448 from bitumen and mix properties, *Road Mater. Pavement* 0 (2017) 1-16.  
449 <https://doi.org/10.1080/14680629.2013.774756>.
- 450 [20] M.Z. Alavi, E.Y. Hajj, Effect of cooling rate on the thermo-volumetric, thermo-  
451 viscoelastic, and fracture properties of asphalt mixtures, *Int. Conf. on Asphalt*  
452 *Pavements*, *Asphalt Pavements* (2014) 405-416.
- 453 [21] P. Ling, W. Huang, Y. Li, N. Tang, F. Xiao, Investigation of influence factors on  
454 low temperature properties of SBS modified asphalt, *Constr. Build. Mater.* 154  
455 (2017) 609-622. <https://doi.org/10.1016/j.conbuildmat.2017.06.118>.
- 456 [22] S.D. Roy, S.A.M. Hesp, Low-temperature binder specification development.  
457 Thermal Stress Restrained Specimen testing of asphalt binders and mixtures,  
458 *Transportat. Res. Rec.* 1766 (2001) 7-14.

- 459 [23] G.N. King, H.W. King, O. Harders, W. Arand, J.P. Planche, Influence of asphalt  
460 grade and polymer concentration on the low temperature performance of polymer  
461 modified asphalt, *Asphalt Paving Technol.* 62 (1993) 1-22.
- 462 [24] M. Bai, Investigation of low-temperature properties of recycling of SBS modified  
463 asphalt binder, *Constr. Build. Mater.* 150 (2017) 766-773.  
464 <https://doi.org/10.1016/j.conbuildmat.2017.05.206>.
- 465 [25] A.L. Epps, A comparison of measured and predicted low temperature cracking  
466 conditions, *Asphalt Paving Technol.* 67 (1998) 277-296.
- 467 [26] D. Sybilski, W. Bańkowski, K. Mirski, R. Hododecka, A. Wróbel, Rubber-  
468 bitumen granulate for asphalt pavements – laboratory comparative analysis, 5th  
469 International Conference on Bituminous Mixtures and Pavements, Thessaloniki,  
470 (2011) 1413-1421.
- 471 [27] M. Pszczoła, M. Jaczewski, C. Szydłowski, J. Judycki, B. Dołycki, Evaluation  
472 of low temperature properties of rubberized asphalt mixtures, *Procedia Eng.* 172  
473 (2017), 897–904. <https://doi.org/10.1016/j.proeng.2017.02.098>.
- 474 [28] L. Porot, D. Broere, M. Wistuba, J. Gronniger, Asphalt and binder evaluation of  
475 asphalt mix with 70% reclaimed asphalt, *Road Mater. Pavement* 18(S2) (2017)  
476 66-75. <https://doi.org/10.1080/14680629.2017.1304259>.
- 477 [29] E.Y. Hajj, M.Z. Alavi, N.E. Morian, P.E. Sebaaly, Effect of select warm-mix  
478 additives on thermos-viscoelastic properties of asphalt mixtures, *Road Mater.*  
479 *Pavement* 14 (2013) 175-186. <https://doi.org/10.1080/14680629.2013.774754>.
- 480 [30] Y. Tasdemir, Investigation of the low temperature performances of polymer and



- 481 fiber modified asphalt mixtures, Indian J. Eng. Mater. S. 14 (2007) 151-157.
- 482 [31] EN 13108-1:2016 Bituminous mixtures. Material specifications. Asphalt  
483 Concrete (2016).
- 484 [32] Polish technical guidelines WT-2:2014, General Directorate for National Roads  
485 and Motorways, (2014).
- 486 [33] P. Jaskuła, M. Stienss, C. Szydłowski, Effect of polymer fibres reinforcement on  
487 selected properties of asphalt mixtures, Procedia Eng. 172 (2017), 441-448.  
488 <https://doi.org/10.1016/j.proeng.2017.02.026>.
- 489 [34] S. Badeli, A. Carter, G. Dore, S. Saliani, Evaluation of the durability and the  
490 performance of an asphalt mix involving Aramid Pulp Fiber (APF): Complex  
491 modulus before and after freeze-thaw cycles, fatigue, and TSRST tests, Constr.  
492 Build. Mater. 174 (2018) 60-71.  
493 <https://doi.org/10.1016/j.conbuildmat.2018.04.103>.
- 494 [35] EN 12697-35:2016 Bituminous mixtures - Test methods for hot mix asphalt -  
495 Part 35: Laboratory mixing (2016).
- 496 [36] EN 12697-33+A1:2008 Bituminous mixtures - Test methods for hot mix asphalt  
497 - Part 33: Specimen prepared by roller compactor (2008).
- 498 [37] K. Kornacka, Evaluation of low-temperature properties of asphalt mixtures based  
499 on selected test methods according to standard PN-EN 12697-46, M.Sc. Thesis  
500 (in Polish) Gdansk University of Technology, (2017).
- 501 [38] EN 12697-46: Bituminous mixtures – Test methods for hot mix asphalt – Part 46:  
502 Low temperature cracking and properties by uniaxial tension tests, (2012).



- 503 [39] EN 12697-26:2012 Bituminous mixtures. Test methods for hot mix asphalt.  
504 Stiffness (2012).
- 505 [40] J. Judycki, Influence of low-temperature physical hardening on stiffness and  
506 tensile strength of asphalt concrete and stone mastic asphalt. *Constr. Build.*  
507 *Mater.* 61 (2017) 191–199. <https://doi.org/10.1016/j.conbuildmat.2014.03.011>.
- 508 [41] S. Hesp, S. Iliuta, J.W. Shirokoff, Reversible aging in asphalt binders, *Energ.*  
509 *Fuel.* 21(2) (2007) 1112–1121. <https://doi.org/10.1021/ef060463b>.
- 510 [42] J.F. Hills, D. Brien, The fracture of bitumen and asphalt mixes by temperature  
511 induced stresses. *Symposium on Pavement Cracking, Asphalt Paving Technol.*  
512 35 (1966) 294–309.
- 513 [43] J. Judycki, Verification of the new viscoelastic method of thermal stress  
514 calculation in asphalt layers of pavements. *Int. J. Pavement Eng.* (2016) 1-20.  
515 <https://doi.org/10.1080/10298436.2016.1199883>.