

1
2 **Factors affecting low-temperature cracking of asphalt pavements:**
3 **analysis of field observations using the ordered logistic model**

4 Rys Dawid^{*1)}, Jaczewski Mariusz¹⁾, Pszczola Marek¹⁾, Kamedulska Agnieszka²⁾,
Kamedulski Bartosz³⁾

5 ¹⁾ *Gdansk University of Technology, Faculty of Civil and Environmental Engineering,*
6 *Gdansk, Poland*

7 ²⁾ *Medical University of Gdansk, Department of Biopharmacy and Pharmacodynamics,*
8 *Gdansk, Poland*

9 ³⁾ *Gdynia Maritime University, Department of Mathematics, Gdynia, Poland*

10 *) corresponding author,

11 Gdansk University of Technology, Faculty of Civil and Environmental Engineering

12 Narutowicza Street 11

13 Gdansk, PL 80-952

14 tel.:+48 58 347 27 82

15 e-mail: dawrys@pg.gda.pl

16

17 **Abstract**

18 Low-temperature cracking is a common distress of asphalt pavements.
19 Accurate identification of factors that primarily affect the number of low-
20 temperature cracks is crucial for selection of road materials and planning
21 of pavement maintenance. In the article several factors were considered
22 and compared in terms of their impact on low-temperature cracks. Field
23 investigations of low-temperature cracks were performed in the years 2014
24 and 2020 on the same 68 road sections being in service in typical traffic
25 conditions. The collected data were statistically analysed using the ordered
26 logistic regression model. Comparison of the odds ratios which were
27 calculated on the basis of the model enabled ordering of the selected
28 factors from those having the greatest effect on low-temperature cracking
29 of pavements to those with the least influence: 1) pavement age, 2) type of
30 asphalt concrete, 3) modification of bitumen, 4) climatic zone (on the basis
31 of low performance grade temperature). It was determined that pavements
32 where high-modulus asphalt concrete was used in the binder course and
33 the asphalt base course belonged to the group of uncracked sections with
34 odds 3.65 times greater than pavements where conventional asphalt
35 concrete was used. The odds of a section belonging to the group of
36 cracked sections decreased by half when a polymer-modified bitumen was
37 used in its binder course and asphalt base. Regardless of the considered
38 factors, the odds of a pavement section being classified into the group of
39 heavily cracked sections are comparable. It means that some external
40 factors, including quality of paving works and bitumen chemistry, may
41 prove the most crucial.

42 **Keywords:** low-temperature cracking, performance grade, logistic
43 regression, field investigations, pavement maintenance, asphalt concrete

44 **1. Introduction**

45 The network of motorways and main roads in Poland is developing intensively.
46 More than 4 000 km of completely new pavements have been constructed since 2004.
47 For most of these relatively new motorways, low-temperature cracks are the only type
48 of pavement distress. In order to counteract the phenomenon effectively and predict the
49 scale of the problem, it is necessary to correctly identify and rank the factors that
50 primarily affect the occurrence of low-temperature cracking. Most previous studies,
51 including Velasquez and Bahia (2013), Baglieri et al. (2021), Marasteanu M. et al.
52 (2007), Zofka and Braham (2009), focus on assessment of the laboratory properties of
53 asphalt mixtures or binders at low temperatures. Some researchers conducted studies
54 using data collected from field observations of low-temperature cracks on road network
55 (Jung and Vinson 1994, Anderson et al. 1998, Yee et al. 2006, Marasteanu et al. 2007,
56 Dong et al. (2017)), but the number of studies available in the literature is limited. The
57 closest to the topic of this paper are the studies performed by Dong et al. (2017), who
58 used a database of 46 LTPP test sections to analyse 36 factors which may influence the
59 scale of thermal cracking. They reported that pavement age, AC layer thickness, binder
60 percentage, bitumen stiffness from the BBR test and monthly freezing index are the key
61 factors. However, asphalt mixtures built in at the LTPP test sections, which are located
62 in North America, differ from asphalt mixtures used in European countries due to
63 different standardization systems, requirements for asphalt mixtures and bitumens, as
64 well as construction and control processes.



65 Most new pavements in Poland are constructed as asphalt pavements. In
66 practice, wearing courses are always made of stone mastic asphalt (SMA) with SBS
67 polymer-modified bitumen (PmB), whereas two types of asphalt mixtures are used for
68 binder courses and asphalt base courses: with high modulus asphalt concrete (HMAC)
69 and with conventional asphalt concrete (AC). According to previous studies, the usage
70 of HMAC instead of AC can lead to an increase in the risk of low-temperature cracks
71 (Moreno-Navarro et al., 2016, Ryś et al., 2017). On the other hand, in the opinion of
72 many experts, the advantages of HMAC resulting from very good resistance to rutting
73 and fatigue outweigh the disadvantages (Bańkowski, 2018, Corte, 2001, Chen et al.
74 2020, Gajewski et al., 2020, Lee et al. 2006, Ouyang et al. 2009, Yang et al. 2020,
75 Zaumanis et al. 2020, Zhu et al. 2021). Moreover, low-temperature cracks are observed
76 in various climatic regions, on pavements of different age and constructed both with AC
77 and HMAC bases, and both on sections where neat and polymer-modified bitumens
78 were applied. Therefore, determination of material requirements or limitations in the
79 usage of mixture types or bitumen types should be supported by field observations of
80 in-service pavements.

81 The main goal of the paper is to compare the following factors in terms of their
82 impact on the number of low-temperature cracks: technology of asphalt pavement (with
83 AC or HMAC binder course and base course), bitumen modification, age of pavement
84 and climatic conditions.. The aim of the analysis is to evaluate each of the considered
85 factors in terms of its contribution to the number of low-temperature cracks observed in
86 the field. To reach these goals, the data collected from field sections were analysed
87 using the ordered logistic regression model.

88 **2. Mechanism of low-temperature cracking and factors that may have**
89 **impact on the number of low-temperature cracks**

90 When cryogenic stresses exceed the tensile strength of the asphalt mixture, the
91 pavement cracks. Cryogenic tension occurs as a consequence of shrinkage of an asphalt
92 layer subjected to a decrease in temperature. Due to the visco-elastic behaviour of the
93 asphalt mixture, cryogenic stresses relax in time – thus, beside the minimum value of
94 temperature, the grade of pavement cooling plays a significant role as well. The
95 mechanism is described in detail in the studies of Judycki (2018). Under model
96 conditions, the low-temperature cracks are initiated on the surface of the asphalt layer in
97 the middle of the carriageway. The theory is confirmed by observations of many field
98 cases of transverse cracks. However, previous works (Judycki et al., 2015, 2020)
99 suggest that when the asphalt base or binder course is made of mixture much stiffer than
100 the wearing course, the crack can be initiated in those lower layers and then penetrate
101 upwards. Such mechanism of low-temperature cracking can be crucial in the case of
102 pavements where HMAC is applied. Therefore, the number of low-temperature cracks
103 is affected not only by the properties of the wearing course, but also by the properties of
104 the binder course as well as the asphalt base course.

105 Very important factors that influence the probability of occurrence of thermal
106 cracks in a pavement include, among others, the grade of the bitumen, its stiffness and
107 capacity for relaxation at low temperatures as well as fracture properties of the asphalt
108 mix. Due to the aging process, mixture properties become more adverse with an
109 increase in pavement age. Asphalt mixtures very often exhibit varying properties even if
110 they are used for the same layer under the same contract and meet all the local technical
111 requirements. The homogeneity of laying and compaction of the mixture as well as
112 quality of working joints plays a significant role in further development of low-

113 temperature cracks (Judycki et al., 2015, 2016). Finally, the climatic conditions are the
 114 main source of the phenomenon (Moreno-Navarro et al. 2016).

115 **3. General properties of asphalt mixtures and bitumens used for**
 116 **construction of the road sections**

117 All the road sections taken into consideration in the presented analysis were constructed
 118 as flexible pavements with crushed stone bases. Lower layers (subbase and capping)
 119 ensured bearing capacity of $E_2 \geq 100$ MPa. The total thickness of the asphalt layers
 120 varies across different sections from 16 cm to 31 cm, while thickness of the granular
 121 base varies from 15 cm to 25 cm. Thickness of the asphalt base and binder courses
 122 varied depending on the used material (AC, HMAC) and the predicted traffic category.
 123 The wearing course is typically made of stone mastic asphalt SMA8 or SMA11, with
 124 the thickness of 3 cm to 4 cm. Typical pavement structures of the analysed road sections
 125 are presented in Figure 1.

| Typical section with AC base | Typical section with HMAC base (neat bitumen) | Typical section with HMAC base (PmB bitumen) |
|---|---|---|
| SMA8 or SMA11 PmB 45/80-55 <i>wearing course</i> | SMA8 or SMA11 PmB 45/80-55 <i>wearing course</i> | SMA8 or SMA11 Pmb 45/80-55 <i>wearing course</i> |
| AC 16W or AC 22W 35/50 <i>binder course</i> | HMAC 16 20/30 <i>binder course</i> | HMAC 16 PmB 25/55-60 <i>binder course</i> |
| AC 22P or AC 32P 35/50 <i>asphalt base course</i> | HMAC 16 20/30 <i>asphalt base course</i> | HMAC 16 PmB 25/55-60 <i>asphalt base course</i> |
| Unbound aggregate <i>base course</i> <small>$\nabla E_2 \geq 100$ MPa or $E_2 \geq 120$ MPa</small> | Unbound aggregate <i>base course</i> <small>$\nabla E_2 \geq 100$ MPa or $E_2 \geq 120$ MPa</small> | Unbound aggregate <i>base course</i> <small>$\nabla E_2 \geq 100$ MPa or $E_2 \geq 120$ MPa</small> |

126
 127 Figure 1. Typical pavement structures of the analysed road sections

128 All of the asphalt mixtures used in the test sections were designed according to
 129 the WT-2:2014 technical requirements (GDDKiA, 2014) or their previous instances.

130 The W The requirements for mixtures are summarised in Table 1. Bitumen content was
131 similar for most type of mixtures and was designed mostly with minimum requirements
132 stated by national requirements, as stated in table 1. In the case of aggregate, where data
133 was available, mostly following types of aggregates were utilized – granite/gneiss,
134 postglacial aggregate or limestone. When needed adhesion agent was utilized.

