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6  
7 **Comparison of low-temperature cracks intensity on pavements with**  
8 **high modulus asphalt concrete and conventional asphalt concrete bases**

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11        **Abstract**

12        High modulus asphalt concrete (HMAC) base courses provide very good  
13        resistance to rutting and fatigue but they can increase the risk of low-  
14        temperature cracking as compared with conventional asphalt concrete  
15        (AC). The article presents the comparison of these two road materials in  
16        terms of low-temperature cracking. The statistical method based on the  
17        ordered logistic regression model was used. The analysis was based on  
18        results of field investigations, that was carried out on 80 selected road  
19        sections being in normal service in Poland. The intensity of low -  
20        temperature cracking was an analysed parameter. The results of the  
21        analysis indicated evident effect of asphalt base type on intensity of low -  
22        temperature cracking. Besides the effect of mixture type, the method  
23        included influence of climatic condition and pavement age on low -  
24        temperature cracking. The essence of the analysis was to compare the  
25        probabilities of being of pavement in the group with a given cracks  
26        intensity. It was revealed that pavements with high modulus asphalt bases  
27        had 2.45 times higher odds of being in the group of cracked pavements  
28        than pavements with conventional asphalt concrete bases.

29        **Keywords:** High modulus asphalt concrete, low-temperature cracking,  
30        logistic regression model, field investigations



## 31 **1. Introduction**

### 32 ***1.1. Background***

33 High modulus asphalt concrete (designated in literature as HMAC, HiMA or  
34 EME) was developed in France in 1980s [1]. As compared to conventional asphalt  
35 concrete (AC) it contains harder grade bitumen and more dense structure what results in  
36 higher stiffness modulus. Pavements with HMAC base provided very good resistance to  
37 rutting and fatigue. Usage of HMAC base in pavement structure allows to reduce the  
38 thickness of the asphalt layers up to 25% [1–3] in comparison to pavement structure  
39 with typical asphalt concretes, while the fatigue life remains unchanged, what can result  
40 in significant savings during pavement construction. Good performance encouraged  
41 other countries to implement HMAC technology on their own road network.

42 In certain countries the technology of HMAC was implemented with the full  
43 compliance with French standards [4–6], in others with some modifications [7,8].  
44 However modifications of French standards could lead to excessive premature  
45 distresses of pavement. Premature distresses appeared on trials sections in UK and were  
46 precisely described in research [9,10]. In Poland [11] as well as in the Baltic countries  
47 [12,13] the HMAC technology was implemented with some changes as compared to  
48 French standards. The most important modifications introduced for HMAC mixes in  
49 Poland are: more closed structure (2-4% voids, while in France is up to 6%), lower  
50 stiffness modulus (14000 MPa in 10°C, while in France 14000 MPa in 15°C) and softer  
51 bitumen (20/30 pen. instead of 10/15 or 15/25 pen.). Moreover, bitumen modified by  
52 SBS polymers: PMB 25-55/60 and 10-40/65, and multigrade bitumen were also used in  
53 Poland. The minimum bitumen content equals 5,0% and it is slightly lower than it is  
54 recommended in French standards.

55           The main reason of changes in terms of French standards was the fact, that the  
56 climate in France is milder than in Poland what results in lower winter temperatures in  
57 Poland. Nevertheless the problem with low-temperature cracking occurred on sections  
58 constructed with HMAC base courses [14], which led to discussion between experts  
59 whether the usage of mixes of such high modulus, made from hard grade bitumen, is  
60 justified in Poland. Low-temperature cracks are one of the major distress observed in  
61 Poland even in pavements with conventional AC bases made from 35/50 and 50/70  
62 penetration grade neat bitumen. Therefore, usage of harder 20/30 neat bitumen could  
63 strongly increase the risk of occurrence of thermal cracking. Up till now no reasonable  
64 and cost-effective solutions to reduce the risk of thermal cracking were introduced. The  
65 most interesting and promising are either the usage of modified or highly modified  
66 bitumen [15], or usage of other additives [16]. But it is worth to consider whether the  
67 typical maintenance of cracks or improvement of the bitumen or mixture properties is  
68 better way to deal with this problem. Taking into consideration all this facts it was  
69 necessary to compare the performance of pavements with HMAC bases to pavements  
70 with conventional AC bases.

71           Grade of bitumen and stiffness of asphalt mix are very important but not the  
72 only factors, that influence the probability of occurrence of thermal cracks in a  
73 pavement. Among others, the most well-known influential factors are: climatic  
74 conditions, pavement age, chemical composition and properties of asphalt binder,  
75 mixture composition and its mechanical properties, and the quality of construction of  
76 pavement structure. Consideration of all these factors on the one hand would increase  
77 the accuracy and reliability of the analysis, but on the other hand would complicate or  
78 even make the analysis impossible. Nevertheless, data as pavement age, climatic

79 conditions and structure are relatively easier to collect as compared to collection data on  
80 binders, asphalt mixtures and layers mechanical properties for particular road sections.

### 81 **1.2. Objectives and scope**

82 The Department of Highway Engineering at the Gdansk University of  
83 Technology was granted a research project from the General Directorate for National  
84 Roads and Motorways to investigate the advantages and disadvantages of the HMAC  
85 technology used in Poland, with particular interest in low-temperature cracking and in  
86 resistance to permanent deformations. The paper present the part of results of the wide  
87 research program [17]. The analysis presented in the paper concerns comparison of the  
88 intensity of low-temperature cracking on pavement with HMAC and conventional AC  
89 base. The objective was to find how much the probability of occurrence of low-  
90 temperature cracks will increase when the high modulus asphalt concrete is used in  
91 pavement structure instead of conventional asphalt concrete. For this purpose the  
92 method based on ordered logistic regression model was used to compare the properties  
93 of two road materials. Parameters of the model were determined on the basis of the  
94 results of field investigations carried out on 80 test sections. Further the parameters of  
95 the model were analysed and interpreted in order to draw conclusions from field  
96 investigation.

