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

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Abstract

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

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

1. Introduction

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

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

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

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

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

Very important factors that influence the probability of occurrence of thermal cracks in a pavement include, among others, the grade of the bitumen, its stiffness and capacity for relaxation at low temperatures as well as fracture properties of the asphalt mix. Due to the aging process, mixture properties become more adverse with an increase in pavement age. Asphalt mixtures very often exhibit varying properties even if they are used for the same layer under the same contract and meet all the local technical requirements. The homogeneity of laying and compaction of the mixture as well as quality of working joints plays a significant role in further development of low-temperature cracks (Judycki et al., 2015, 2016). Finally, the climatic conditions are the main source of the phenomenon (Moreno-Navarro et al. 2016).

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

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

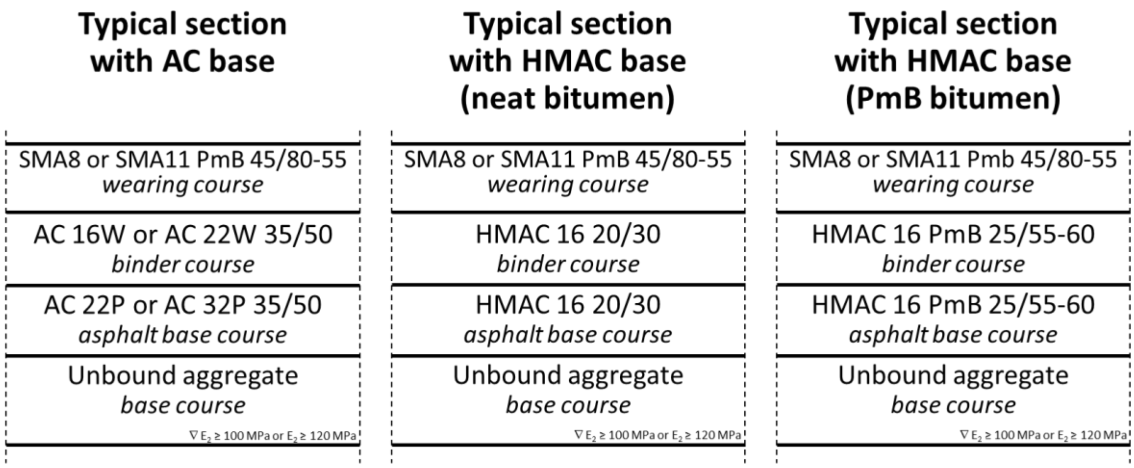

Figure 1. Typical pavement structures of the analysed road sections

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

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

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

Table 1. Standard requirements for mixtures used in the test sections according to WT-2 (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]	$WTS_{AIR\ 0.10}$ $PRD_{AIR\ 7.0}$	$WTS_{AIR\ 0,10}$ $PRD_{AIR\ 7.0}$	$WTS_{AIR\ 0.10}$ $PRD_{AIR\ 5.0}$	$WTS_{AIR\ 0.15}$ $PRD_{AIR\ 7.0}$	$WTS_{AIR\ 0.10}$ $PRD_{AIR\ 5.0}$

Table 2. Selected low-temperature properties of asphalt mixtures based on previous own 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 / Min	- 21.5 - 30.0	- 24.3 - 31.1	-20.2 -22.9	-12.5 -22.5	-16.8 -22.8	-20.2 -30.9
ITS [MPa] After STA [EN 12697-23]	@-10°C	n/a	n/a	4.876	4.545	5.001	5.311
	@-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

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]