135 Since the requirements for low-temperature performance are not included in the
136 Polish requirements WT-2, the supplementary Table 2 is presented. Table 2 includes the
137 TSRST cracking temperatures as well as Indirect Tensile Strength (ITS) test results,
138 obtained for the same types of mixtures and binders in previous research projects. The
139 TSRST test results are expressed by two indices – the mean value of all the results and
140 the range of the results. The basic properties of bitumens used in the test sections are
141 given in Table 3. Tables 2 and 3 present the results of tests performed on representative
142 mixtures and bitumens during previous research performed on materials very similar to
143 those used in the test sections. Due to the large number of test sections (68, see
144 supplement A), collection of detailed material data from each individual test sections for
145 the presented work was impossible. The laboratory tests of low-temperature properties
146 of considered asphalt mixtures were conducted on specimens drill out from pavements
147 for following test sections with id according to supplement A: 55, 59, 60, 62. The
148 results were described in details by Pszczola et al. (2022) and both with the results
149 described by Rys et al. (2020) allows to state that the values presented in Tables 1-3 can
150 be treated as reliable and representative for the considered materials.

151

152 Table 1. Standard requirements for mixtures used in the test sections according to WT-2
 153 (GDDKiA, 2014)

| Property | SMA8 | SMA11 | AC 16 W | AC 22 P | HMAC 16 |
|--|---|---|---|---|---|
| Max. aggregate size, mm | 8 | 11 | 16 | 22 | 16 |
| Bitumen type [EN 12591, EN 14023] | 50/70 PmB 45/80-55 | | 35/50 | | 20/30 PmB 25/55-60 |
| Bitumen, % (mass) | min. 7.2 | min. 6.6 | min. 4.6 | min. 4.0 | min. 5.0 |
| Voids, % [EN 12697-8] | 2.0 – 3.5 | 2.0 – 3.5 | 4.0 – 7.0 | 4.0 – 7.0 | 2.0 – 4.0 |
| Resistance to water, [EN 12697-12] | ITSR ₉₀ | ITSR ₉₀ | ITSR ₈₀ | ITSR ₇₀ | ITSR ₈₀ |
| Resistance to permanent deformation, [EN 12697-22] | WTS _{AIR 0.10} PRD _{AIR 7.0} | WTS _{AIR 0.10} PRD _{AIR 7.0} | WTS _{AIR 0.10} PRD _{AIR 5.0} | WTS _{AIR 0.15} PRD _{AIR 7.0} | WTS _{AIR 0.10} PRD _{AIR 5.0} |

154

155 Table 2. Selected low-temperature properties of asphalt mixtures based on previous own
 156 research

| Property | | Mixture and bitumen type | | | | | |
|-----------------------------|---------------------|--------------------------|-----------------|---------|---------|---------|-----------------|
| | | SMA 8 / SMA 11 | | AC 16 W | AC 22 P | HMAC 16 | |
| | | 50/70 | PmB 45/55-80 | 35/50 | 35/50 | 20/30 | PmB 25/55-60 |
| TSRST [°C] [EN 12697-46] | Mean | -24.5 | -27.0 | -21.1 | -17.3 | -20.7 | -24.2 |
| | Max / | - 21.5 | - 24.3 | -20.2 | -12.5 | -16.8 | -20.2 |
| | Min | - 30.0 | - 31.1 | -22.9 | -22.5 | -22.8 | -30.9 |
| ITS [MPa] [EN 12697-23] | @-10°C | n/a | n/a | 4.876 | 4.545 | 5.001 | 5.311 |
| | After STA @-20°C | 5.010 | 5.480 | 4.864 | 4.934 | 4.990 | 4.673 |
| | @-30°C | n/a | n/a | 4.195 | 3.928 | 4.147 | 4.868 |

157

158 Table 3. Properties of bitumens used in the tested sections (Rys et al., 2020)

| Property | | Type of bitumen | | | |
|-------------------------------|-----------|-----------------------|-----------------------|-----------------------|----------------------------------|
| | | 20/30 | 35/50 | PmB 25/55-60 | PmB 45/80-55 |
| Performance Grade | | PG76-10 ^{a)} | PG70-22 ^{a)} | PG88-16 ^{a)} | PG70-22 to PG76-22 ^{a)} |
| Penetration, 0.1 mm | Virgin | 20-30 ^{b)} | 35-50 ^{b)} | 25-55 ^{b)} | 45-80 ^{b)} |
| | RTFOT | 18.5 ^{a)} | 30 ^{a)} | 27 ^{a)} | 40 ^{a)} |
| Ring and Ball temperature, °C | Virgin | 55-63 ^{b)} | 50-58 ^{b)} | > 60 ^{b)} | > 55 ^{b)} |
| | RTFOT | 70.1 ^{a)} | 62.5 ^{a)} | 74.8 ^{a)} | 69 ^{a)} |
| BBR, S [MPa], | S @ -12°C | 273 ^{a)} | 238 ^{a)} | 169 ^{a)} | 143 ^{a)} |
| | S @ -18°C | 547 ^{a)} | 440 ^{a)} | 338 ^{a)} | 309 ^{a)} |
| m [-] | m @ -12°C | 0.260 ^{a)} | 0.304 ^{a)} | 0.284 ^{a)} | 0.321 ^{a)} |
| | m @ -18°C | 0.209 ^{a)} | 0.219 ^{a)} | 0.246 ^{a)} | 0.271 ^{a)} |

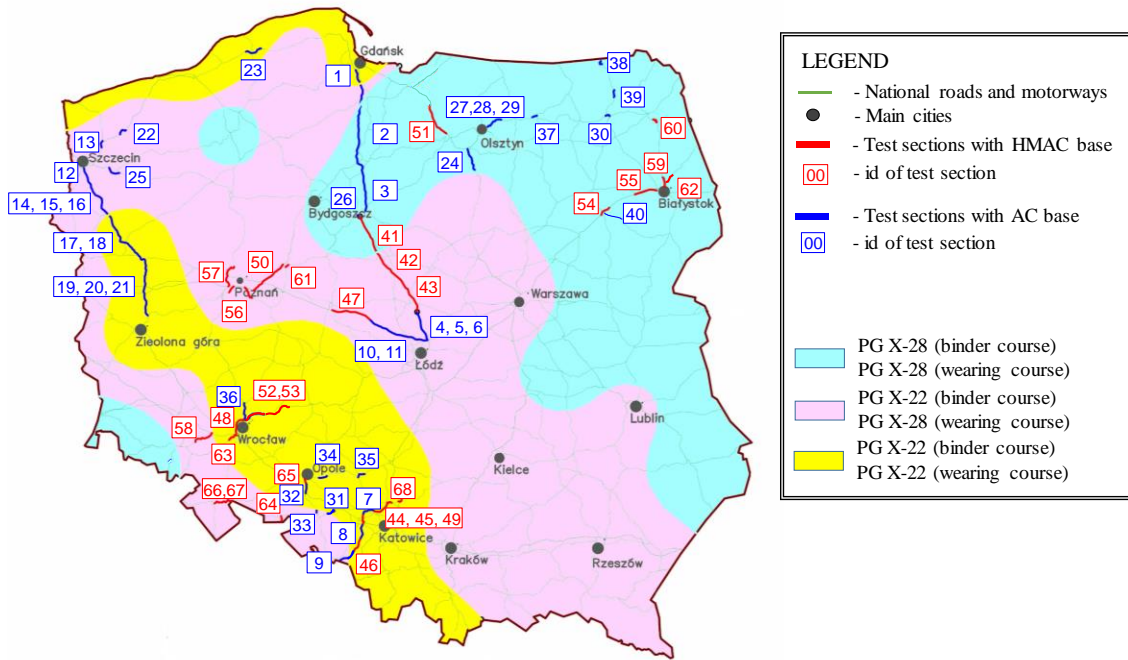
159 Remarks: a) measured, b) according to producer specification

160 As shown in Table 1, AC mixtures contain less bitumen than HMAC mixtures
161 and have a more open structure. Also, in the case of mechanical properties, the
162 requirements stated for HMAC mixtures are slightly higher than those for AC mixes. In
163 the case of low-temperature properties expressed by TSRST test, for neat bitumen the
164 obtained mean values are very similar for both types of mixtures, but HMAC mixtures
165 present worse results in terms of range. The best results (the lowest cracking
166 temperature) were obtained for HMAC mixtures with PmB bitumen that were used to
167 binder and base course. In the case of low-temperature strength, mixtures with neat
168 bitumen present very similar results, reaching the maximum value for either -10°C or -
169 20°C. Below that temperature an intense decrease in strength is observable. In the case
170 of HMAC mixtures with PmB bitumen, the values obtained for low-temperature
171 strength show only a small reduction even at the temperature of -30°C. Taking into
172 consideration both indices (TSRST temperature and ITS values), AC and HMAC
173 mixtures with neat bitumen present similar behaviour, while HMAC mixture with PmB
174 bitumen presents much better low-temperature performance.