### 97 **2. Field investigation**

98 In many cases investigations of new road materials like HMAC are based on  
99 laboratory test results compared with data acquired from especially constructed trial  
100 sections e.g. [18,19] or compared with set of data after improvement of a specific  
101 element, like type of bitumen e.g. [20–23]. Such methods and their results, which are  
102 available in literature, have following limitations: the number of test section is very

103 limited and located in one region, also the length of the sections is relatively short, trial  
104 test sections are constructed under strong supervision and high quality, most often  
105 deviating from the typical contract conditions, only single factors (like bitumen  
106 properties) are taken into account. Often, there are not available direct comparisons of  
107 high modulus asphalt concrete to conventional asphalt concrete.

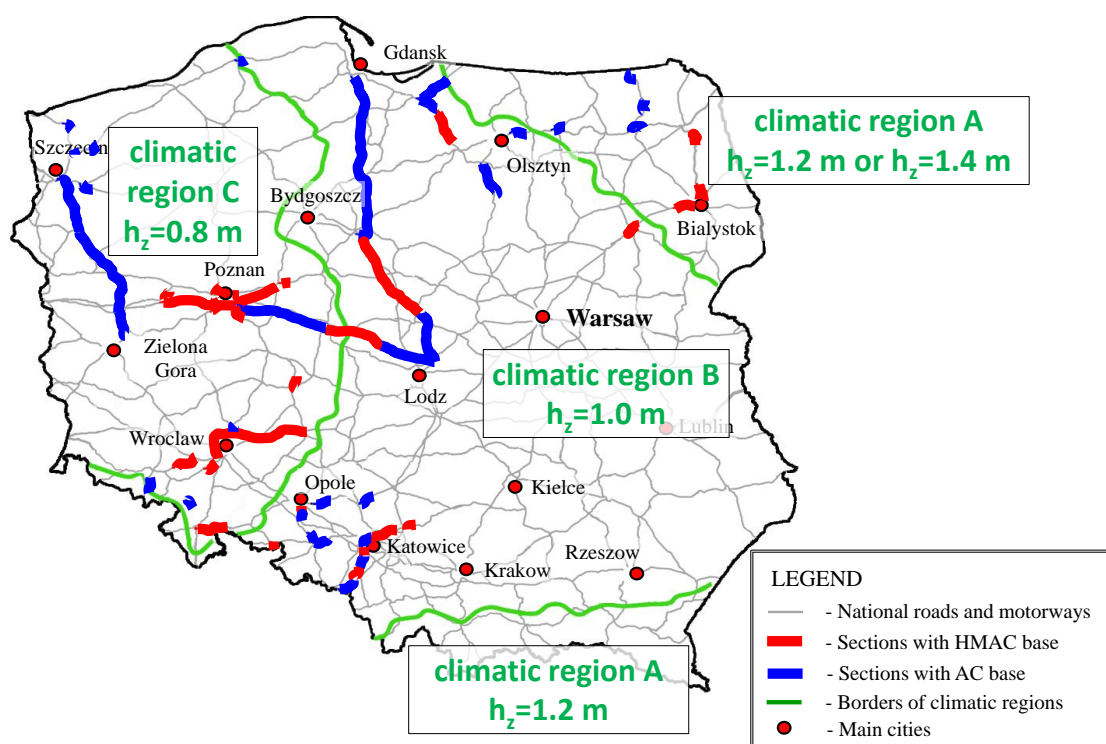
108         The purpose of the presented new method of field investigations was to fill these  
109 gaps. The field investigation was conducted on 80 road sections, 33 of them were  
110 constructed with HMAC and 47 with conventional AC. They were located throughout  
111 whole Poland. All those sections were constructed under normal contract conditions and  
112 have been in normal service and maintenance. The type of structure is the same in all of  
113 cases: asphalt layers are laid directly on the subbase made from unbounded crushed  
114 stone. Foundation and capping layer varies but the risk of reflected cracks from cement  
115 treated layers in foundation is minimalized because crushed stone in subbase is used in  
116 all cases. Thickness of asphalt layers varies in different sections from 11 to 31 cm and  
117 thickness of subbase varies from 15 to 25 cm. Each of section separately is  
118 characterized by the same pavement structure, age, the asphalt mix parameters and the  
119 contractor who executed pavement works. 50 sections were located on motorways or  
120 expressways, 28 on major national roads, and the remaining 2 on major province roads.  
121 Age of sections tested in 2014 varied from 1 to 12 years. All road sections were heavily  
122 loaded by commercial vehicles. Sections were located in three different climatic regions  
123 of Poland. Climatic regions were assumed on the basis of the maximum depth of frost  
124 penetration, used for pavement design, in accordance with the Polish standard PN-81/B-  
125 03020. The following regions show in Figure 1 are included:

126         A – the coldest – maximum depth of frost penetration equals  $h_z = 1,2$  or  $1,4$  m,

127 B – the medium – maximum depth of frost penetration equals  $h_z = 1,0$  m,

128 C – the warmest – maximum depth of frost penetration equals  $h_z = 0,8$  m.

129 The total length of selected road sections was around 503 km for pavements  
130 with HMAC and 800 km for pavements with AC. The length of particular sections  
131 ranged from 1 km to 63 km. Localizations of investigated sections are presented in  
132 Figure 1.