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

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

4. Methodology of field investigation and data analysis

4.1. Description of the tested sections

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

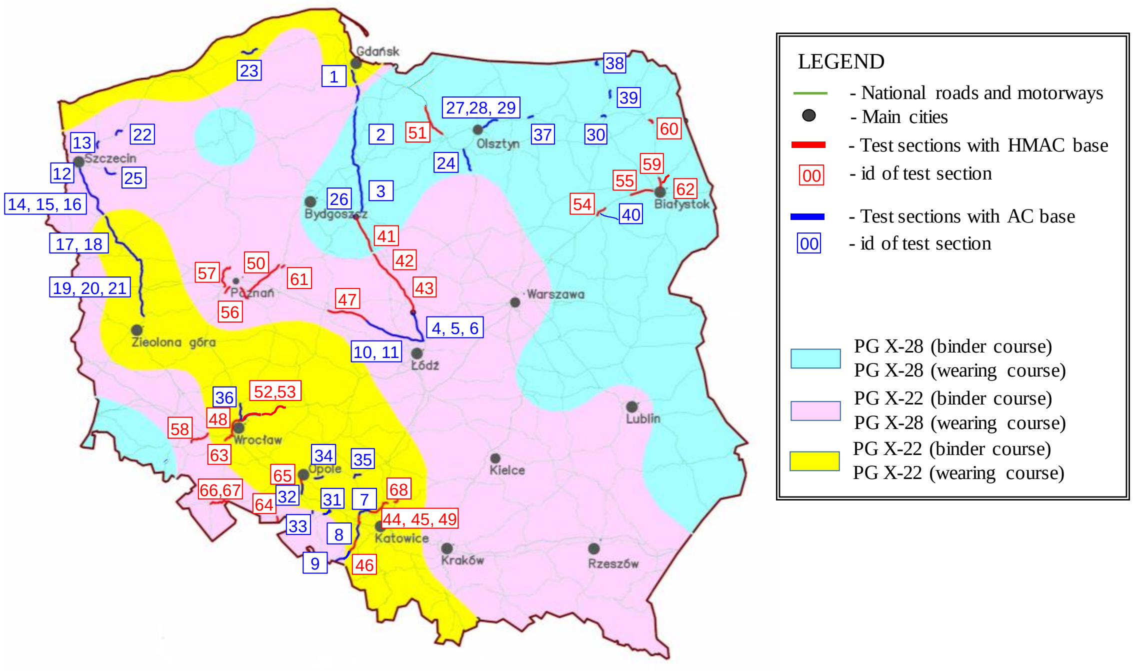

Figure 2. Location of road sections and climatic zones according to performance grade

