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

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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><math>\nabla E_2 \geq 100</math> MPa or <math>E_2 \geq 120</math> MPa</small>	Unbound aggregate <i>base course</i> <small><math>\nabla E_2 \geq 100</math> MPa or <math>E_2 \geq 120</math> MPa</small>	Unbound aggregate <i>base course</i> <small><math>\nabla E_2 \geq 100</math> MPa or <math>E_2 \geq 120</math> 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 <sub>90</sub>	ITSR <sub>90</sub>	ITSR <sub>80</sub>	ITSR <sub>70</sub>	ITSR <sub>80</sub>
Resistance to permanent deformation, [EN 12697-22]	WTS <sub>AIR 0.10</sub> PRD <sub>AIR 7.0</sub>	WTS <sub>AIR 0.10</sub> PRD <sub>AIR 7.0</sub>	WTS <sub>AIR 0.10</sub> PRD <sub>AIR 5.0</sub>	WTS <sub>AIR 0.15</sub> PRD <sub>AIR 7.0</sub>	WTS <sub>AIR 0.10</sub> PRD <sub>AIR 5.0</sub>

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

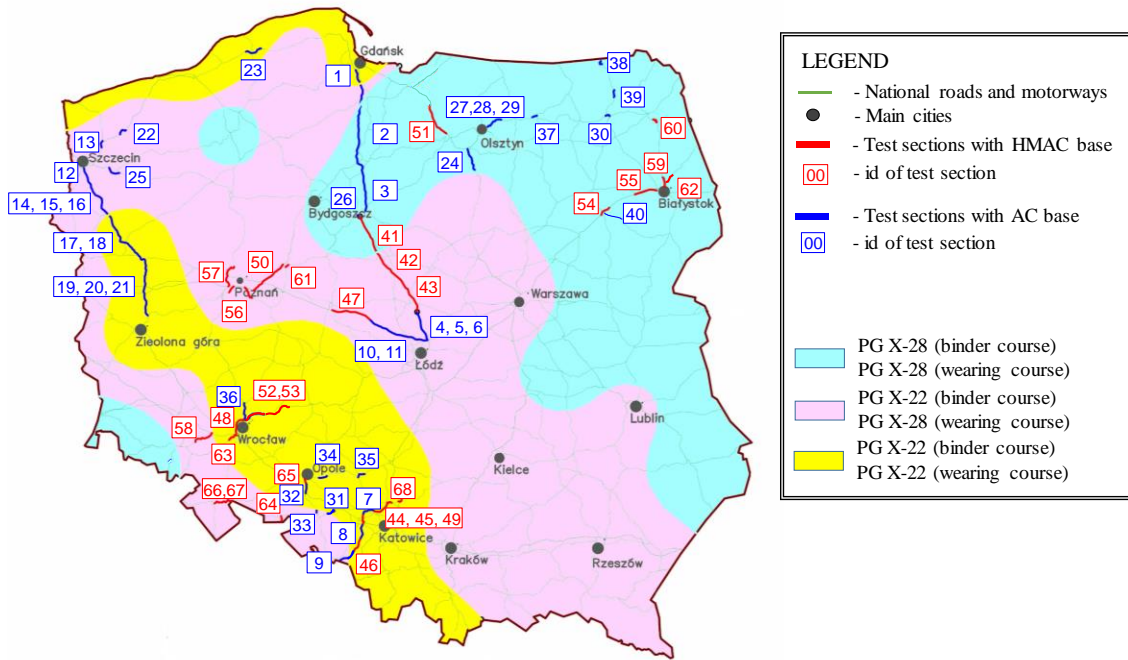
159 Remarks: a) measured, b) according to producer specification