133

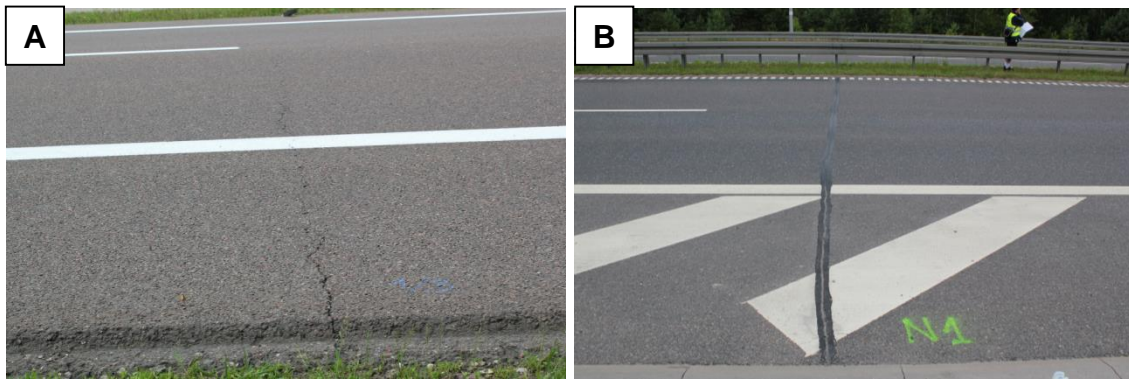
134 Figure 1. Localization of road sections included in the field investigation

135 The field investigation consisted of visual assessment of pavement distresses  
136 including cracks, ruts, roughness and surface condition and it was conducted in  
137 accordance with the Polish standardized method SOSN *Evaluation of pavement*  
138 *condition system* [24], supplemented if necessary by the *American Distress*  
139 *Identification Manual* [25]. The condition of the top of wearing course was observed  
140 and it was next rated in relation to what was the material used in the base course  
141 underneath, either HMAC or AC. However for the analysis presented in this article,

142 solely information about low-temperature cracks is presented. Cracks which originated  
143 from other causes than low-temperature, like fatigue cracks or cracks which occurred  
144 near bridges, culverts, manholes etc. were excluded from the analysis. The low-  
145 temperature cracks were identify as single transverse cracks that were visible on the  
146 surface of each investigated section. The possibility of occurrence of reflective cracks  
147 from cement treated layers was excluded due to the fact that subbase layers directly  
148 under the asphalt layers were made from unbound aggregate.

149         The theory of development of low-temperature cracking assumed that crack is  
150 initiated in the point where the thermal stress are higher than tension strength of asphalt  
151 mix [26,27]. The probable mechanism of transverse cracks observed on surfaces of  
152 pavements with HMAC bases was such that the HMAC base course cracked first at cold  
153 winter due to it very high stiffness. Next the low-temperature crack in the HMAC base  
154 penetrated upward and eventually appeared on the surface. Initiation of thermal cracks  
155 in HMAC base is possible due to higher thermal stresses in asphalt base than in wearing  
156 course, despite lower minimum temperature occurs in wearing course [14]. That  
157 mechanism of low-temperature transverse cracks is very difficult to identify during field  
158 investigation in case when the HMAC binder or base course already cracked but that  
159 failure is not yet observed at wearing course layer. The probable mechanism of  
160 transverse cracks in pavements with conventional AC base courses might be different.  
161 As stiffness of AC base is relatively low due to use of rather soft bitumen, the low-  
162 temperature cracks in such pavements are likely to start in cold winter from the top of  
163 surface course. Examples of typical low-temperature cracks observed during field  
164 investigation are presented in Figure 2.





165

166 Figure 2. Examples of low-temperature cracks a) not repaired b) repaired

167 The priority for the statistical analysis was to collect the data from as high  
 168 number of different sections as possible. Due to the limited time and funds of the  
 169 project the detailed investigation for the whole 1300 km was impossible, thus the  
 170 following methodology of test sections selection was used:

- 171
- sections shorter than 3 km were investigated precisely on their whole length,
  - 172 • for single carriageways sections longer than 3 km – 3 test sections each one-
  - 173 kilometer long were selected randomly from the whole length of a section,
  - 174 • for dual carriageways sections longer than 3 km – 3 test sections each one-
  - 175 kilometer long sections in each direction (6 test sections in both direction) were
  - 176 selected randomly from the whole length of section.

177 Additionally for sections longer than 3 km the overall simplified investigations  
 178 for the whole length of sections were conducted in order to verify whether the technical  
 179 parameters over the entire length of sections did not significantly deviate from the 3 km  
 180 long test sections selected for detailed observations. An additional analysis, which is not  
 181 included in this article, confirmed that the methodology of random selection of test  
 182 sections is proper to assess low-temperature cracks intensity.

183 The result of field investigation was the average cracking index CI, which means  
 184 the average number of low-temperature cracks per kilometer. For further analysis the  
 185 cracking index was a base to qualify a section to one of the four categories of cracks  
 186 intensity: not cracked ( $CI = 0$ ), little cracked ( $0 < CI \leq 2$ ), middle cracked ( $2 < CI \leq 10$ )  
 187 and heavy cracked ( $CI > 10$ ). Heavy cracked section were not observed during field  
 188 investigation on any tested road, and therefore were excluded from further analysis. The  
 189 summary of field investigation is presented in the tables 1 and 2, which include  
 190 information about road sections and parameters used for further statistical analysis.