175 **4. Methodology of field investigation and data analysis**

176 ***4.1. Description of the tested sections***

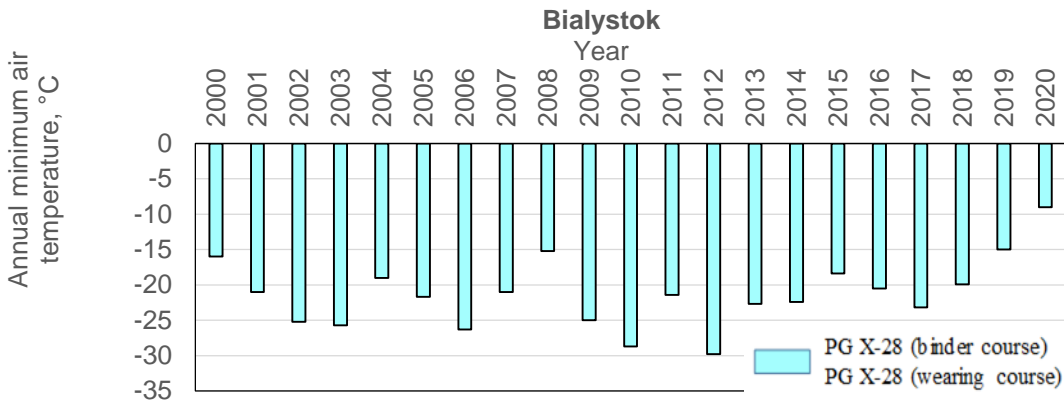
177 The field investigation was conducted on 68 road sections: 40 with conventional
178 AC and 28 with HMAC asphalt base. Figure 2 presents a map with locations of the
179 tested sections. Each section is labelled with an id number. The detailed data for all
180 sections are attached in Supplement A and the video records from the visual
181 investigations are available in a public repository. All of the sections were constructed
182 under normal contract conditions and have been in normal service and maintenance.
183 The type of pavement structure is the same in all cases: asphalt layers are laid directly
184 on the base course of unbound crushed aggregate. Foundation and capping layer vary,
185 but the risk of reflected cracks from cement-treated base course is negligible. Each
186 section is characterised by the same set of factors: pavement structure, age, asphalt mix
187 parameters and the contractor who performed paving works. All road sections are
188 heavily loaded by commercial vehicles and with comparable structures (see figure 1).
189 Figure 2 presents the climatic zones which were determined according to the low
190 temperature of performance grade. Zones were determined on the basis of analysis of
191 climatic data collected from 61 meteorological stations, which was performed according
192 to methodology given in the report no. FHWA-RD-97-104 (1998). The 95% reliability
193 level was assumed, which means that pavement temperature can decrease below the
194 given low PG value once in 20 years. The analysis is presented in more detail in
195 previous publication by the authors (Pszczola et al., 2017). The lowest winter
196 temperatures recorded for the period of 2000-2020 are shown for representative stations
197 for each climatic zone (shown in Figure 2) in Figure 3. Figure 4 shows the number of
198 sections in particular climatic regions, grouped according to the technology of asphalt
199 mixture used for base and binder courses.



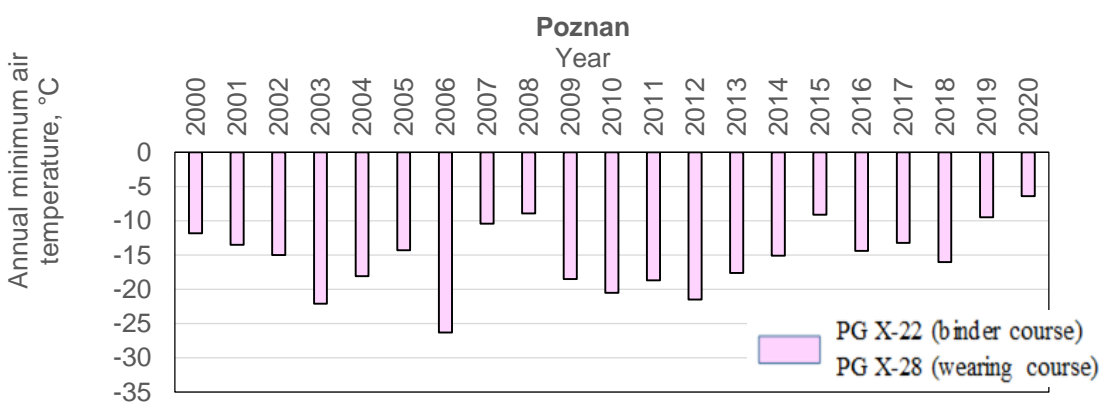
200

201 Figure 2. Location of road sections and climatic zones according to performance grade

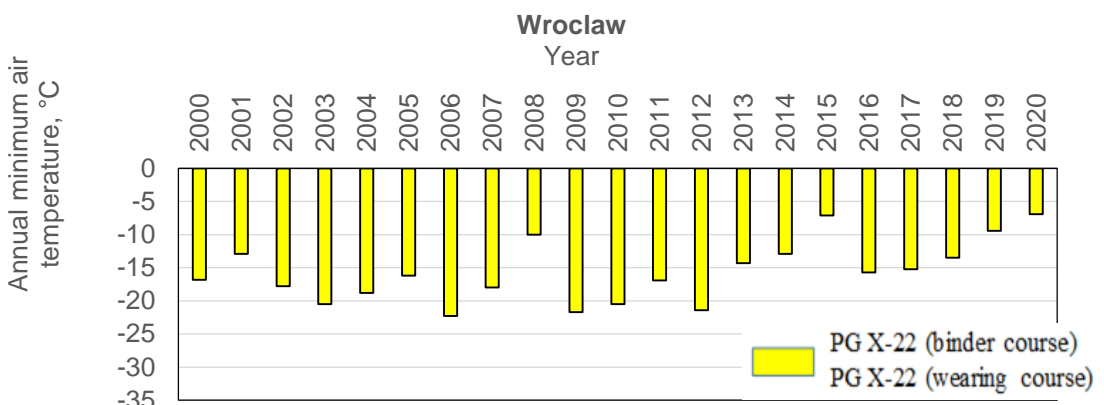
202



203



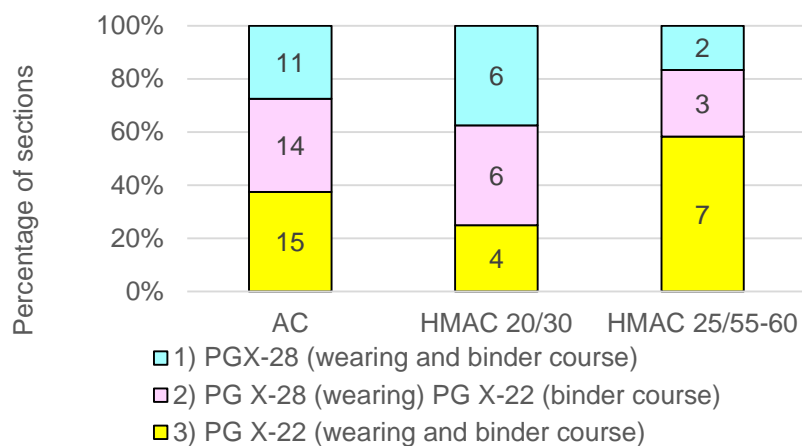
204



205

206 Figure 3. The minimum winter air temperatures recorded for representative station for

207 each climatic zone



208

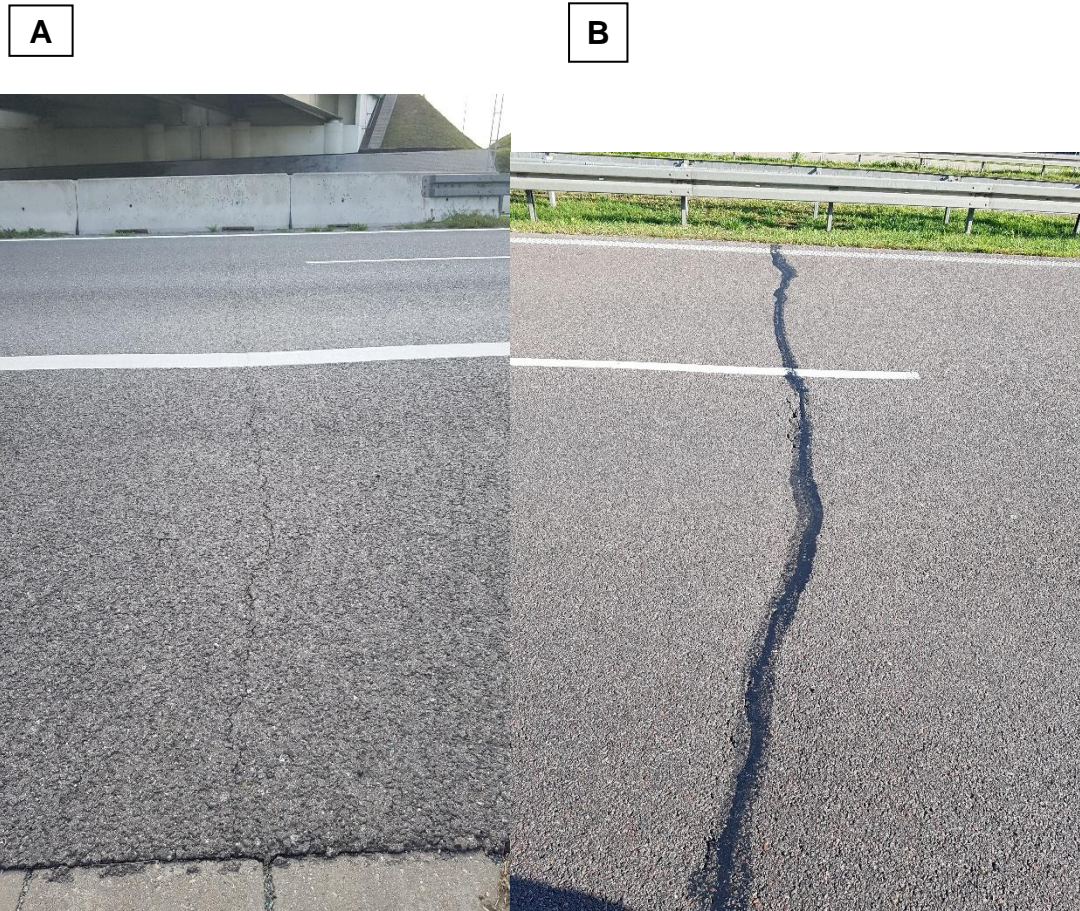
209 Figure 4. Number of road sections located in particular climatic regions and grouped

210 according to the three types of asphalt base

211 ***4.2.Method of identification of low-temperature cracking intensity***

212 The field investigation consisted in visual assessment of pavement distresses
 213 including cracks, ruts, roughness and surface condition. For the analysis presented in
 214 this article, solely the information about low-temperature cracks is taken into account. It
 215 is noteworthy that for almost all the considered sections transverse low-temperature
 216 cracks were the only visible form of distress. Only in a few cases rut with depth less
 217 than 10 mm or block cracks on a small area of wearing course occurred. All the cracks
 218 which originated from causes other than low-temperature action were excluded from the
 219 analysis. The low-temperature cracks were clearly identified as single transverse cracks
 220 that were visible on the surface of each investigated section. Figure 5 presents examples
 221 of typical low-temperature transverse cracks occurring across the entire width of the
 222 carriageway which were observed during the field investigation. In some rare cases
 223 transverse cracks spanned only a portion of the width of the carriageway or were
 224 grouped as two or more cracks at a very low distance. In all the mentioned cases they
 225 were counted as a single crack.

226
227



228

229 Figure 5. Examples of low-temperature cracks a) unrepaired b) sealed

230 Cracking index CI is defined as the average number of transverse cracks per 1
231 km of roadway. In the analysis the cracking index served as a basis for qualification of a
232 section to one of the four categories of crack intensity according to Table 4.