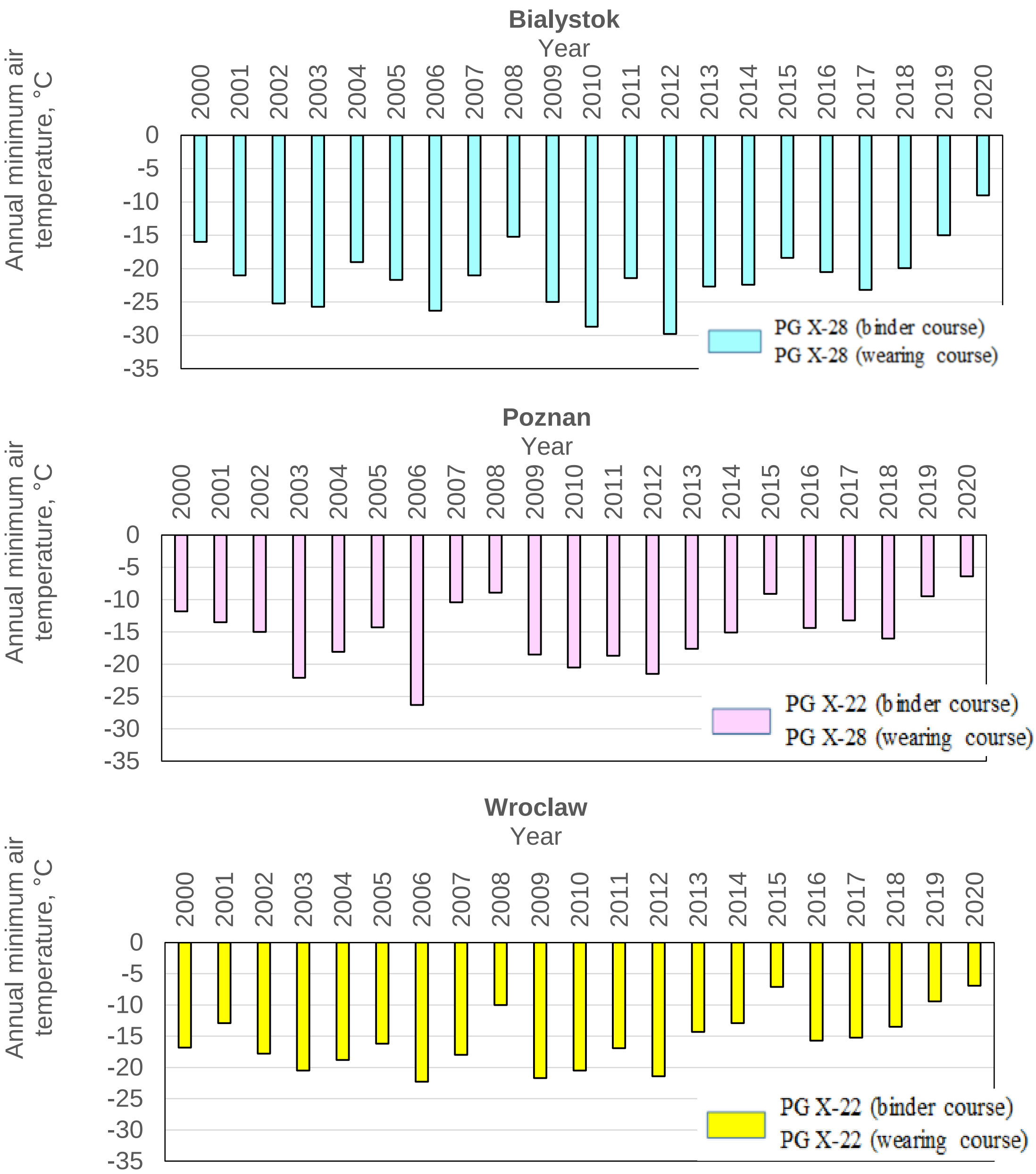

Figure 3. The minimum winter air temperatures recorded for representative station for each climatic zone

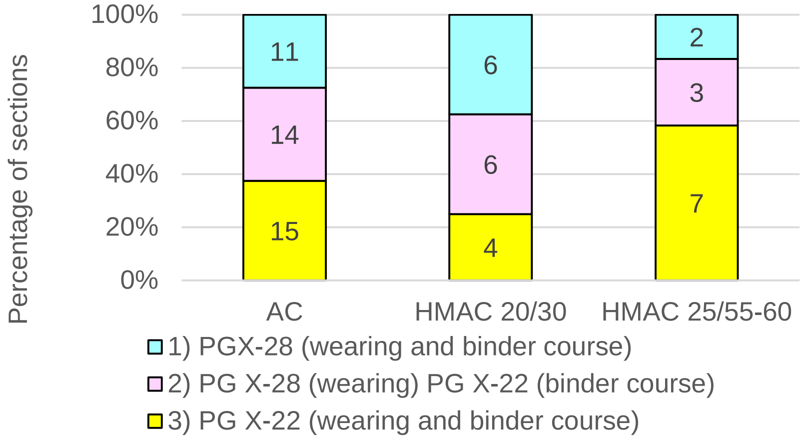

Figure 4. Number of road sections located in particular climatic regions and grouped according to the three types of asphalt base