191 Table 1. Summary of field investigation of sections with HMAC base

Route number	Sections km from/to	Total length [km]	Highway description	Design traffic load (million 100 kN ESALS)	Year of construction	Climatic region	Age group	Cracking index group
A8	0+000 28+368	28,40	Motorway - International	22 - 52	2011	C	1	2
S8	0+500 22+593	22,09	Expressway - International	22 - 52	2012	C	1	2
S8	29+800 54+910	25,11	Expressway - International	22 - 52	2012	C	1	2
DK 5	370+700 389+407	18,71	Principal route - International	22 - 52	2010	C	2	1
DK 35	79+850 85+000	5,15	Principal route - National	22 - 52	2011	C	1	1
DK 46	1+705 7+810	6,11	Principal route - National	22 - 52	2011	C	1	1
DK 46	7+810 20+894	13,08	Principal route - National	22 - 52	2010	C	2	2
DK 41	29+520 33+270	3,75	Principal route - National	2,5 - 7,3	2011	B	1	2
DK 45	89+650 94+100	4,45	Principal route - National	2,5 - 7,3	2011	B	1	2
S 8	614+850 639+365	24,50	Expressway - International	22 - 52	2012	A	1	3
S 8	575+550 586+620	11,07	Expressway - International	22 - 52	2012	A	1	2
DK 8	717+982 723+236	5,25	Principal route - International	22 - 52	2005	A	2	3
DK 8	648+117 654+548	6,43	Principal route - International	22 - 52	2009	A	2	3
DK 19	0+000 4+950	4,95	Principal route - National	22 - 52	2011	A	1	2
A 2	206+800 215+872	13,30	Motorway - International	22 - 52	2003	C	3	2
A 2	107+900 158+300	50,40	Motorway - International	22 - 52	2009	C	2	2
A 2	257+560 303+145	45,58	Motorway - International	22 - 52	2005	B	2	1
S 5	0+000 34+615	34,64	Expressway - International	22 - 52	2012	C	1	2
S 11	0+000 21+940	21,94	Expressway - National	22 - 52	2012	C	1	2
S 11	288+720 297+825	9,10	Expressway - National	22 - 52	2006/2009	C	2	1
DK 5	195+100 197+800	2,70	Principal route - International	22 - 52	2003	C	3	3

DK 15	0+000 6+260	6,26	Principal route - National	7,3 - 22	2005	C	2	2
DW 196	4+100 7+200	3,10	Principal route - Regional	2,5 - 7,3	2003	C	3	3
DK92	119+390 120+400	1,01	Principal route - National	7,3 - 22	2002	C	3	3
A1	d 0+000 d 14+500	14,50	Motorway - International	22 - 52	2009	B	2	2
A1	b 0+000 b 6+030	6,03	Motorway - International	22 - 52	2011	B	1	1
A1	a 15+500 a 29+612	14,11	Motorway - International	22 - 52	2009	B	2	2
S1	0+300 2+158	1,86	Expressway - National	22 - 52	2004/2007	B	2	1
DK78	0+000 5+710	5,70	Principal route - National	22 - 52	2010	B	2	1
A1	151+300 186+366	35,06	Motorway - International	22 - 52	2014	B	1	1
A1	186+348 215+850	29,50	Motorway - International	22 - 52	2014	B	1	1
S7	97+866 134+903	36,5	Expressway - International	22 - 52	2012	B	1	2
A1	215+850 245+800	29,50	Motorway - International	22 - 52	2012	B	1	2

192

Table 2. Summary of field investigation of sections with AC base

Route number	Sections km from/to	Total length [km]	Highway description	Design traffic load (million 100 kN ESALS)	Year of construction	Climatic region	Age group	Cracking index group
DW 381	0+700 3+760	3,06	Principal route - Regional	2,5 - 7,3	2008	B	2	3
DK5	0+000 3+301	3,30	Principal route - International	0,5 - 2,5	2005	B	2	3
DK5	340+485 352+927	7,50	Principal route - International	7,3 - 22	2011	C	1	1
DK 46	110+867 116+100	5,23	Principal route - National	7,3 - 22	2010	B	2	1
DK 45	82+814 86+663	3,85	Principal route - National	7,3 - 22	2011	B	1	1
DK 45	86+887 89+650	2,76	Principal route - National	7,3 - 22	2011	B	1	1
DK45	57-748 60+853	3,10	Principal route - National	2,5 - 7,3	2007	B	2	2
DK40	1+000 2+460	1,46	Principal route - National	7,3 - 22	2008	B	2	1
DK40	2+460 5+933	3,47	Principal route - National	7,3 - 22	2008	B	2	2
DK46	0+000 5+620	5,62	Principal route - National	22 - 52	2009	B	2	2
A1	c 0+000 c 20+300	20,30	Motorway - International	22 - 52	2009-2012	B	2	2
A1	a 0+000 a 15+500	15,50	Motorway - International	22 - 52	2007-2009	B	2	2
A1	a 29+612 a 49+212	19,60	Motorway - International	22 - 52	2012	B	1	1
DK66	0+000 16+600	16,60	Principal route - National	7,3 - 22	2008	A	2	3
DK16	162+100 180+500	18,40	Principal route - National	7,3 - 22	2010	B	2	3
DK65	0+000 5+600	5,60	Principal route - National	0,5 - 2,5	2010	A	2	2
DK65	0+000 7+600	7,60	Principal route - National	2,5 - 7,3	2013	A	1	1
DK16/65	0+000 4+800	4,80	Principal route - National	7,3 - 22	2012	A	1	1
DK59	0+000 6+500	6,50	Principal route - National	2,5 - 7,3	2011	A	1	1
S22	387+531 439+429	50,60	Expressway - International	7,3 - 22	2008	B	2	2
S7	83+040 97+867	13,70	Expressway - International	22 - 52	2011	B	1	2