233 Table 4. Classification of road sections according to crack intensity

| Cracking index category Y | Interpretation of the category | Average cracking index CI (cracks per km) |
|-----------------------------|--|---|
| 1 | Sections without low-temperature cracks | $CI = 0$ |
| 2 | Slightly cracked sections | $0 < CI \leq 3$ |
| 3 | Moderately cracked sections | $3 < CI \leq 10$ |
| 4 | Heavily cracked sections, requiring maintenance treatments | $10 < CI$ |

234 The priority of the research was to assess as many various road sections as
235 possible. Due to limited time and funds, it was impossible to investigate the whole
236 length of each section. Therefore, three 1-km-long subsections were selected randomly
237 from each section, the only assumption being that engineering facilities (bridges,
238 tunnels etc.) and road junctions shall be avoided. The limiting of the length of each
239 section to 3 km in total was associated with some uncertainty in determination of CI
240 representing a given road section. An additional investigation of thermal cracks with the
241 accompanying statistical analysis were performed on the entire 24 km length of the
242 section no. 55. The accurate average CI calculated for section no. 55 equals 4.48 cracks
243 per 1 km. Cracking indexes were also calculated for every possible combination of three
244 selected subsections. In total 13.8 million of cases were considered. The distribution of
245 CI obtained for all of these cases is very close to normal distribution with mean equal to
246 4.48 and standard deviation equal to 1.53. The coefficient of variance (COV) of the
247 distribution of CI, which may be a measure of the accuracy of the method, equals 0.34.
248 For comparison, selection of four 1-km-long subsections results in a decrease of COV
249 to 0.29, while selection of only two subsections results in an increase of COV to 0.43.
250 The accuracy of the method resulting from randomly selecting three subsections has a
251 minor effect on classification of sections into cracking index categories. In very rare
252 cases, due to the accuracy of the method, some sections may have fallen into CI
253 categories adjacent to those that would have been determined on the basis of the full
254 length of the sections.

255 Field investigations were performed twice – in the years 2014 and 2020. The
256 particular mileages of subsections were adopted in the year 2014 and the investigations
257 in 2020 were performed precisely on the same previously selected subsections. Ten road

258 sections investigated in 2014 were rebuilt in the meantime. Therefore, they were
259 excluded from investigation in 2020 and they are not mentioned in this work.

260 ***4.3. Methodology of statistical analysis of the collected data***

261 At the first stage of analysis, basic two-parameter relationships between CI and
262 the remaining properties of the tested sections were investigated. Sections were grouped
263 depending on: performance grade (climatic conditions), pavement age, type of asphalt
264 base and bitumen modification. Since the single relationships proved inadequate in
265 identification of the factors with the highest impact on the CI, the authors proposed
266 adoption of methodology based on the ordered logistic model.

267 All parameters considered in the analysis take on categorical values and can be
268 expressed in binary form. Logistic regression is the standard method of modelling
269 categorical or binary outcomes (Gelman and Hill, 2007). Logistic regression was
270 developed by statistician David Cox (1958) and is now widely used in various fields of
271 science. Earlier applications of logistic regression in pavement engineering concerned
272 modelling of pavement deterioration (Tabatabaee et al. 2012) or fatigue of asphalt
273 mixes tested in laboratory conditions (Mateos et al. 2015). Implementation of logistic
274 regression for comparison of the factors that may have effect on the scale of pavement
275 distresses, as proposed in this study, has not been presented in the literature yet.

276 The logistic regression is a generalised linear model where logit is a link
277 function. If the response variable Y takes on categorical values from 1 to k , then the
278 logistic regression model can be expressed as follows (Cox, 1958):

$$279 \quad \text{logit}(p(Y \leq g)) = \ln \frac{p(Y \leq g)}{p(Y > g)} = \beta_{0g} - (\beta_1 X_1 + \dots + \beta_n X_n) \quad (1)$$

280 where:

281 Y : response (dependent) variable,

282 $p(Y \leq g)$: the probability of a particular outcome,

283 $p(Y > g)$ – the probability of the complement of a particular outcome,

284 $\beta_{0g}, \beta_1, \dots, \beta_n$: parameters of regression model,

285 X_1, \dots, X_n : dependent variables,

286 $g = 1, \dots, k - 1$.

287 Dependent variable Y takes on natural values from 1 to 4, according to Table 4. All

288 independent variables X_1, \dots, X_n are presented in binary form in order to simplify the

289 interpretation of the results. The independent variables X_1, \dots, X_n are listed in Table 5,

290 where the meaning of their record in binary form is also explained.

291 Table 5. Independent variables X and their interpretation

| Group of properties | Variable designation | Variable description | Value | Interpretation | Value | Interpretation |
|---|----------------------|--|-------|---|-------|-----------------------------------|
| Technology of asphalt mixture | X_1 | Base type | 0 | AC base | 1 | HMAC base |
| | X_2 | Bitumen type | 0 | Neat bitumen (35/50 for AC) or 20/30 (for HMAC) | 1 | Polymer-modified bitumen 25/55-60 |
| Climatic region | X_3 | Performance grade on the level of wearing course | 0 | Low PG X-22 | 1 | Low PG X-28 |
| | X_4 | Performance grade on the level of binder course | 0 | Low PG X-22 | 1 | Low PG X-28 |
| Pavement age at the moment of investigation | X_5 | New pavements | 0 | Age ≤ 3 years | 1 | Age > 3 years |
| | X_6 | Long-serviced pavements | 0 | Age ≤ 10 years | 1 | Age > 10 years |

292

293

294 According to table 5 three groups of asphalt pavements are distinguished (see
295 also Fig.1):

- 296 1. Pavements with AC base where neat bitumen 35/50 are used ($X_1 = 0, X_2 = 0$)
- 297 2. Pavements with HMAC base where neat bitumen 20/30 are used ($X_1 = 1, X_2 = 0$)
- 298 3. Pavements with HMAC base where polymer modified bitumen PMB 25/55-60
299 are used ($X_1 = 1, X_2 = 1$)

300 Three climatic regions assumed in presenting analysis are described by variable
301 X_3 and X_4 in following manner according to table 5 (see also Fig. 2):

- 302 1. The coldest climatic region, PG X-28 both for wearing and binder course, $X_3 = 1$
303 and $X_4 = 1$,
- 304 2. The moderate climatic region, PG X-28 for wearing course, PG X-22 for binder
305 course, $X_3 = 1$ and $X_4 = 0$,
- 306 3. The warmest climatic region, PG X-22 both for wearing and binder course, $X_3 =$
307 0 and $X_4 = 0$.

308 Pavement age can be classified into one from three groups and it is described by
309 variable X_5 and X_6 in following manner according to table 5:

- 310 1. new pavements, up to 3 years in service $X_5 = 0$ and $X_6 = 0$,
- 311 2. pavements being in service longer than 3 years but not longer than 10 years
312 $X_5 = 1$ and $X_6 = 0$,
- 313 3. pavements being in service longer than $X_5 = 1$ and $X_6 = 1$.

314 In order to interpret the ordered logistic regression model, the odds ratio and
 315 marginal effects were determined. The interpretations of the odds ratio and marginal
 316 effects are presented with the assumption of *ceteris paribus*. *Ceteris paribus* is a Latin
 317 phrase meaning “with other things the same” or “all or other things being equal or held
 318 constant”.

319 The odds express a quotient of probability of particular outcome $p(Y \leq g)$ to its
 320 complement $p(Y > g)$. The ratio of two odds is called odds ratio *OR*. For the
 321 considered analysis, the odds ratio represents a change in probability of a given
 322 cracking intensity when one of independent variables X_i increases from 0 to 1 and the
 323 probabilities change from p_0 to p_1 . The odds ratio is defined as follows (Gelman and
 324 Hill, 2007):

$$325 \quad OR = \frac{p_0(Y \leq g)/p_0(Y > g)}{p_1(Y \leq g)/p_1(Y > g)} \quad (2)$$

326 where symbols used in the formula are as explained above.

327 The marginal effects express a deviation of probabilities of belongingness to a
 328 given category of crack intensity. This probability can be directly determined from the
 329 logit regression model:

$$330 \quad \hat{p}(Y \leq g) = \frac{e^{\hat{\beta}_{0g} - (\hat{\beta}_1 X_1 + \dots + \hat{\beta}_n X_n)}}{1 + e^{\hat{\beta}_{0g} - (\hat{\beta}_1 X_1 + \dots + \hat{\beta}_n X_n)}} \quad (3)$$

331 where:

332 $\hat{p}(Y \leq g)$: probability of pavement being in a given category of crack intensity,

333 $\hat{\beta}_{0g}, \hat{\beta}_1, \dots, \hat{\beta}_n$: parameters of the regression model,

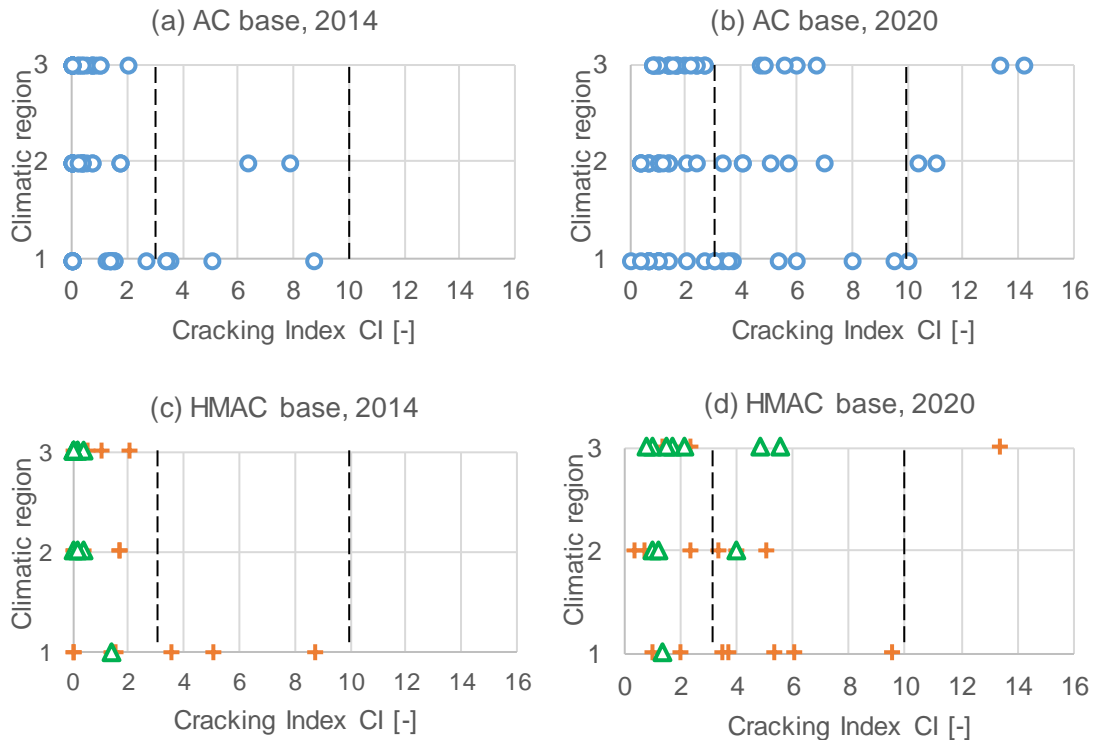
334 X_1, \dots, X_n : dependent variables.