4.2.Method of identification of low-temperature cracking intensity

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

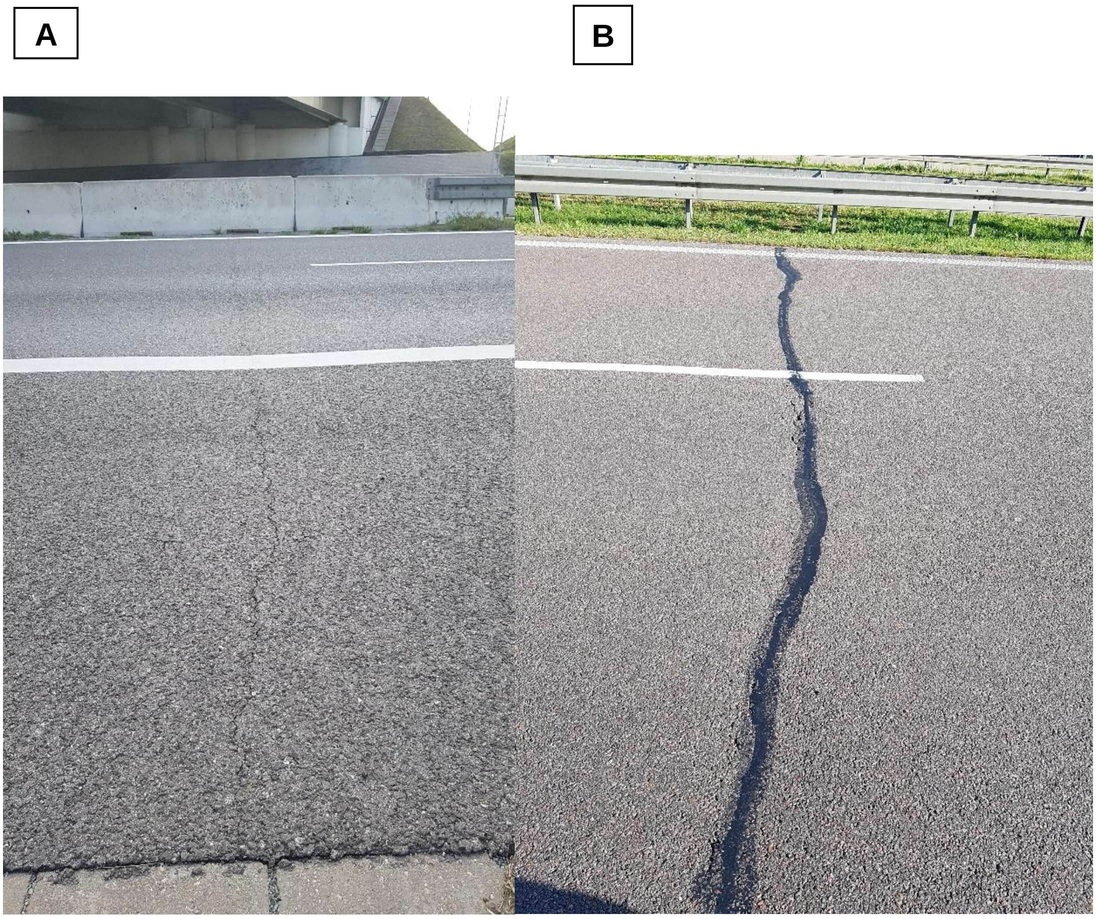

Figure 5. Examples of low-temperature cracks a) unrepaired b) sealed

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

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 ≤ 3
3	Moderately cracked sections	3 < CI ≤ 10
4	Heavily cracked sections, requiring maintenance treatments	10 < CI

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

Field investigations were performed twice – in the years 2014 and 2020. The particular mileages of subsections were adopted in the year 2014 and the investigations in 2020 were performed precisely on the same previously selected subsections. Ten road sections investigated in 2014 were rebuilt in the meantime. Therefore, they were excluded from investigation in 2020 and they are not mentioned in this work.

4.3.Methodology of statistical analysis of the collected data

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

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

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

$$logit\big(p(Y \le g)\big) = ln\frac{p(Y\le g)}{p(Y>g)} = \beta_{0g} - (\beta_1 X_1 + \cdots + \beta_n X_n) \qquad (1)$$

where:

Y: response (dependent) variable,

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

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

β_{0g}, β_1.., β_n: parameters of regression model,

X_1, ..., X_n: dependent variables,

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

Dependent variable Y takes on natural values from 1 to 4, according to Table 4. All independent variables X_1, ..., X_n are presented in binary form in order to simplify the interpretation of the results. The independent variables X_1, ..., X_n are listed in Table 5, where the meaning of their record in binary form is also explained.

