Comparison of low-temperature cracks intensity on pavements with 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

1. Introduction

1.1.Background

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

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

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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

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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

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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 nationals 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,

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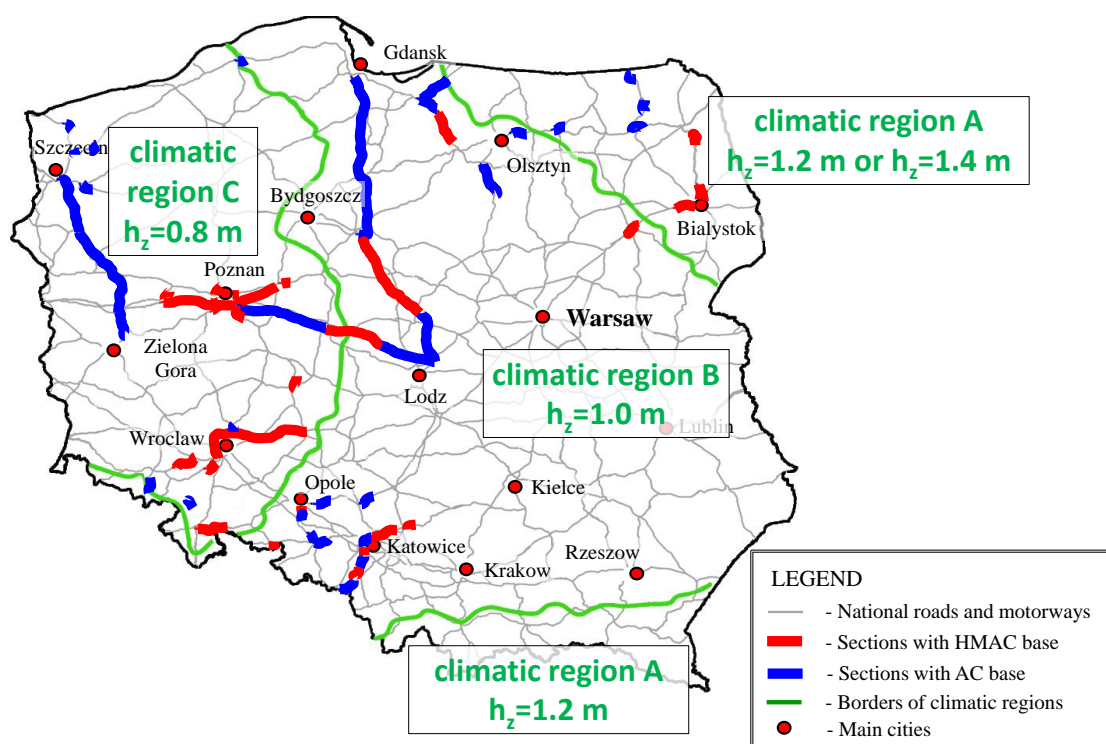
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134   Figure 1. Localization of road sections included in the field investigation

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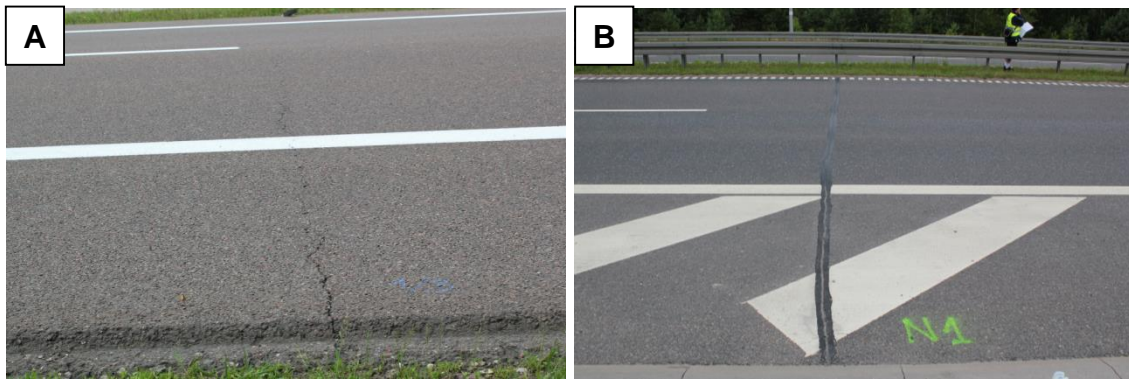
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166   Figure 2. Examples of low-temperature cracks a) not repaired b) repaired

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.