335 The calculated values of odds ratios as well as marginal effects enable ordering
336 of factors considered in the independent variables X according to their influence on the
337 dependent variable Y .

338 **5. Statistical analysis of field observations**

339 ***5.1. Analysis of Cracking Index and Annual Increase of Cracking Index***

340 Cracking indexes CI were determined for individual sections in 2014 and 2020.
341 Figure 6 presents CI in relation to technology of asphalt mixture (AC or HMAC) and in
342 relation to climatic region. Figure 7 is analogous to Figure 6, but it presents CI in
343 relation to the age of pavements in the year of investigation. In further analysis, sections
344 are categorised into one of four categories depending on CI, thus the borders of
345 categories of CI are marked both in Figure 6 and 7. In Figure 7 the borders of pavement
346 age groups are marked as well.



Legend:

- AC base with neat 35/50 bitumen
- + HMAC base with neat 20/30 bitumen
- △ HMAC base with PMB 25/55-60 bitumen

Climatic regions:

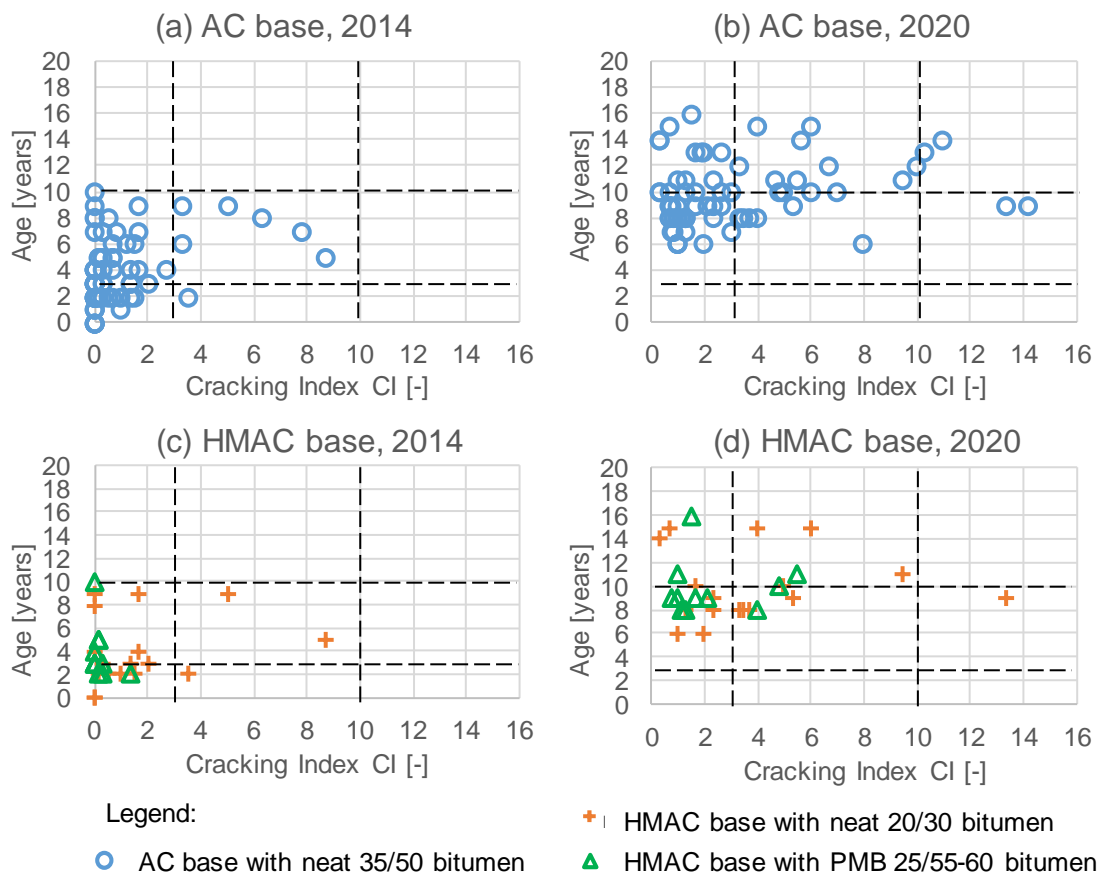
1. PG X-28 both for wearing and binder course
2. PG X-28 for wearing course, PG X-22 for binder course
3. PG X-22 both for wearing and binder course

347

348 Figure 6. Cracking index CI obtained for sections in 3 climatic regions for pavements
 349 constructed in AC technology (a, b) or HMAC technology (c, d) on the basis of
 350 investigation from 2014 (a, c) and 2020 (b, d)

351 In the first investigation in 2014 pavements in the coldest region 1 with PG X-28
 352 exhibited greater tendency to low-temperature cracking than those in other regions (see
 353 figure 6 a and 6 c). However, after six further years of service, in the year 2020, the
 354 tendency was not as obvious and even in the case of sections located in the warmest
 355 region 3 more heavily cracked sections were observed than in the colder regions 1 and
 356 2. The statistics suggest that climatic region may have a significant influence on the
 357 time of crack initiation, but after several years of service the meaning of climatic

358 performance grade is minor and the scale of cracks is similar, regardless of the region. It
 359 should be noted that the entire territory of Poland is located in temperate zone – if the
 360 same pavements were considered in a much wider range of performance grade low
 361 temperature zones, the observations could have been different.



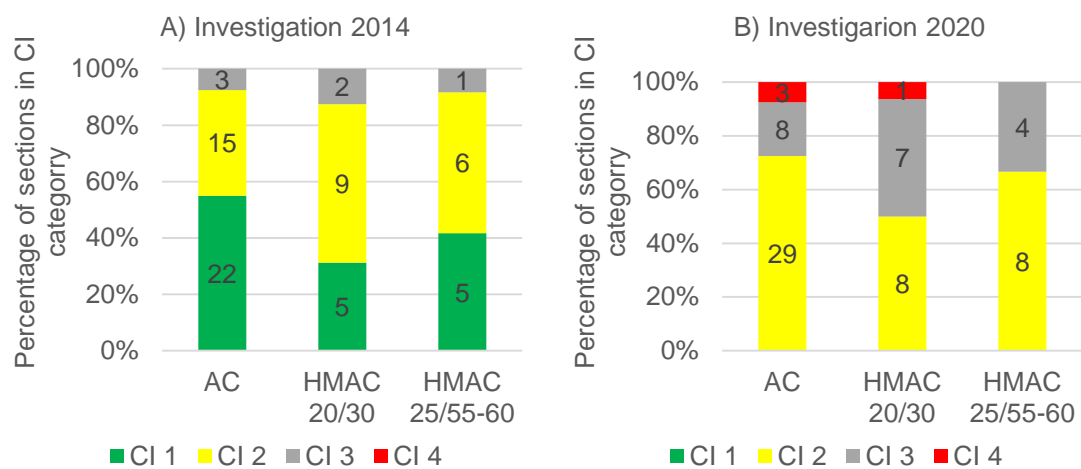
362

363 Figure 7. Cracking index CI in relation to the age of pavements constructed in AC
 364 technology (a, b) or HMAC technology (c, d), on the basis of investigations from 2014
 365 (a, c) and 2020 (b, d)

366 As clearly shown in Figure 7, when the age of the pavement increases, the
 367 number of low-temperature cracks increases as well. However, several sections with age
 368 >14 years still remain in the group of slightly cracked sections. It may also be observed
 369 in Figure 7 d that sections where polymer-modified bitumen was applied in the asphalt

370 base and wearing course belong to the group of slightly cracked sections ($CI \leq 3$) more
 371 often, regardless of their age and location.

372 Figure 8 presents a comparison of the number of sections ordered according to
 373 particular cracking index categories. While in the year 2014 30% to 55% of sections
 374 belonged to the uncracked category, in the year 2020 all the considered sections were
 375 cracked. The scale of low-temperature cracks increases over the time.



376

377 Figure 8. Number of sections grouped according to asphalt mixture technology and
 378 categorised according to cracking index CI A) in the base year 2014 B) in the year 2020

379 The basic statistics presented in Figures 6, 7 and 8 show that every factor –
 380 asphalt mixture type, bitumen, age and climatic region – has an impact on the number of
 381 low-temperature cracks expressed by cracking index. It is impossible to identify the
 382 factor that has the greatest effect based solely on statistics presented in Figures 6-8.
 383 Therefore, a model combining all factors is needed. Authors proposed to adopt a
 384 statistical analysis methodology based on the ordered logistic model to identify the most
 385 influential factors.