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

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

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

Three climatic regions assumed in presenting analysis are described by variable X3 and X4 in following manner according to table 5 (see also Fig. 2):

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

Pavement age can be classified into one from three groups and it is described by variable X5 and X6 in following manner according to table 5:

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

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

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

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

where symbols used in the formula are as explained above.

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

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

where:

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

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

X_1, ..., X_n: dependent variables.

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

5. Statistical analysis of field observations

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

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

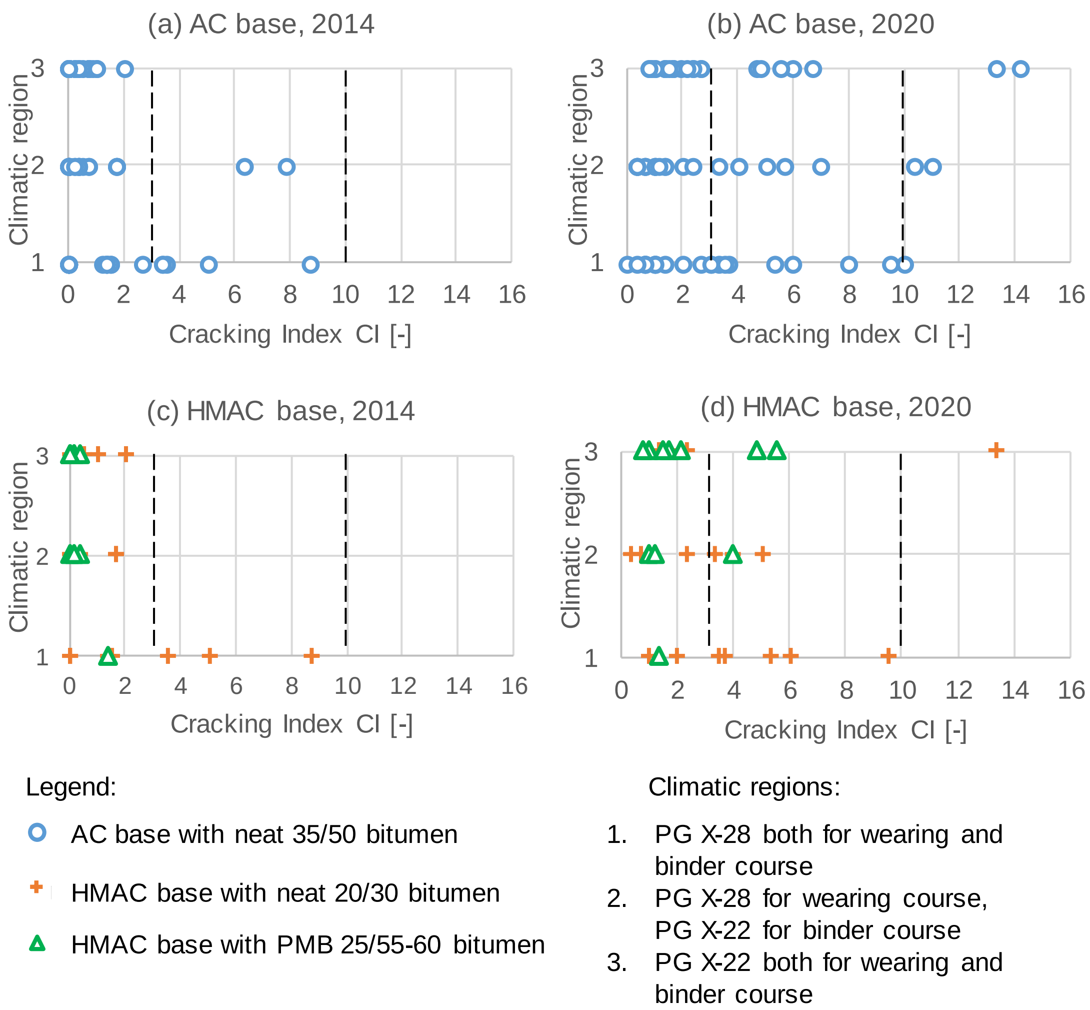

Figure 6. Cracking index CI obtained for sections in 3 climatic regions for pavements constructed in AC technology (a, b) or HMAC technology (c, d) on the basis of investigation from 2014 (a, c) and 2020 (b, d)