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**

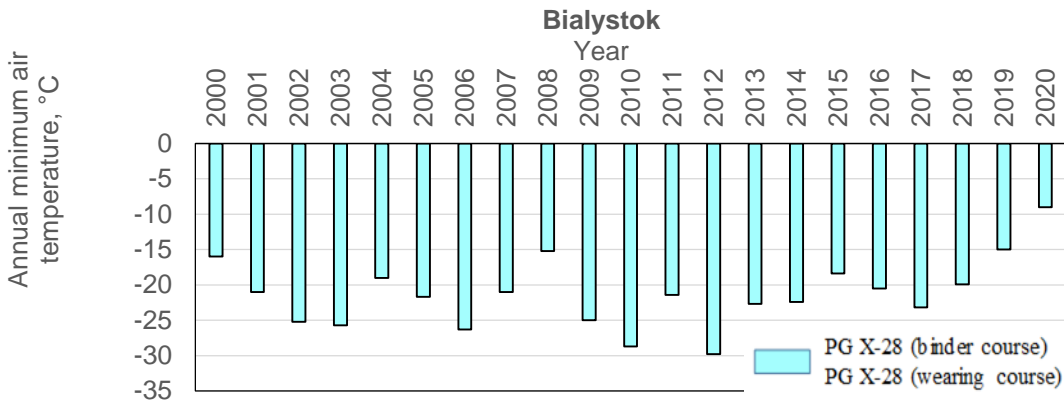
177 The field investigation was conducted on 68 road sections: 40 with conventional  
178 AC and 28 with HMAC asphalt base. Figure 2 presents a map with locations of the  
179 tested sections. Each section is labelled with an id number. The detailed data for all  
180 sections are attached in Supplement 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.



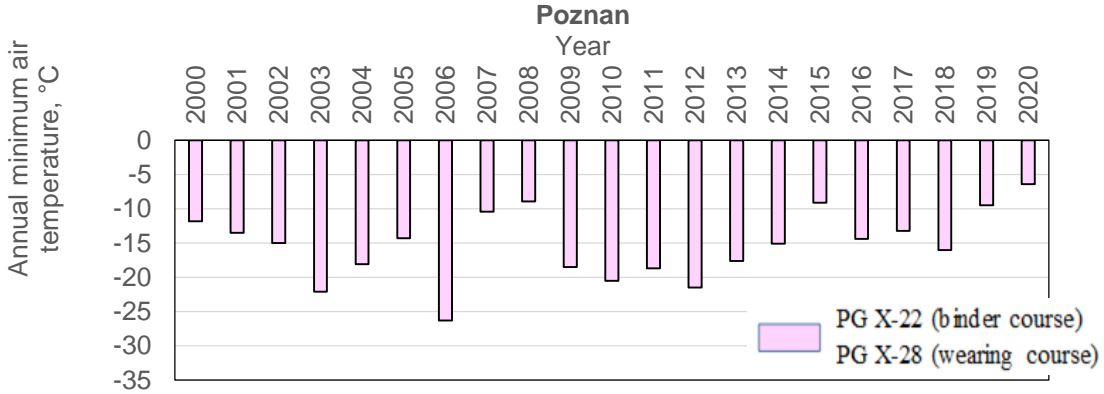
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201 Figure 2. Location of road sections and climatic zones according to performance grade

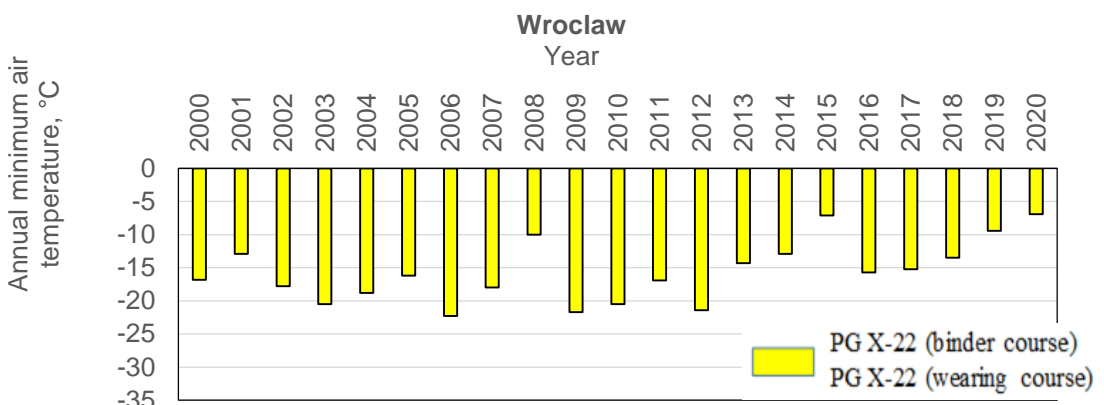
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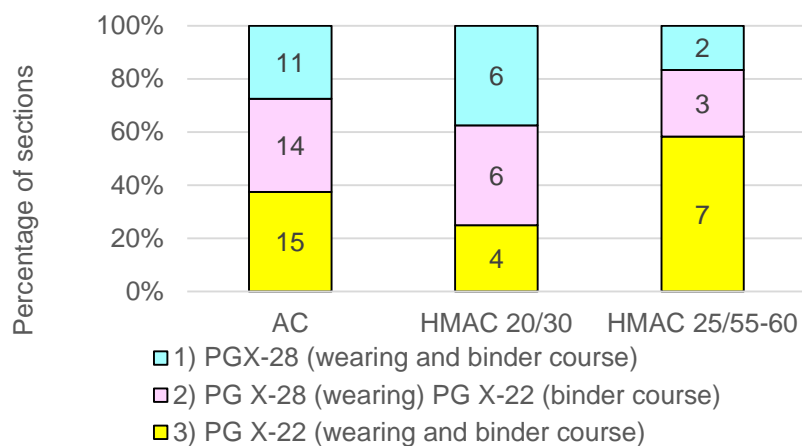
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206 Figure 3. The minimum winter air temperatures recorded for representative station for