386 **5.2. Building and analysis of the ordered logistic model**

387 Parameters of regression were calculated using the R software. Calculations were
 388 conducted for each of the independent variables. The obtained results are presented in
 389 Table 6. The standard errors of the estimation and 95% confidence intervals are also
 390 presented in Table 6. . The detailed description of all in depended variables is clarified
 391 in table 5. Table 6. Parameters of the ordered logistic regression model

| Independent variables/ designation | Parameters of regression β | | The standard error of the estimate | 95% confidence interval | | |
|---------------------------------------|----------------------------------|--------------|---------------------------------------|-------------------------|--------|--------|
| | Designation | Value | | min | Max | |
| Base type | X_1 | β_1 | 1.213 | 0.431 | 0.377 | 2.073 |
| Bitumen modification | X_2 | β_2 | -0.704 | 0.599 | -1.900 | 0.459 |
| Climatic region | X_3 | β_3 | 0.239 | 0.451 | -0.647 | 1.128 |
| | X_4 | β_4 | 0.603 | 0.454 | -0.282 | 1.503 |
| Pavement age group | X_5 | B_5 | -2.600 | 0.486 | -3.594 | -1.681 |
| | X_6 | B_6 | 1.605 | 0.499 | 0.637 | 2.604 |
| Model constant | | β_{01} | -1.328 | 0.410 | -2.131 | -0.525 |
| Model constant | | β_{02} | 2.130 | 0.430 | 1.288 | 2.972 |
| Model constant | | β_{03} | 4.624 | 0.675 | 3.300 | 5.948 |

392 The ordered logit regression model assumes that the distance between the
 393 categories of the outcome is proportional. The Brant test result is statistically
 394 insignificant, which indicates that the parallel regression assumption is true. The
 395 Hosmer-Lemeshow test p-value is 0.2198, which suggests a good overall fit. The
 396 Lipsitz test and the Pulkstenis-Robinson test are statistically insignificant, which also
 397 confirms that the model is a good fit (Fagerland and Hosmer, 2017).

398 The ordinal logistic regression confusion matrix given in Table 7 shows
 399 sensitivity and specificity for each group. The total sum of cells by rows represents the
 400 total number of true cases present, while each column shows how many cases the model
 401 classified into a given category. Table 7 shows that 56% of roads in crack category 1
 402 were classified correctly by the model whereas 93% of roads in crack categories other
 403 than 1 were classified correctly. Due to the small number of roads in crack category 4,

404 the sensitivity is equal to 0. Accuracy is the measure that indicates how much the
 405 prediction differs from the observed data. While 100% indicates perfect prediction, in
 406 the presented case the accuracy is equal to 65.44%.

407 Table 7. The ordinal logistic regression confusion matrix

| | | Predicted Value | | | |
|-------------|---|-----------------|--------|--------|---------|
| | | 1 | 2 | 3 | 4 |
| True Value | 1 | 18 | 14 | 0 | 0 |
| | 2 | 7 | 66 | 2 | 0 |
| | 3 | 0 | 20 | 5 | 0 |
| | 4 | 0 | 4 | 0 | 0 |
| Sensitivity | | 56.25% | 88.00% | 20.00% | 0.00% |
| Specificity | | 93.27% | 37.70% | 98.20% | 100.00% |

408 On the basis of the regression model characterised by parameters presented in
 409 Table 6, the odds ratios were calculated according to equation (2). They are presented in
 410 Table 8. The following example illustrates interpretation of the odds ratios. Let us
 411 consider a change of the type of the base course expressed by variable X_1 : when the
 412 value changes from $X_1 = 0$ (AC base) to $X_1 = 1$ (HMAC base), the odds ratio is equal to
 413 3.65 (see Table 8). Two groups of road sections: cracked ($Y > 1$) and uncracked ($Y = 1$)
 414 are compared. According to the formula (2), it can be stated that pavements with
 415 HMAC bases will belong to the group of cracked pavements with odds 3.65 times
 416 greater than pavements with conventional AC bases. Another important example
 417 concerns the significance of bitumen modification, expressed by variable X_2 . The odds
 418 ratio is equal to 0.494, which means that the probability of a section belonging to the
 419 group of cracked sections decreases approximately by half when polymer-modified
 420 bitumens are used.

421

422 Table 8. Odds ratios for dependent variable – crack intensity

| Dependent variables/ designation | | Odds ratio <i>OR</i> | The standard error of the estimate | 95% confidence interval | |
|-------------------------------------|-------|----------------------|---------------------------------------|-------------------------|--------|
| | | | | min | Max |
| Base type | X_1 | 3.365 | 1.450 | 1.458 | 7.951 |
| Bitumen modification | X_2 | 0.494 | 0.296 | 0.150 | 1.582 |
| Climatic region | X_3 | 1.270 | 0.573 | 0.524 | 3.089 |
| | X_4 | 1.827 | 0.829 | 0.754 | 4.494 |
| Pavement age | X_5 | 0.074 | 0.036 | 0.027 | 0.186 |
| group | X_6 | 4.975 | 2.480 | 1.891 | 13.521 |

423 The odds ratios presented in Table 8 were used to rank the significance of
 424 variables X_1 to X_6 in terms of probability of low-temperature crack occurrence. Factors
 425 ordered from the most influential to the least influential are given in Table 9 with
 426 justification.

427 Table 9. Ranking of the factors affecting low-temperature cracking of pavements
 428 based on odds ratio

| Significance (1- the most influential) | Variable | OR | Justification |
|--|----------|-------|--|
| 1 | X_5 | 0.074 | The odds of occurrence of low-temperature cracks in new pavements with age less than 3 years are 13.5 times lower than for pavements older than 3 years |
| 2 | X_6 | 4.974 | Pavements older than 10 years belong to the group of cracked sections with odds almost 5 times higher than for pavements with age less than 10 years |
| 3 | X_1 | 3.65 | Pavements with HMAC bases will belong to the group of cracked pavements with odds 3.65 times higher than pavements with conventional AC bases |
| 4 | X_2 | 0.494 | The odds of a section belonging to the group of cracked sections decreases twofold when polymer-modified bitumens are used |
| 5 | X_4 | 1.827 | A change in performance grade (in the binder course) to lower temperature class (from X-22 to X-28) causes an increase in the odds of pavement cracking by a factor of 1.87 |
| 6 | X_3 | 1.270 | A change in performance grade (in the wearing course) to lower temperature class (from X-22 to X-28) causes a slight increase in the odds of pavement cracking by a factor of 1.27 |

429 Results of calculation of marginal effects are presented in Table 10. Standard
430 errors of the estimation of marginal effects range from 0.007 to 0.084. The absolute
431 value of marginal effect was used to make a ranking of factors from the most influential
432 (the highest absolute value of marginal effects), to the least influential (the lowest
433 absolute value of marginal effects). Regardless of the variable *Y*, the order of factors
434 was always the same as the one presented in Table 6. Age of the pavement is the most
435 influential factor, followed by the type of asphalt concrete and bitumen modification.
436 The climatic region displayed the least significant impact among the considered factors,
437 but it is noteworthy that the low PG value determined for the binder course had a more
438 pronounced impact than the PG value determined for the wearing course.

439 Based on marginal effects given in Table 10, other findings may be formulated:

- 440 • Pavements with HMAC base will belong to the group of uncracked sections
441 with probability lower by 16% than pavements with AC base, and to the group
442 of moderately cracked sections with probability higher by 13% than pavements
443 with AC base.
- 444 • Pavements with modified bitumens will belong to the group of uncracked
445 sections with probability 10% higher than pavements with neat bitumens.
- 446 • Sections located in climatic zone PG X-22 (on the level of binder course) belong
447 to the group of uncracked sections with probability greater by 8% than the ones
448 located in PG X-28 zone. Sections located in climatic zone PG X-28 belong to
449 the group of moderately cracked sections with 6% greater probability than those
450 located in PG X-22. Climatic zone has a negligible impact on classification of
451 section into the heavily cracked group.

- 452 • Pavements belong to the group of heavily cracked sections with similar
 453 probability regardless of any of the considered factors. It means that some
 454 external factors related with technology and quality of the construction process
 455 may be the main source of intensive cracking of those sections.

456 Table 10. Marginal effects for uncracked sections ($Y = 1$)

| Dependent variables/ designation | | Marginal effects dy/dx for pavements | | | |
|-------------------------------------|-------|--|-----------------------------|----------------------------------|-------------------------------|
| | | No cracking $Y = 1$ | Slightly cracked $Y = 2$ | Moderately cracked $Y = 3$ | Heavily cracked $Y = 4$ |
| Base type | X_1 | -0.166 | 0.021 | 0.129 | 0.016 |
| Bitumen modification | X_2 | 0.096 | -0.012 | -0.075 | -0.009 |
| Climatic region | X_3 | -0.033 | 0.004 | 0.025 | 0.003 |
| | X_4 | -0.083 | 0.011 | 0.064 | 0.008 |
| Pavement age group | X_5 | 0.356 | -0.046 | -0.277 | -0.034 |
| | X_6 | -0.220 | 0.028 | 0.171 | 0.021 |

457 **6. Summary and conclusions**

458 The low temperature cracks are still one of the main pavement distress observed
 459 on Polish roads. In order to effectively predict and counteract the problem, the key is to
 460 correctly identify and rank the factors that mostly affect the low-temperature cracking.
 461 Field investigations of low-temperature cracks were performed in years 2014 and 2020
 462 on the same 68 sections constructed and being in service in typical traffic conditions.
 463 Collected data were statistically analysed with the use of ordered logistic regression
 464 model. Based on the conducted analysis, the following conclusions can be drawn:

- 465 1) The most important factor affecting the probability of low-temperature cracking
 466 is the age of the pavement that is associated with ageing of asphalt mixtures. It
 467 was confirmed both by odds ratio and marginal effects. New pavements (age
 468 less than 3 years) exhibit low-temperature cracks with odds 13.5 times lower

469 than pavements older than 3 years. Pavements older than 10 years belong to the
470 group of cracked sections with odds almost 5 times higher than pavements with
471 age less than 10 years.

472 2) Climatic zone typical for Polish climate conditions in which the road is located
473 has minor effect on pavement cracking. The greatest influence of the region is
474 visible in the beginning of the service life of the road section, but it diminishes
475 with time.

476 3) Pavements with HMAC bases will belong to the groups of cracked pavements
477 with odds 3.65 times greater than pavements with conventional AC bases. It is
478 noteworthy that AC mixes contain less bitumen and have more open structure
479 than HMAC mixtures. Simultaneously, AC contains 35/50 bitumen with lower
480 stiffness according to the BBR tests. However, TSRTS tests show comparable
481 cracking temperature for both AC and HMAC with neat bitumen.

482 4) The probability of a section belonging to the group of cracked sections decreases
483 by half when polymer-modified bitumens 25/55-60 are used in the binder course
484 and asphalt base. The modified bitumen is characterised both by lower stiffness
485 S and higher m according to the BBR test than the remaining bitumens 20/30 and
486 35/50. The effect of bitumen modification is also visible in lower cracking
487 temperature of mixtures in the TSRST test (indicating better low-temperature
488 performance).