In the first investigation in 2014 pavements in the coldest region 1 with PG X-28 exhibited greater tendency to low-temperature cracking than those in other regions (see figure 6 a and 6 c). However, after six further years of service, in the year 2020, the tendency was not as obvious and even in the case of sections located in the warmest region 3 more heavily cracked sections were observed than in the colder regions 1 and 2. The statistics suggest that climatic region may have a significant influence on the time of crack initiation, but after several years of service the meaning of climatic performance grade is minor and the scale of cracks is similar, regardless of the region. It should be noted that the entire territory of Poland is located in temperate zone – if the same pavements were considered in a much wider range of performance grade low temperature zones, the observations could have been different.

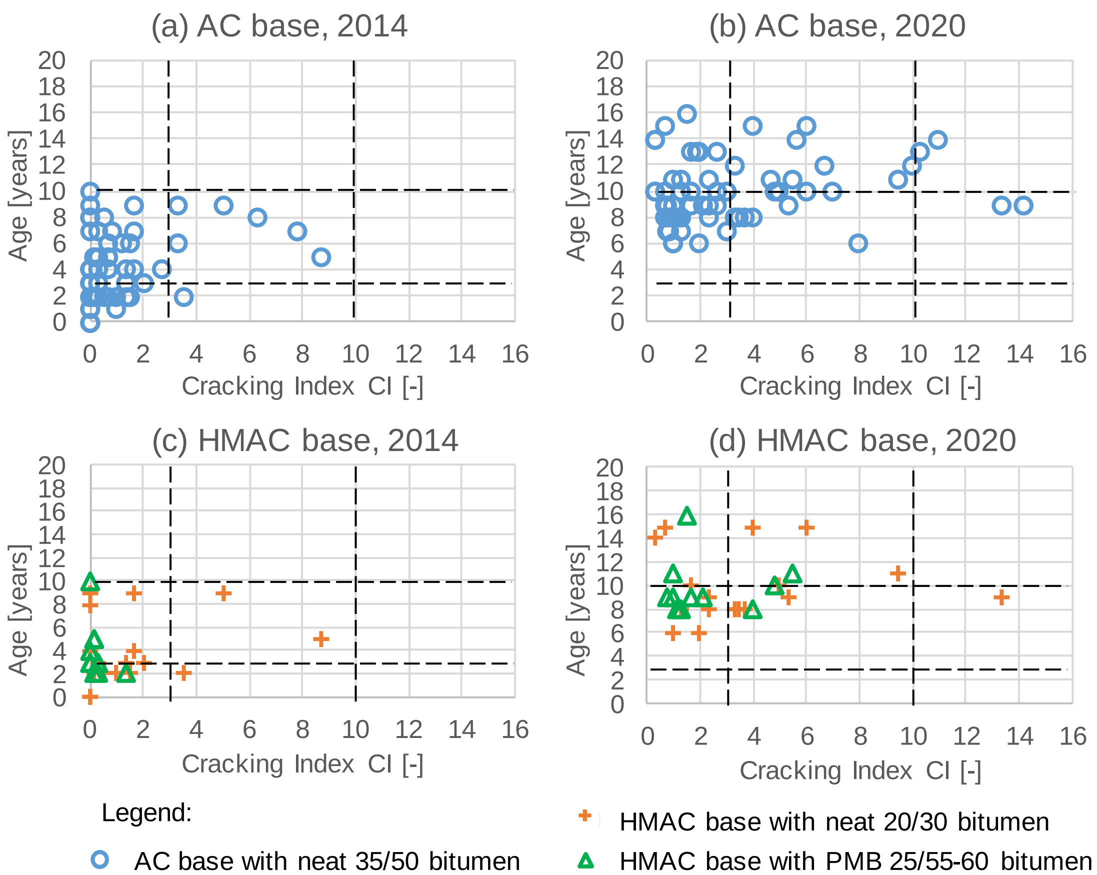

Figure 7. Cracking index CI in relation to the age of pavements constructed in AC technology (a, b) or HMAC technology (c, d), on the basis of investigations from 2014 (a, c) and 2020 (b, d)