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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 ≤ 2), middle cracked (2 < CI ≤ 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

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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 - Intrnational	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 - Intrnational	7,3 - 22	2008	B	2	2
S7	83+040 97+867	13,70	Expressway - Intrnational	22 - 52	2011	B	1	2

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|								
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

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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.
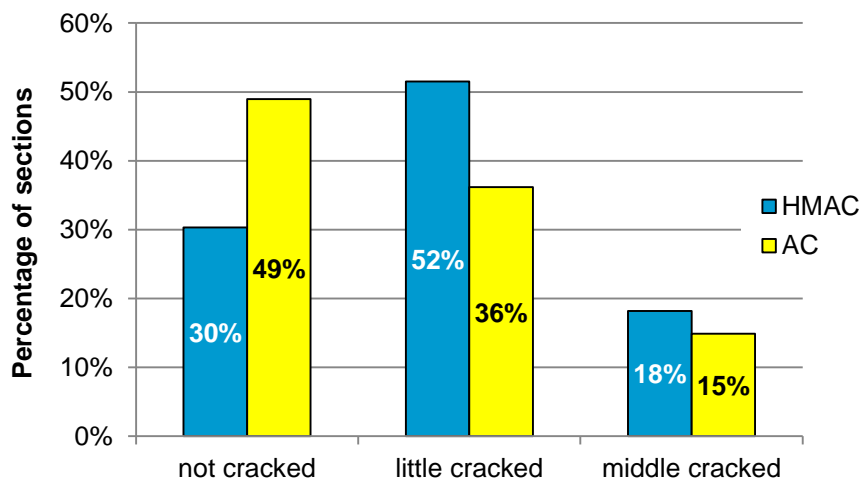
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208   Figure 3. Percentage of sections with HMAC and AC pavement base courses in three

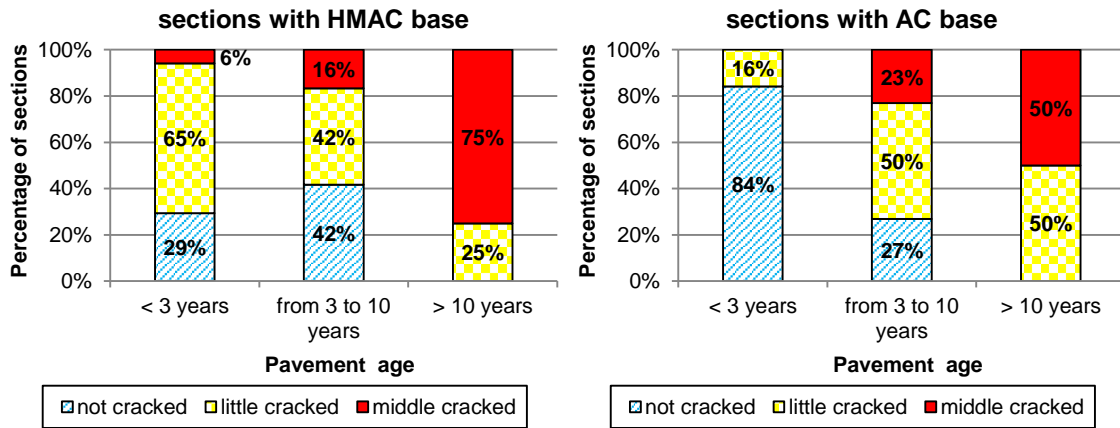209   groups of cracks intensity, according to observations in 2014