207 each climatic zone



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

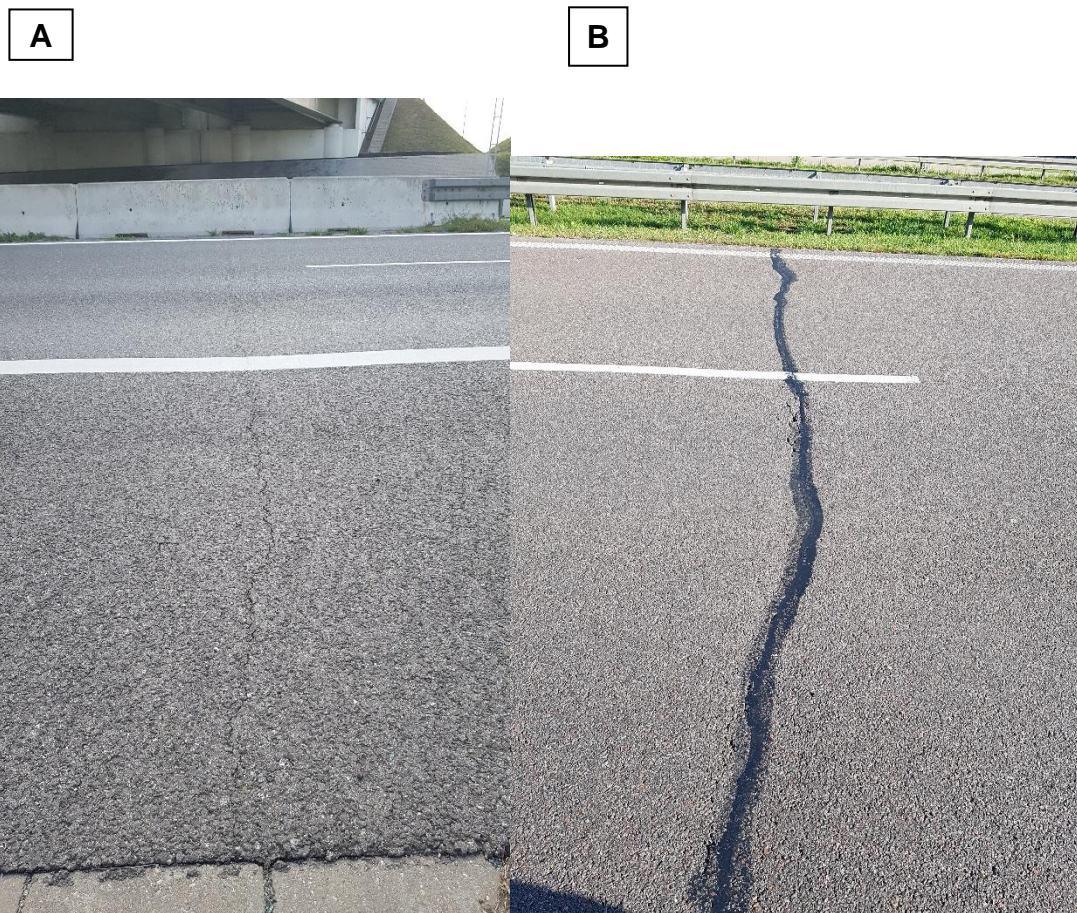
210 according to the three types of asphalt base