As clearly shown in Figure 7, when the age of the pavement increases, the number of low-temperature cracks increases as well. However, several sections with age >14 years still remain in the group of slightly cracked sections. It may also be observed in Figure 7 d that sections where polymer-modified bitumen was applied in the asphalt base and wearing course belong to the group of slightly cracked sections (CI ≤ 3) more often, regardless of their age and location.

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

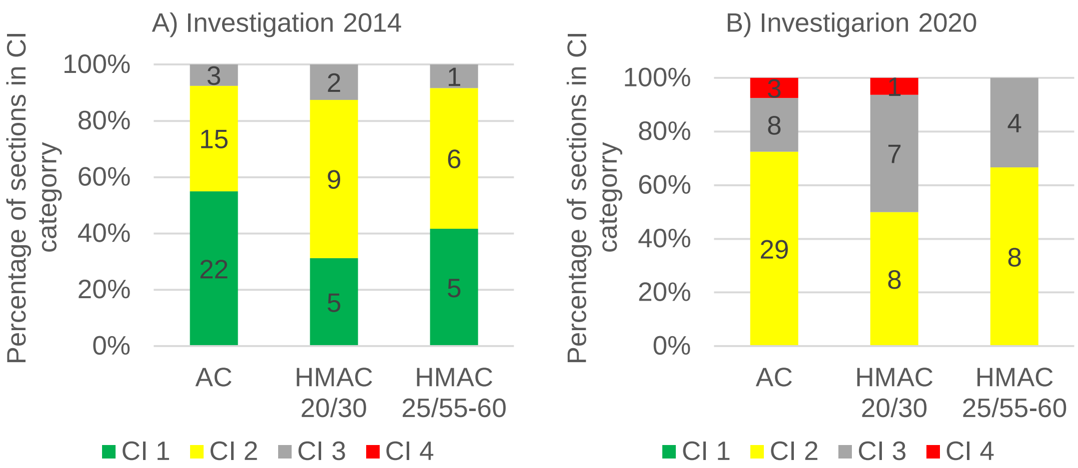

Figure 8. Number of sections grouped according to asphalt mixture technology and categorised according to cracking index CI A) in the base year 2014 B) in the year 2020

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

5.2. Building and analysis of the ordered logistic model

Parameters of regression were calculated using the R software. Calculations were conducted for each of the independent variables. The obtained results are presented in Table 6. The standard errors of the estimation and 95% confidence intervals are also presented in Table 6. . The detailed description of all in depended variables is clarified 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

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

The ordinal logistic regression confusion matrix given in Table 7 shows sensitivity and specificity for each group. The total sum of cells by rows represents the total number of true cases present, while each column shows how many cases the model classified into a given category. Table 7 shows that 56% of roads in crack category 1 were classified correctly by the model whereas 93% of roads in crack categories other than 1 were classified correctly. Due to the small number of roads in crack category 4, the sensitivity is equal to 0. Accuracy is the measure that indicates how much the prediction differs from the observed data. While 100% indicates perfect prediction, in the presented case the accuracy is equal to 65.44%.

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%

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

Table 8. Odds ratios for dependent variable – crack intensity

Dependent variables/ designation		Odds ratio *OR*	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 group	X_5	0.074	0.036	0.027	0.186
	X_6	4.975	2.480	1.891	13.521

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

Table 9. Ranking of the factors affecting low-temperature cracking of pavements 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

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

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

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

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

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

6. Summary and conclusions

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

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

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

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

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

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

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

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

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8. Data Availability

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

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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

615