489 5) Pavements belong to the group of heavily cracked sections with similar
490 probability, regardless of any of the considered factors. Thus, it could be stated
491 that there are other factors, apart from the analysed, which can have influence on

492 pavement low-temperature performance. The authors suspect that the most
493 influential factors include the quality of works and the chemical composition of
494 bitumen. These factors will be analysed in further studies.

495 **7. Acknowledgement**

496 It is gratefully acknowledged that the field investigation and its statistical analysis were
497 performed in a research project sponsored by Polish National Centre for Science under
498 the grant Miniatura 3, grant id. 2019/03/X/ST8/00338

499 **8. Data Availability**

500 The data presented in this study are openly available in repository: Investigation of
501 Low-Temperature Cracks on Selected National Roads and Motorways in Poland 2020,
502 Bridge of Data. Gdansk University of Technology at doi: 10.34808/an8a-3k90,

503 **References**

504 Anderson K.O., Christison J.T., Bai B-Q., Johnston C.D., Quinn T., McCullough D.
505 (1998) Temperature and thermal contraction measurements as related to the
506 development of low temperature cracking on the Lamont test road. *Canadian Technical*
507 *Asphalt Association Proceedings*, 16-46.

508 Baglieri, O., Tozzi, C., Dalmazzo, D., Tsantilis, L., & Santagata, E. (2021). A novel
509 methodology for the evaluation of low temperature failure properties of asphalt binders.
510 *Materials and Structures/Materiaux Et Constructions*, 54(1)
511 <http://dx.doi.org/10.1617/s11527-020-01610-9>

512 Bańkowski W. (2018) Analysis of fatigue life of asphalt concretes considering different
513 types of mixtures and binders. *Roads and Bridges - Drogi i Mosty*, 17(4), 253-280.

- 514 <http://dx.doi.org/10.7409/rabdim.018.016>
- 515 Corté J. F. (2001) Development and uses of hard-grade asphalt and of high-modulus
516 asphalt mixes in France. *Transportation Research Circular*, 503, 12-31.
- 517 Cox D.R. (1958) The regression analysis of binary sequences (with discussion). *Journal*
518 *of the Royal Statistical Society, Series B (Methodological)*, XX, 2, 215–242.
- 519 Chen Y., Wang H., Xu S., You Z. (2020) High modulus asphalt concrete: A state-of-
520 the-art review. *Construction and Building Materials*, 237, 117653.
521 <http://dx.doi.org/10.1016/j.conbuildmat.2019.117653>
- 522 Dong S., Zhong J., Hao P., Zhang W., Chen J., Lei Y. (2018) Schneider A., Mining
523 multiple association rules in LTPP database: An analysis of asphalt pavement thermal
524 cracking distress. *Construction and Building Materials*, 191, 2018, Pages 837-852,
525 ISSN 0950-0618, <https://doi.org/10.1016/j.conbuildmat.2018.09.162>.
- 526 Fagerland M.W., Hosmer D.W. (2017) How to Test for Goodness of Fit in Ordinal
527 Logistic Regression Models. *The Stata Journal*, 17(3), 668-686.
528 <http://dx.doi.org/10.1177/1536867X1701700308>
- 529 FHWA (1998) LTPP Data Analysis: Improved Low Pavement Temperature Prediction.
530 Federal Highway Administration, Report No. FHWA-RD-97-104
- 531 Gajewski M., Bańkowski W., Pronk A.C. (2020) Evaluation of fatigue life of high
532 modulus asphalt concrete with use of three different definitions. *International Journal*
533 *of Pavement Engineering*, 21(14), 1717-1728.
534 <http://dx.doi.org/10.1080/10298436.2018.1564302>
- 535 GDDKiA (2014) Nawierzchnie asfaltowe na drogach krajowych WT-2 2014 - część I -



- 536 Mieszanki mineralno-asfaltowe, Wymagania techniczne (in Polish)
- 537 Gelman A., Hill J. (2007) Data analysis using regression and multilevel/hierarchical
538 models. Cambridge University Press. ISBN: 9780521686891
- 539 Judycki J., Jaskuła P., Dołycki B., Pszczoła M., Jaczewski M., Ryś D., Stienss M.
540 (2015) Investigation of low-temperature cracking in newly constructed high-modulus
541 asphalt concrete base course of a motorway pavement. *Road Materials and Pavement
542 Design, Special Issue: EATA 2015*. 16(supp1), 362-388.
543 <http://dx.doi.org/10.1080/14680629.2015.1029674>
- 544 Judycki J., Jaskuła P., Dołycki P., Pszczoła M., Jaczewski M., Ryś D., Stienss M.
545 (2016) The Impact of Homogeneity of High Modulus Asphalt Concrete Layer on Low-
546 Temperature Cracking. *8th RILEM International Conference on Mechanisms of
547 Cracking and Debonding in Pavements*, 13, V, 319-326. [http://dx.doi.org/10.1007/978-
548 94-024-0867-6_45](http://dx.doi.org/10.1007/978-94-024-0867-6_45)
- 549 Judycki J. (2018) Verification of the new viscoelastic method of thermal stress
550 calculation in asphalt layers of pavements. *International Journal of Pavement
551 Engineering*, 19, 725-737. <https://doi.org/10.1080/10298436.2016.1199883>
- 552 Judycki J. (2020) Application of the new viscoelastic method of thermal stress
553 calculation to the analysis of low-temperature cracking of asphalt layers. *Roads and
554 Bridges - Drogi i Mosty*, 19(1), 27-49. <http://dx.doi.org/10.7409/rabdim.020.002>
- 555 Jung D.H., Vinson T.S., (1994) Low-Temperature Cracking: Test Sections, Strategic
556 Highway Research Program, SHRP-A-400, ISBN: 0309058074
- 557 Lee H. J., Lee J. H., Park H. M. (2007) Performance evaluation of high modulus asphalt

558 mixtures for long life asphalt pavements. *Construction and Building Materials*, 21,
559 1079-1087. <https://doi.org/10.1016/j.conbuildmat.2006.01.003>

560 Marasteanu M., Zofka A., Turos M., Li X., Velasquez R., Li X., Buttlar W., Paulino G.,
561 Braham A., Dave E., Ojo J., Bahia H., Williams C., Bausano J., Gallistel A., McGraw J.
562 (2007) Investigation of low temperature cracking in asphalt pavements national pooled
563 fund study 776, Minnesota Department of Transportation

564 Mateos A., Antonio J., Hernández R., Tan Y., Guillermo L., Salazar L., Vargas-
565 Nordbeck A. (2015) Application of the logit model for the analysis of asphalt fatigue
566 tests results. *Construction and Building Materials*, 82, 53–60.
567 <https://doi.org/10.1016/j.conbuildmat.2015.02.029>

568 Moreno-Navarro F., Sol-Sanches M., Tomas-Fortun E., Rubio-Gamez M. C. (2016)
569 High-Modulus Asphalt Mixtures Modified with Acrylic Fibers for Their Use in
570 Pavements under Severe Climate Conditions. *Journal of Cold Regions Engineering*,
571 30(4), 04016003.

572 Ouyang W., Fan X., Wang L. (2009) Research on Anti-rutting Performance of High
573 Modulus Asphalt Concrete Pavement. *Journal of Highway and Transportation Research*
574 *and Development*, 4(2), 77-79.

575 Pszczola M., Rys D., Jaskula P., (2017), Analysis of Climatic Zones in Poland with
576 Regard to Asphalt Performance Grading, *Roads and Bridges - Drogi i Mosty*, 16(4),
577 245-269. <https://doi.org/10.7409/rabdim.017.016>

578 Ryś D., Judycki J., Pszczola M., Jaczewski M., Mejłun Ł. (2017), Comparison of low-
579 temperature cracks intensity on pavements with high modulus asphalt concrete and
580 conventional asphalt concrete bases. *Construction and Building Materials*, 147, 478–



- 581 487. <https://doi.org/10.1016/j.conbuildmat.2017.04.179>
- 582 Rys D., Jaczewski M., Pszczoła M., Jaskula P., Bańkowski W. (2020) Effect of bitumen
583 characteristics obtained according to EN and Superpave specifications on asphalt
584 mixture performance in low-temperature laboratory tests. *Construction and Building*
585 *Materials*, 231, 117156. <https://doi.org/10.1016/j.conbuildmat.2019.117156>
- 586 Pszczola M., Rys D., Jaczewski M., (2022) Field Evaluation of High Modulus Asphalt
587 Concrete Resistance to Low-Temperature Cracking. *Materials*, 15(1), 369.
588 <https://doi.org/10.3390/ma15010369>
- 589 Tabatabaee H.A., Velasquez R., Bahia H.U. (2012) Modeling Thermal Stress in Asphalt
590 Mixtures Undergoing Glass Transition and Physical Hardening. *Transportation*
591 *Research Record: Journal of the Transportation Research Board*, 2296, 106–114.
592 <https://doi.org/10.3141/2296-11>.
- 593 Velasquez R., Bahia H. (2013) Critical factors affecting thermal cracking of asphalt
594 pavements: towards a comprehensive specification, *Road Materials and Pavement*
595 *Design*, 14:sup1, 187-200, DOI: 10.1080/14680629.2013.774755
- 596 Yang G., Wang X. (2020) Rationality of Applying High-modulus Asphalt Concrete in
597 Long-life Asphalt Pavement with Semi-rigid Base. *Journal of Highway and*
598 *Transportation Research and Development*, 14(2), 16-24.
- 599 Yee P., Aida B., Hesp A.M., Marks P., Tam K.K. (2006) Analysis of premature low-
600 temperature cracking in three Ontario, Canada. *Transportation Research Record:*
601 *Journal of the Transportation Research Board*, 1962, 44–51.
- 602 Zaumanis M., Arraigada M., Poulikakos L.D. (2020) 100% recycled high-modulus

603 asphalt concrete mixture design and validation using vehicle simulator. *Construction*
604 *and Building Materials*, 260, 119891.
605 <https://doi.org/10.1016/j.conbuildmat.2020.119891>

606 Zhu J., Ma T., Cheng H., Li T., Fu J. (2021) Mechanical Properties of High-Modulus
607 Asphalt Concrete Containing Recycled Asphalt Pavement: A Parametric Study. *Journal*
608 *of Materials in Civil Engineering*, 33(5), 04021056.