#### 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 $\leq 3$ years	1	Age $> 3$ years
	$X_6$	Long-serviced pavements	0	Age $\leq 10$ 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,

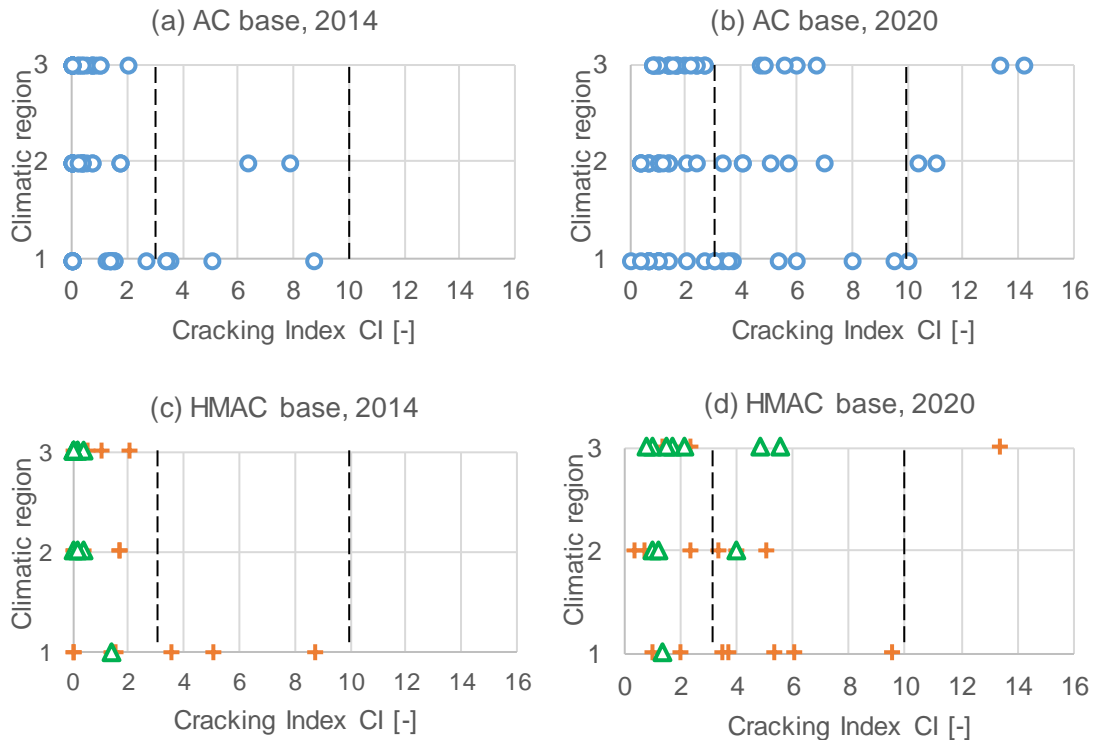
334  $X_1, \dots, X_n$ : dependent variables.

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:

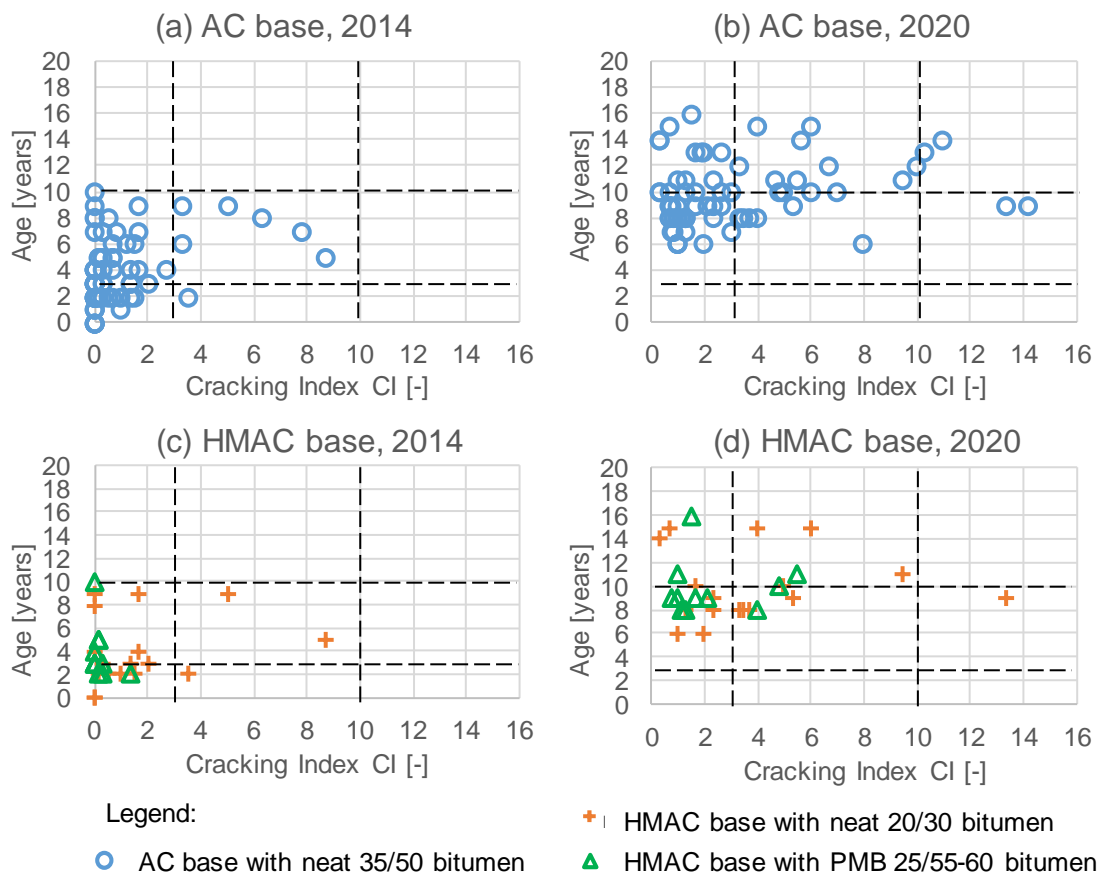
1. PG X-28 both for wearing and binder course
2. PG X-28 for wearing course, PG X-22 for binder course
3. PG X-22 both for wearing and binder course

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.



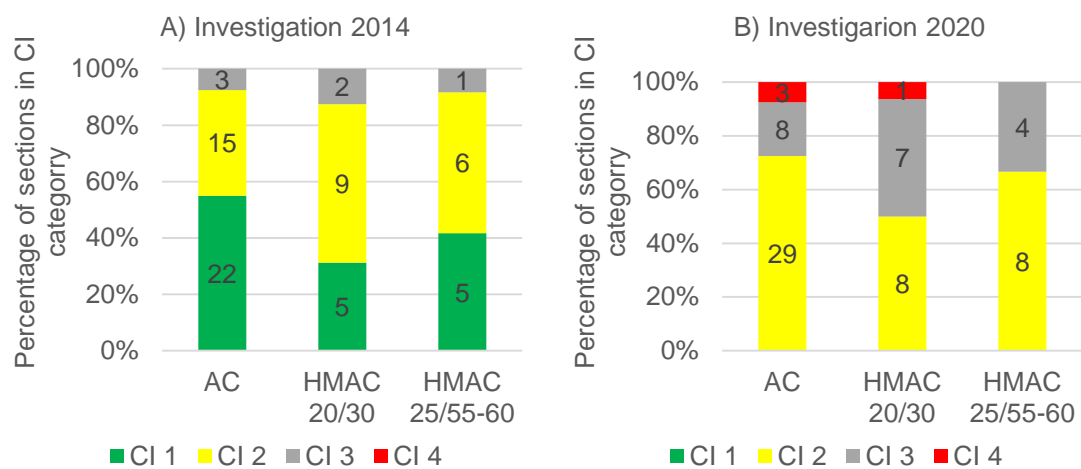
362

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 $\beta$		The standard error of the estimate	95% confidence interval		
	Designation	Value		min	Max	
Base type	$X_1$	$\beta_1$	1.213	0.431	0.377	2.073
Bitumen modification	$X_2$	$\beta_2$	-0.704	0.599	-1.900	0.459
Climatic region	$X_3$	$\beta_3$	0.239	0.451	-0.647	1.128
	$X_4$	$\beta_4$	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		$\beta_{01}$	-1.328	0.410	-2.131	-0.525
Model constant		$\beta_{02}$	2.130	0.430	1.288	2.972
Model constant		$\beta_{03}$	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,

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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