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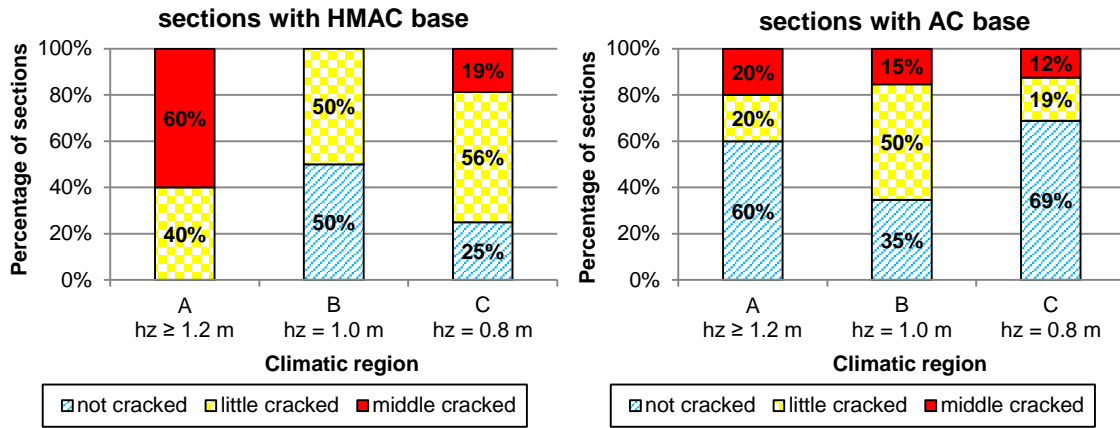
Figure 4. Intensity of cracking in pavements with HMAC and AC base courses in relation to depth of frost penetration (h_z) in regions A, B, and C in Poland (2014)
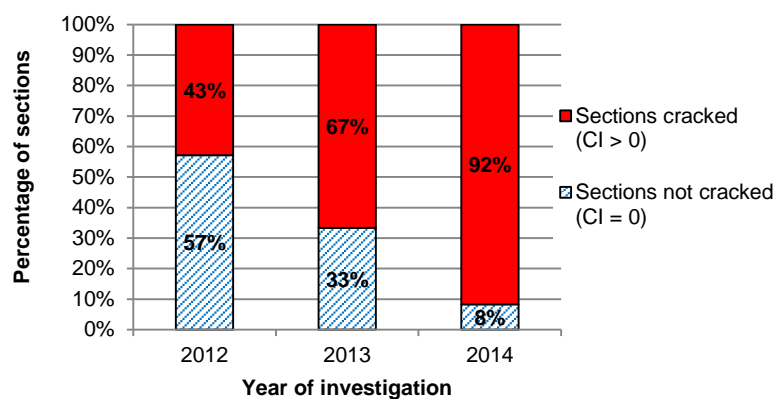

Figure 5. Intensity of cracking in pavements with HMAC and AC base courses in relation to age of pavements (2014)

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 tasted 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.

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

240   β_1.., β_n – parameters of regression model, X_1, ..., X_n – dependent variables, g = 1,.. 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   o   cracks intensity of road section in categories: not cracked, little cracked

246   and middle cracked.

247   • Independent variables X:

248   o   asphalt mix type: conventional asphalt concrete AC and high modulus

249   asphalt concrete HMAC,

250   o   climatic region: A, B or C (according to Figure 1, Tables 1 and 2),

251   o   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 β		The standard error of the estimate	95% confidence interval	
		Designation	Value		min	max
Base type	X_1	β_1	0,8954	0,4875	-0,0601	1,8509
Climatic region	X_2	β_2	2,0292	0,7761	0,5080	3,5503
	X_3	β_3	0,7143	0,5411	-0,3463	1,7749
Pavement age group	X_4	β_4	-4,3180	2,0698	-6,4148	-2,2212
	X_5	β_5	-2,7643	1,0349	-4,7926	-0,7359
Model constant		β_{01}	-2,8338	0,9833	-4,7611	-0,9066
Model constant		β_{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
$$OR = \frac{p_0(Y \leq g)/p_0(Y > g)}{p_1(Y \leq g)/p_1(Y > g)} \tag{2}$$

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

286   in Table 6.

287

18

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_1	2.45	1.19	0.94	6.37
Climatic region	X_2	7.61	5.91	1.66	34.83
	X_3	2.04	1.11	0.70	5.908
Pavement age group	X_4	0.01	0.01	0.00	0.11
	X_5	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_1 changes from $X_1=0$ (AC

291 base) to $X_1=1$ (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.

19

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

310 where: $\hat{p}(Y \le g)$ – probability of being a pavement in a given category of cracks

311 intensity, $\hat{\beta}_{0g}, \hat{\beta}_1..., \hat{\beta}_n$ – parameters of regression model (see Table 5),

312 $X_1, ..., X_n$ – 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_1	-0.20	0.11	-0.41	0.01
Climatic region	X_2	-0.34	0.09	-0.51	-0.12
	X_3	-0.16	0.12	-0.40	0.08
Pavement age group	X_4	0.79	0.10	0.58	0.99
	X_5	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_1	0.11	0.06	-0.01	0.23
Climatic region	X_2	0.01	0.12	-0.22	0.23
	X_3	0.09	0.07	-0.05	0.24
Pavement age group	X_4	-0.34	0.09	-0.51	-0.16
	X_5	-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).

21

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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