609 Zofka A., Braham A. (2009) Comparison of low-temperature field performance and
610 laboratory testing of 10 test sections in the Midwestern United States, *Transportation*
611 *Research Record: Journal of the Transportation Research Board*, 2127, 107–114.

612
613

614 Supplement A: Detailed list of tested sections

| Id. | Route number | Distance (km from / to) | Cracking index in | | Type of asphalt base / bitumen | Year of construction | Lower PG on the level of | |
|-----|--------------|-------------------------|-------------------|-------|--------------------------------|----------------------|--------------------------|----------------|
| | | | 2014 | 2020 | | | binder course | wearing course |
| 1 | A1 | 0+000 24+300 | 1.67 | 2.00 | AC 35/50 | 2007 | -22 | -28 |
| 2 | A1 | 24+300 87+800 | 1.17 | 3.33 | AC 35/50 | 2008 | -28 | -28 |
| 3 | A1 | 87+800 139+500 | 0.00 | 0.67 | AC 35/50 | 2011 | -28 | -28 |
| 4 | A1 | 245+800 261+000 | 0.67 | 1.00 | AC 35/50 | 2012 | -22 | -28 |
| 5 | A1 | 261+000 270+000 | 0.00 | 0.67 | AC 35/50 | 2012 | -22 | -28 |
| 6 | A1 | 270+000 291+000 | 0.00 | 0.33 | AC 35/50 | 2006 | -22 | -28 |
| 7 | A1 | c 0+000 c 20+300 | 0.67 | 2.33 | AC 35/50 | 2009 | -22 | -22 |
| 8 | A1 | a 0+000 a 15+500 | 0.83 | 2.67 | AC 35/50 | 2007 | -22 | -22 |
| 9 | A1 | a 29+612 49+212 | 0.00 | 0.83 | AC 35/50 | 2012 | -22 | -22 |
| 10 | A2 | 301+372 343+500 | 0.50 | 5.67 | AC 35/50 | 2006 | -22 | -28 |
| 11 | A2 | 343+500 362+300 | 6.33 | 11.00 | AC 35/50 | 2006 | -22 | -28 |
| 12 | A6 | 14+200 21+900 | 7.83 | 10.33 | AC 35/50 | 2007 | -22 | -28 |
| 13 | S3 | 61+600 66+400 | 0.00 | 1.00 | AC 35/50 | 2012 | -22 | -28 |
| 14 | S3 | 0+000 28+200 | 0.00 | 1.33 | AC 35/50 | 2010 | -22 | -28 |
| 15 | S3 | 28+200 54+900 | 0.00 | 0.33 | AC 35/50 | 2010 | -22 | -28 |
| 16 | S3 | 54+900 81+600 | 0.00 | 0.33 | AC 35/50 | 2010 | -22 | -28 |
| 17 | S3 | 0+000 9+500 | 0.00 | 1.67 | AC 35/50 | 2007 | -22 | -22 |
| 18 | S3 | 0+500 18+040 | 0.00 | 1.00 | AC 35/50 | 2014 | -22 | -22 |
| 19 | S3 | 0+000 17+000 | 1.00 | 1.33 | AC 35/50 | 2013 | -22 | -22 |
| 20 | S3 | 17+000 24+500 | 0.00 | 0.80 | AC 35/50 | 2013 | -22 | -22 |
| 21 | S3 | 24+500 42+954 | 0.00 | 0.83 | AC 35/50 | 2013 | -22 | -22 |
| 22 | S6 | 0+000 9+400 | 0.00 | 1.33 | AC 35/50 | 2012 | -22 | -22 |
| 23 | S6 | 201+900 216+600 | 0.33 | 0.67 | AC 35/50 | 2010 | -22 | -28 |
| 24 | S7 | 175+800 203+600 | 0.00 | 1.00 | AC 35/50 | 2012 | -28 | -28 |
| 25 | S10 | 8+800 21+400 | 0.33 | 1.33 | AC 35/50 | 2009 | -22 | -28 |
| 26 | S10 | 0+000 | 0.67 | 7.00 | AC | 2010 | -22 | -28 |

| Id. | Route number | Distance (km from / to) | Cracking index in | | Type of asphalt base / bitumen | Year of construction | Lower PG on the level of | |
|-----|--------------|-------------------------|-------------------|-------|--------------------------------|----------------------|--------------------------|----------------|
| | | | 2014 | 2020 | | | binder course | wearing course |
| | | 12+000 | | | 35/50 | | | |
| 27 | DK16 | 0+000 12+400 | 0.00 | 8.00 | AC 35/50 | 2014 | -28 | -28 |
| 28 | DK16 | 162+100 180+500 | 2.67 | 3.00 | AC 35/50 | 2010 | -28 | -28 |
| 29 | DK16 | 31+500 39+700 | 0.00 | 1.00 | AC 35/50 | 2014 | -28 | -28 |
| 30 | DK16 | 0+000 4+800 | 0.00 | 0.67 | AC 35/50 | 2012 | -28 | -28 |
| 31 | DK40 | 1+000 2+460 | 0.67 | 6.67 | AC 35/50 | 2008 | -22 | -22 |
| 32 | DK45 | 82+814 86+663 | 0.00 | 14.17 | AC 35/50 | 2011 | -22 | -22 |
| 33 | DK45 | 57748 60+853 | 0.33 | 1.94 | AC 35/50 | 2007 | -22 | -22 |
| 34 | DK46 | 110+867 116+100 | 0.00 | 6.00 | AC 35/50 | 2010 | -22 | -22 |
| 35 | DK46 | 0+000 5+620 | 0.67 | 4.67 | AC 35/50 | 2009 | -22 | -22 |
| 36 | DK5 | 340+485 352+927 | 0.00 | 2.67 | AC 35/50 | 2011 | -22 | -22 |
| 37 | DK59 | 0+000 6+500 | 0.00 | 0.67 | AC 35/50 | 2011 | -28 | -28 |
| 38 | DK65 | 0+000 5+600 | 1.33 | 2.67 | AC 35/50 | 2010 | -28 | -28 |
| 39 | DK65 | 0+000 7+600 | 0.00 | 3.00 | AC 35/50 | 2013 | -28 | -28 |
| 40 | DK66 | 0+000 16+600 | 3.33 | 10.00 | AC 35/50 | 2008 | -28 | -28 |
| 41 | A1 | 151+300 186+366 | 0.00 | 2.00 | HMAC HMAC 20/30 | 2014 | -28 | -28 |
| 42 | A1 | 186+348 215+850 | 0.00 | 1.00 | HMAC 20/30 | 2014 | -28 | -28 |
| 43 | A1 | 215+850 245+800 | 0.17 | 3.33 | HMAC 20/30 | 2012 | -22 | -28 |
| 44 | A1 | d 0+000 d 14+500 | 0.17 | 5.50 | HMAC 25/55-60 | 2009 | -22 | -22 |
| 45 | A1 | b 0+000 b 6+030 | 0.00 | 1.67 | HMAC 25/55-60 | 2011 | -22 | -22 |
| 46 | A1 | a 15+500 a 29+612 | 0.17 | 1.00 | HMAC 25/55-60 | 2009 | -22 | -22 |
| 47 | A2 | 257+560 303+145 | 0.00 | 0.67 | HMAC 20/30 | 2005 | -22 | -28 |
| 48 | A8 | 0+000 28+368 | 0.33 | 0.75 | HMAC 25/55-60 | 2011 | -22 | -22 |
| 49 | S1 | 0+300 2+158 | 0.00 | 1.50 | HMAC 25/55-60 | 2004 | -22 | -22 |
| 50 | S5 | 0+000 34+615 | 0.17 | 4.00 | HMAC 25/55-60 | 2012 | -22 | -28 |
| 51 | S7 | 97+866 134+903 | 1.33 | 1.33 | HMAC 25/55-60 | 2012 | -28 | -28 |

| Id. | Route number | Distance (km from / to) | Cracking index in | | Type of asphalt base / bitumen | Year of construction | Lower PG on the level of | |
|-----|--------------|-------------------------|-------------------|-------|--------------------------------|----------------------|--------------------------|----------------|
| | | | 2014 | 2020 | | | binder course | wearing course |
| 52 | S8 | 0+500 22+593 | 1.00 | 2.33 | HMAC 20/30 | 2012 | -22 | -22 |
| 53 | S8 | 29+800 54+910 | 0.50 | 1.33 | HMAC 20/30 | 2012 | -22 | -22 |
| 54 | S8 | 575+550 586+620 | 1.50 | 3.50 | HMAC 20/30 | 2012 | -28 | -28 |
| 55 | S8 | 614+850 639+365 | 3.50 | 3.67 | HMAC 20/30 | 2012 | -28 | -28 |
| 56 | S11 | 288+720 297+825 | 0.00 | 0.33 | HMAC 20/30 | 2006 | -22 | -28 |
| 57 | S11 | 0+000 21+940 | 0.33 | 1.17 | HMAC 25/55-60 | 2012 | -22 | -28 |
| 58 | DK5 | 370+700 389+407 | 0.00 | 1.67 | HMAC 20/30 | 2010 | -22 | -22 |
| 59 | DK8 | 648+117 654+548 | 8.67 | 9.50 | HMAC 20/30 | 2009 | -28 | -28 |
| 60 | DK8 | 717+982 723+236 | 5.00 | 6.00 | HMAC 25/55-60 | 2005 | -28 | -28 |
| 61 | DK15 | 0+000 6+260 | 1.67 | 4.00 | HMAC 20/30 | 2005 | -22 | -28 |
| 62 | DK19 | 45+700 50+700 | 1.33 | 5.33 | 35/50 | 2011 | -28 | -28 |
| 63 | DK35 | 79+850 85+000 | 0.00 | 2.14 | HMAC 25/55-60 | 2011 | -22 | -22 |
| 64 | DK41 | 29+520 33+270 | 0.33 | 2.33 | HMAC 20/30 | 2011 | -22 | -28 |
| 65 | DK45 | 89+650 94+100 | 2.00 | 13.33 | HMAC 20/30 | 2011 | -22 | -22 |
| 66 | DK46 | 1+705 7+810 | 0.00 | 1.00 | 25-55-60 | 2011 | -22 | -28 |
| 67 | DK46 | 7+810 20+894 | 1.67 | 5.00 | HMAC 20/30 | 2010 | -22 | -28 |
| 68 | DK78 | 0+000 5+700 | 0.00 | 4.83 | HMAC 25/55-60 | 2010 | -22 | -22 |