S7	175+800 203+600	31,30	Expressway - Intrnational	22 - 52	2012	B	1	1
S3	0+000 9+500	9,50	Expressway - Intrnational	22 - 52	2007	C	2	1
S3	0+500 18+040	17,46	Expressway - Intrnational	22 - 52	2014	C	1	1
S3	0+000 17+000	17,00	Expressway - Intrnational	22 - 52	2013	C	1	2
S3	17+000 24+500	7,50	Expressway - Intrnational	22 - 52	2013	C	1	1
S3	24+500 42+954	18,50	Expressway - Intrnational	22 - 52	2013	C	1	1
S3	0+000 28+200	28,20	Expressway - Intrnational	22 - 52	2010	C	2	1
S3	28+200 54+900	26,70	Expressway - Intrnational	22 - 52	2010	C	2	1
S3	54+900 81+600	26,70	Expressway - Intrnational	22 - 52	2010	C	2	1
S3	61+600 66+400	4,80	Expressway - Intrnational	22 - 52	2012	C	1	1
S10	8+800 21+400	13,50	Expressway - National	22 - 52	2009	C	2	2
S6	0+000 9+400	9,40	Expressway - Intrnational	22 - 52	2012	C	1	1
S3	0+000 6+100	6,10	Expressway - Intrnational	22 - 52	2011	C	1	1
A6	14+200 21+900	7,70	Motorway - International	22 - 52	2007	C	2	3
A1	87+800 139+500	51,70	Motorway - International	22 - 52	2011	B	1	1
S10	0+000 12+000	12,00	Expressway - National	22 - 52	2010	B	2	2
A1	0+000 24+300	24,30	Motorway - International	22 - 52	2007	B	2	2
A1	24+300 87+800	63,50	Motorway - International	22 - 52	2008	B	2	2
S6	201+900 216+600	16,30	Expressway - Intrnational	22 - 52	2010	B	2	2
A1	245+800 261+000	15,20	Motorway - International	22 - 52	2012	B	1	2
A1	261+000 270+000	9,00	Motorway - International	22 - 52	2012	B	1	1
A1	270+000 291+000	21,00	Motorway - International	22 - 52	2006	B	2	1
A2	343+500 362+300	18,80	Motorway - International	22 - 52	2006	B	2	3
A2	301+372 343+500	40,40	Motorway - International	22 - 52	2006	B	2	2
A2	253+372 301+372	48,00	Motorway - International	22 - 52	2002	C	3	3
A2	215+872 253,372	37,50	Motorway - International	22 - 52	2003	C	3	2

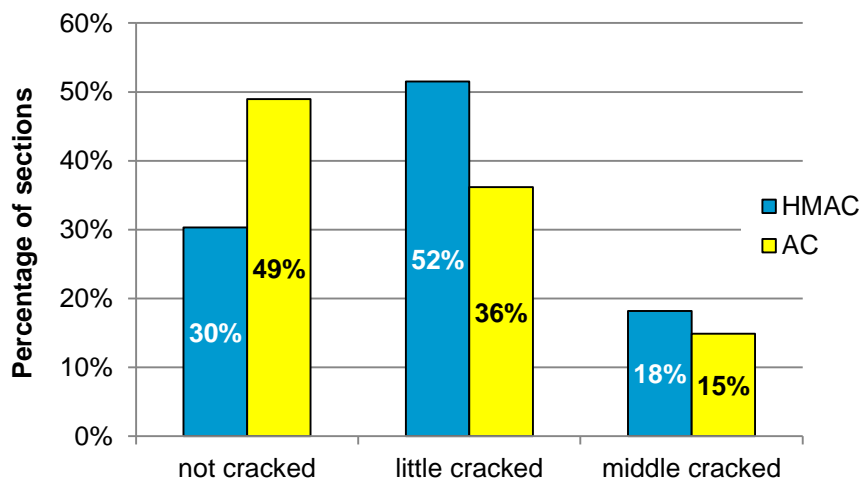
### 193 3. Selected results from field investigations

194 The field investigations were conducted during three consecutive years from  
195 2012 to 2014. Results showed in Figures 3-5 and further statistical analysis are based on  
196 the investigations from 2014. The percentage of road sections classified into particular  
197 groups of cracks intensity, according to observations in 2014, are presented in the  
198 Figure 3. Figures 4 and 5 present effect of climatic region and pavement age,  
199 respectively. The results showed in Figures 3 – 5 indicate evident effect of the asphalt

200 base type on the intensity of low-temperature cracks. Figure 6 shows the increase of  
201 cracked pavements with HMAC base courses in consecutive years of observations.

202 Figures 3 – 6 show that number of low-temperature cracks is:

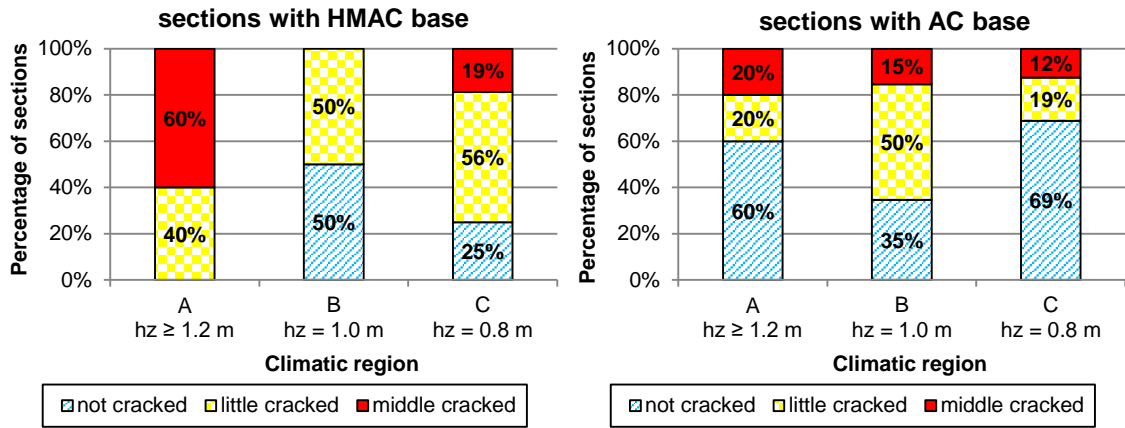
- 203 • higher for HMAC in comparison with AC bases,
- 204 • mostly higher in colder regions with higher frost depth penetration,
- 205 • higher for older pavements,
- 206 • increases in consecutive years of observation.



