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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.

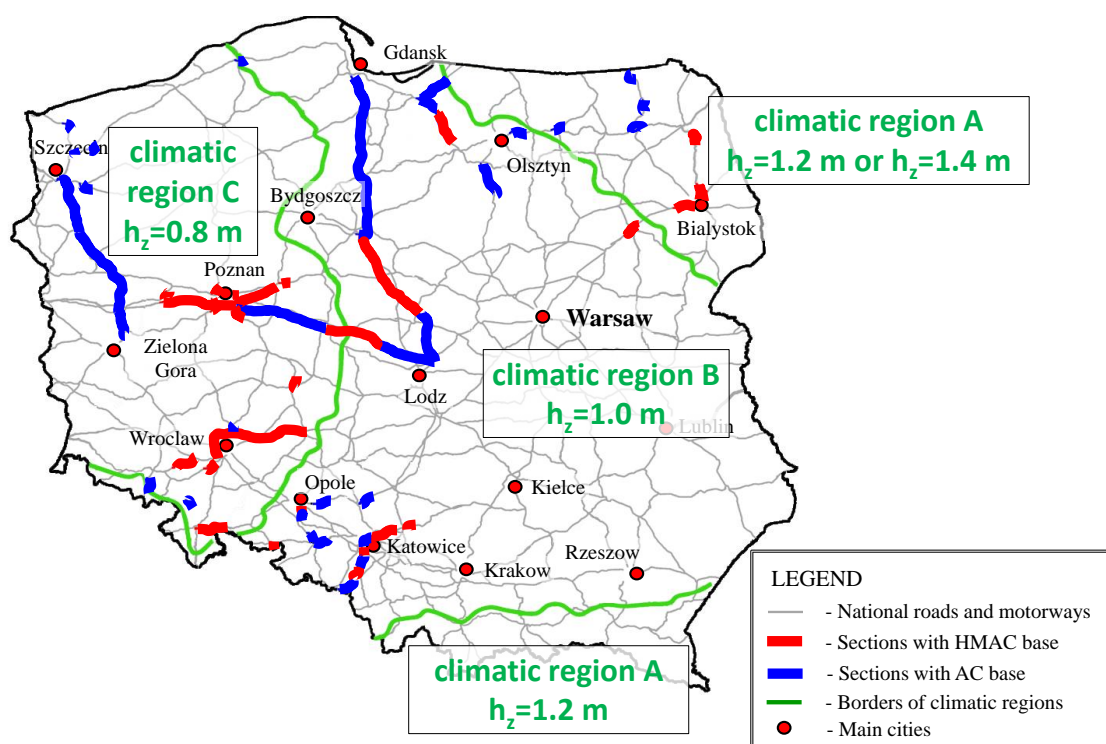
108 The purpose of the presented new method of field investigations was to fill these
109 gaps. The field investigation was conducted on 80 road sections, 33 of them were
110 constructed with HMAC and 47 with conventional AC. They were located throughout
111 whole Poland. All those sections were constructed 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.



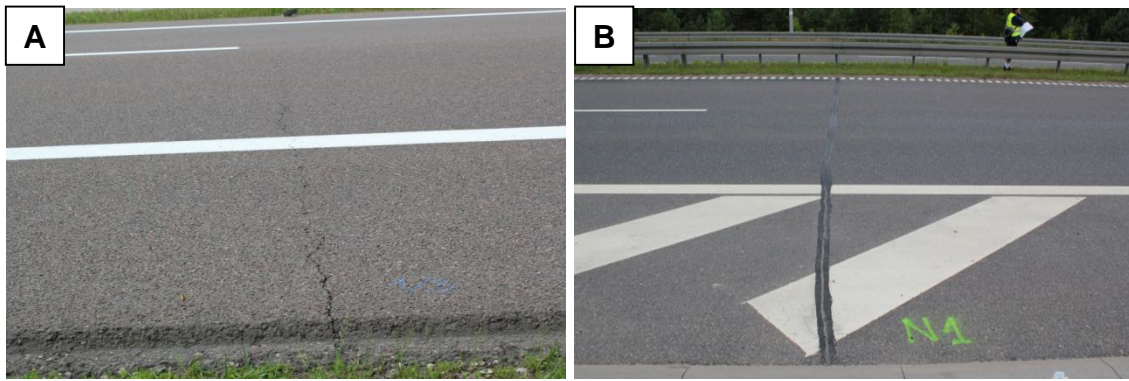
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134 Figure 1. Localization of road sections included in the field investigation

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.