207

208 Figure 3. Percentage of sections with HMAC and AC pavement base courses in three  
209 groups of cracks intensity, according to observations in 2014

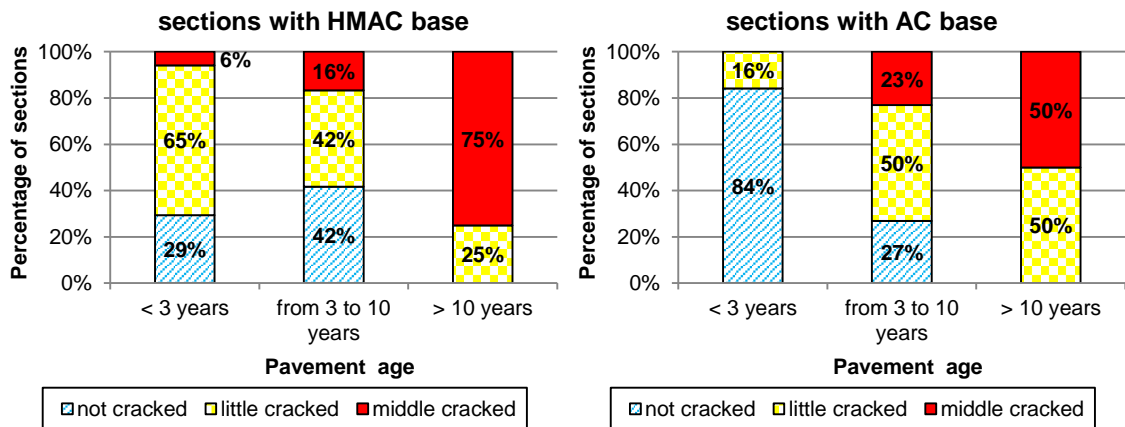
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211

212 Figure 4. Intensity of cracking in pavements with HMAC and AC base courses in

213 relation to depth of frost penetration ( $h_z$ ) in regions A, B, and C in Poland (2014)

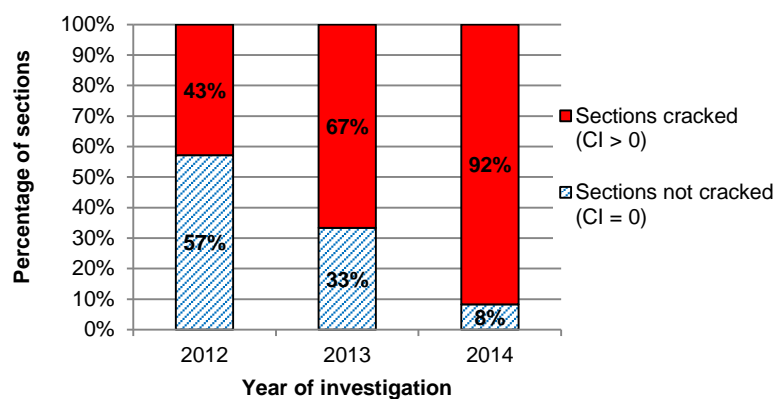


214

215 Figure 5. Intensity of cracking in pavements with HMAC and AC base courses in

216 relation to age of pavements (2014)

217



218

219 Figure 6. The increase of cracked pavements with HMAC base courses in consecutive  
 220 years of observations

#### 221 4. Statistical analysis of the impact of the mix type on the number of low- 222 temperature cracks

##### 223 4.1. General data on used statistical method

224 The essence of the analysis was to compare the probabilities of being in a given  
 225 groups of cracks intensity for pavements with HMAC base and AC base. All parameters  
 226 considered in analysis: cracks intensity, base type, climatic region, pavement age take  
 227 categorical values and can be expressed in binary form. Logistic regression is the  
 228 standard way to model categorical or binary outcomes [28]. Logistic regression was  
 229 developed in 1958 by statistician David Cox [29] and now is widely used in various  
 230 fields of science. The earlier applications of logistic regression for pavement  
 231 engineering concerned modelling of pavement deterioration [30] or fatigue of asphalt  
 232 mixes tested in laboratory conditions [31]. As to our study the implementation of the  
 233 logistic regression for comparison of two road materials is not available in the literature.

234 The logistic regression is a generalized linear model where logit is a link  
235 function. If the response variable Y takes categorical values from 1 to k then the logistic  
236 regression model can be written as [29]:

$$237 \quad \text{logit}(p(Y \leq g)) = \ln \frac{p(Y \leq g)}{p(Y > g)} = \beta_{0g} - (\beta_1 X_1 + \dots + \beta_n X_n) \quad (1)$$

238 where: Y – response (dependent) variable,  $p(Y \leq g)$  – the probability of a particular  
239 outcome,  $p(Y > g)$  – the probability of the complement of a particular outcome,  $\beta_{0g}$ ,  
240  $\beta_1, \dots, \beta_n$  – parameters of regression model,  $X_1, \dots, X_n$  – dependent variables,  $g = 1, \dots, k-1$ .

#### 241 **4.2. Statistical model**

242 In order to estimate the parameters of logistic regression model (1) the following,  
243 categorical variables were used:

- 244 • Dependent variable Y:
  - 245 ○ cracks intensity of road section in categories: not cracked, little cracked
  - 246 and middle cracked.
- 247 • Independent variables X:
  - 248 ○ asphalt mix type: conventional asphalt concrete AC and high modulus
  - 249 asphalt concrete HMAC,
  - 250 ○ climatic region: A, B or C (according to Figure 1, Tables 1 and 2),
  - 251 ○ pavement age: 1-3 years old (group 1), 3-10 years old (group 2) and
  - 252 more than 10 years old (group 3).

253 In the analysed case, response variable Y represents a category of cracks  
254 intensity. The basis of classification is cracking index for a given road section obtained  
255 from field investigation. Each section was classified into one of  $k = 3$  categories of



256 cracks intensity, as it is presented in Table 3. Heavy cracked sections ( $Y = 4$ ) did not  
 257 occur on evaluated road sections thus they are not listed in Table 1 and were excluded  
 258 from the further analysis.

259 Table 3. Dependent variable Y – cracks intensity categories

Y	Cracks intensity category	Average cracking index CI (cracks per km)
1	Not cracked	CI = 0
2	Little cracked	$0 < CI \leq 2$
3	Middle cracked	$2 < CI \leq 10$

260 Asphalt mix type and pavement age were obtained from the interview with road  
 261 authorities. The independent variables X are presented in binary form in order to  
 262 simplify the results interpretation. The variables are listed in Table 4, where the method  
 263 of its record in binary form is also explained. For base type there are only two  
 264 categories thus one binary variable  $X_1$  is adequate. For climatic region and pavement  
 265 age there are three categories thus two binary variables ( $X_2, X_3$  or  $X_4, X_5$  respectively),  
 266 are required.

267 Table 4. Independent variables X and interpretation of their records

Independent variables/ designation		Case 1		Case 2		Case 3	
		Value	Interpretation	Value	Interpretation	Value	Interpretation
Base type	$X_1$	0	AC base	1	HMAC base	-	-
Climatic region	$X_2$	1	A - coldest (see Figure 1)	0	B - medium, (see Figure 1)	0	C - warmest (see Figure 1)
	$X_3$	0		1		0	
Pavement age group	$X_4$	1	Age less than 3 years	0	Age between 3 and 10 years	0	Age more than 10 years
	$X_5$	0		1		0	

268 Parameters of regression were calculated with the usage of the computer  
 269 program [32]. Calculations were conducted for each of independent variables and  
 270 obtained results are presented in Table 5. The standard errors of the estimation and 95%  
 271 confidence intervals are also presented.

272 Table 5 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	$X_1$	$\beta_1$	0,8954	0,4875	-0,0601	1,8509
Climatic region	$X_2$	$\beta_2$	2,0292	0,7761	0,5080	3,5503
	$X_3$	$\beta_3$	0,7143	0,5411	-0,3463	1,7749
Pavement age group	$X_4$	$\beta_4$	-4,3180	2,0698	-6,4148	-2,2212
	$X_5$	$\beta_5$	-2,7643	1,0349	-4,7926	-0,7359
Model constant		$\beta_{01}$	-2,8338	0,9833	-4,7611	-0,9066
Model constant		$\beta_{02}$	-0,1854	0,9151	-1,9789	1,6081

273 **4.3. Interpretation of the statistical model**

274 In order to interpret the ordered logistic regression model the odds ratio and  
 275 marginal effects were determined. The interpretation of the odds ratio and marginal  
 276 effects are presented with the assumption of *ceteris paribus*. *Ceteris paribus* is a Latin  
 277 phrase meaning "with other things the same" or "all or other things being equal or held  
 278 constant".

279 The odds expresses a quotient of probability of particular outcome  $p(Y \leq g)$  to  
 280 its complement  $p(Y > g)$ . The ratio of two odds is called odds ratio OR. For the  
 281 considered analysis the odds ratio provides a change of probability of a given cracking  
 282 intensity when one of independent variables  $X_i$  increases from 0 to 1 and the  
 283 probabilities change from  $p_0$  to  $p_1$ . The odds ratio is defined as follows [28]:

$$284 \quad OR = \frac{p_0(Y \leq g)/p_0(Y > g)}{p_1(Y \leq g)/p_1(Y > g)} \quad (2)$$

285 where symbols in formula are explained above. The results of odds ratios are presented  
 286 in Table 6.

287

288 Table 6. Odds ratio for dependent variable – cracks intensity

Dependent variables/ designation		Odds ratio OR	The standard error of the estimate	95% confidence interval	
				min	max
Base type	X <sub>1</sub>	2.45	1.19	0.94	6.37
Climatic region	X <sub>2</sub>	7.61	5.91	1.66	34.83
	X <sub>3</sub>	2.04	1.11	0.70	5.908
Pavement age group	X <sub>4</sub>	0.01	0.01	0.00	0.11
	X <sub>5</sub>	0.06	0.07	0.01	0.45

289 The following example illustrates how the odds ratios should be interpreted. Let  
 290 us consider that the type of base expressed by variable X<sub>1</sub> changes from X<sub>1</sub>=0 (AC  
 291 base) to X<sub>1</sub>=1 (HMAC base) the odds ratio is equal to 2.45 (see Table 4). Two groups of  
 292 road sections: cracked (Y>1) and not cracked (Y=1) are compared. According to the  
 293 formula (2) it can be stated that pavements with HMAC bases with 2.45 times higher  
 294 odds will belong to the groups of cracked pavements than pavements with conventional  
 295 AC bases. The remaining results of odds ratio should be interpreted as follows:

- 296 • Pavements located in the climatic region A (the coldest) with 7.6 times higher  
 297 odds will belong to the group of cracked pavements than pavements located in  
 298 climatic region C (the warmest).
- 299 • Pavements located in the climatic region B with 2.1 times higher odds will  
 300 belong to the group of cracked pavements than pavements located in climatic  
 301 region C (the warmest).
- 302 • The odds of low-temperature cracks occurrence decrease by 99% for pavements  
 303 younger than 3 years in comparison to pavements older than 10 years.
- 304 • The odds of low-temperature cracks occurrence decrease by 94% for pavements  
 305 between 3 and 10 years old in comparison to pavements older than 10 years.

306 The marginal effects express a deviation of probabilities of belongingness to a  
 307 given category of cracks intensity. These probability can be directly determined from  
 308 the logit regression model:

$$309 \quad \hat{p}(Y \leq g) = \frac{e^{\hat{\beta}_{0g} - (\hat{\beta}_1 X_1 + \dots + \hat{\beta}_n X_n)}}{1 + e^{\hat{\beta}_{0g} - (\hat{\beta}_1 X_1 + \dots + \hat{\beta}_n X_n)}} \quad (3)$$

310 where:  $\hat{p}(Y \leq g)$  – probability of being a pavement in a given category of cracks  
 311 intensity,  $\hat{\beta}_{0g}, \hat{\beta}_1, \dots, \hat{\beta}_n$  – parameters of regression model (see Table 5),  
 312  $X_1, \dots, X_n$  – dependent variables. Results of calculation of marginal effects are  
 313 presented in Tables from 7 to 9.

314 Table 7. Marginal effects for not cracked sections ( $Y = 1$ )

Dependent variables/ designation		Marginal effect dy/dx	The standard error of the estimate	95% confidence interval	
				min	max
Base type	X <sub>1</sub>	-0.20	0.11	-0.41	0.01
Climatic region	X <sub>2</sub>	-0.34	0.09	-0.51	-0.12
	X <sub>3</sub>	-0.16	0.12	-0.40	0.08
Pavement age group	X <sub>4</sub>	0.79	0.10	0.58	0.99
	X <sub>5</sub>	0.58	0.17	0.25	0.91

315 Table 9. Marginal effects for little cracked sections ( $Y = 2$ )

Dependent variables/ designation		Marginal effect dy/dx	The standard error of the estimate	95% confidence interval	
				min	Max
Base type	X <sub>1</sub>	0.11	0.06	-0.01	0.23
Climatic region	X <sub>2</sub>	0.01	0.12	-0.22	0.23
	X <sub>3</sub>	0.09	0.07	-0.05	0.24
Pavement age group	X <sub>4</sub>	-0.34	0.09	-0.51	-0.16
	X <sub>5</sub>	-0.29	0.10	-0.49	-0.10

316

317 Table 9. Marginal effects for middle cracked sections ( $Y = 3$ )

Dependent variables/ designation		Marginal effect $dy/dx$	The standard error of the estimate	95% confidence interval	
				min	Max
Base type	$X_1$	0.09	0.06	-0.02	0.21
Climatic region	$X_2$	0.33	0.17	0.00	0.66
	$X_3$	0.07	0.06	-0.04	0.18
Pavement age group	$X_4$	-0.45	0.13	-0.73	-0.19
	$X_5$	-0.28	0.13	-0.53	-0.04

318 Marginal effects were interpreted for different cases of belongingness of a  
 319 pavement to a given group (base type, climatic zone, age). The most important  
 320 interpretations of the obtained results of marginal effects are given as follows.

321 Probability of the low-temperature cracks occurrence is higher for pavements with  
 322 HMAC base than for pavements with conventional AC base. Moreover pavements with  
 323 HMAC as compared with AC base will belong to the group of:

- 324 • not cracked sections with probability lower by 20% (Table 7),
- 325 • little cracked sections with probability higher by 11% (Table 8),
- 326 • middle cracked sections with probability higher by 9% (Table 9).

327 Probability of the low-temperature cracks occurrence is higher for pavements located in  
 328 colder climatic regions. Pavements both with HMAC and AC base located in the coldest  
 329 climatic region A (depth of frost penetration  $h_z = 1.2$  m and  $h_z = 1.4$  m) as compared  
 330 with pavements located in the warmest climatic region C ( $h_z = 0.8$  m) will belong to the  
 331 group of:

- 332 • not cracked sections in coldest climatic region with probability lower than in  
 333 warmest climatic region by 34% (Table 7),
- 334 • little cracked sections with comparable probability (Table 8),
- 335 • middle cracked sections with probability higher by 33% (Table 9).

336 With the increase of pavement age the probability of low-temperature cracks occurrence  
337 also increases. Newly constructed pavements, younger than 3 years old, towards  
338 pavements older than 10 years will belong to the group of:

- 339 • not cracked sections of newly constructed sections with probability higher than  
340 pavements older than 10 years by 79% (Table 7),
- 341 • little cracked sections with probability lower by 33% (Table 8),
- 342 • middle cracked sections with probability lower by 45% (Table 9).

343 Pavements, between 3 and 10 years old, as compared with pavements older than 10  
344 years will belong the group of:

- 345 • not cracked pavement sections between 3 and 10 years old with probability  
346 higher than pavements older than 10 years by 58% (Table 7),
- 347 • little cracked sections with probability lower by 29% (Table 8),
- 348 • middle cracked sections with probability lower by 28% (Table 9).

## 349 **5. Summary and conclusions**

- 350 (1) The presented analysis was based on the field investigations carried out on 80  
351 selected road sections in Poland, of total length of about 1 300 km. The sections  
352 were constructed under normal contract conditions and were in normal way used  
353 by traffic. The intensities of low-temperature cracking for pavements with high  
354 modulus asphalt concrete HMAC and conventional asphalt concrete AC base  
355 were determined and compared.
- 356 (2) In order to include several effects, such as base type - high modulus asphalt  
357 concrete HMAC as compared with conventional asphalt concrete AC, pavement

358 age, and climatic conditions on low-temperature cracks intensity the statistical  
359 method based on ordered logistic regression model was used.

360 (3) The results of the analysis indicate evident effect of asphalt base type on  
361 intensity of low-temperature cracking. Probability of low-temperature cracks  
362 occurrence is higher for pavements with high modulus asphalt base HMAC than  
363 for pavements with conventional asphalt concrete AC base courses. It was  
364 revealed that pavements with high modulus asphalt bases have 2.45 times higher  
365 odds of being in group of cracked pavements than pavements with conventional  
366 asphalt concrete base.

367 (4) Probability of low-temperature cracks occurrence is higher for pavements  
368 located in colder climatic regions. With the increase of pavement age the  
369 probability of low-temperature cracks occurrence also increases.

370 (5) The results of analysis for types of asphalt mixtures used for base courses, for  
371 climatic conditions and for pavement ages confirmed that the statistical method  
372 based on the ordered logistic regression model provides reasonable results.

373 (6) The ordered logistic regression model, as well as the methodology of field  
374 investigation used in this research, can be adapted for comparisons of the  
375 behaviour of any different road materials or pavements.

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