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 |

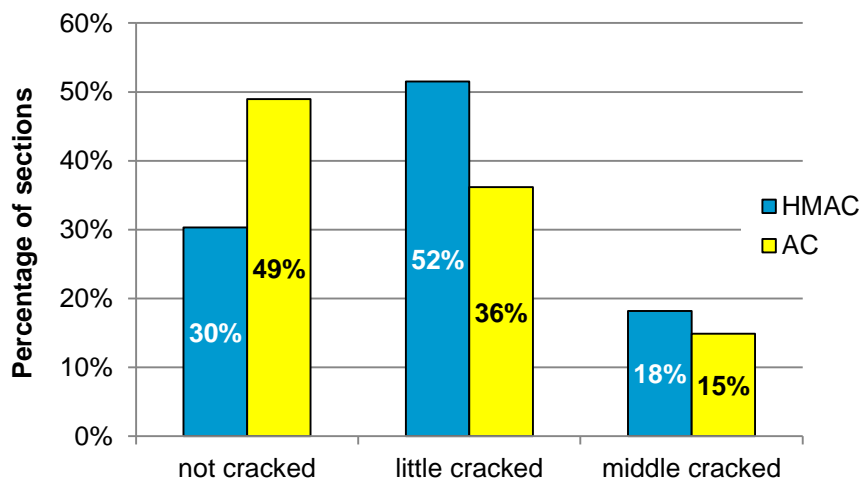
193 3. Selected results from field investigations

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:

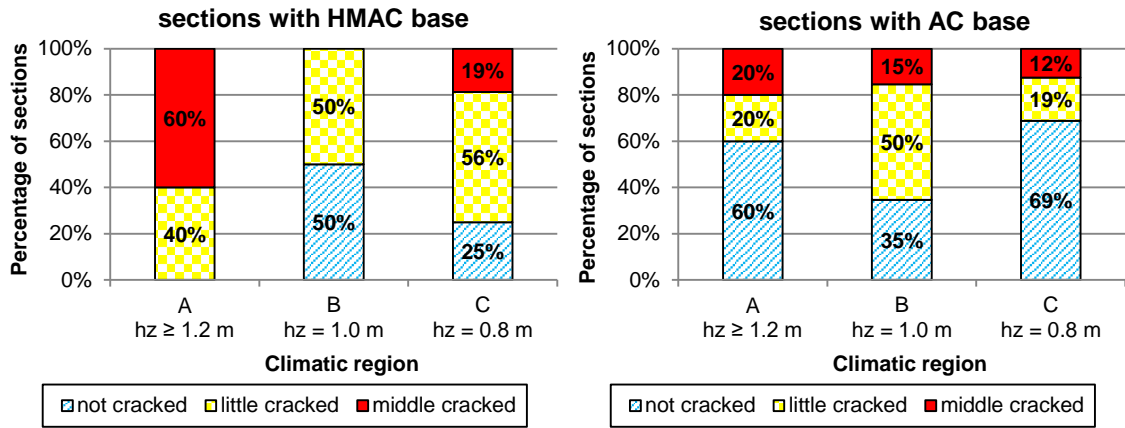
- 203 • higher for HMAC in comparison with AC bases,
- 204 • mostly higher in colder regions with higher frost depth penetration,
- 205 • higher for older pavements,
- 206 • increases in consecutive years of observation.



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

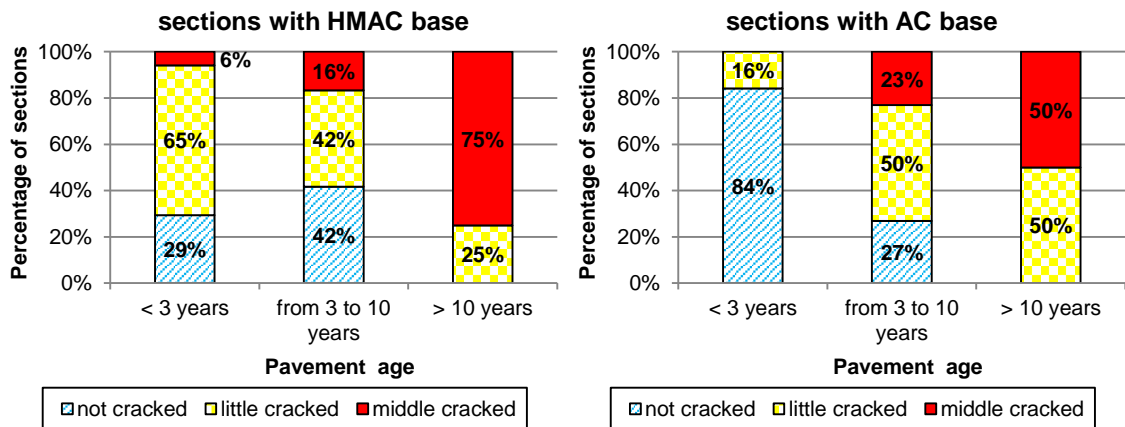
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212 Figure 4. Intensity of cracking in pavements with HMAC and AC base courses in

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

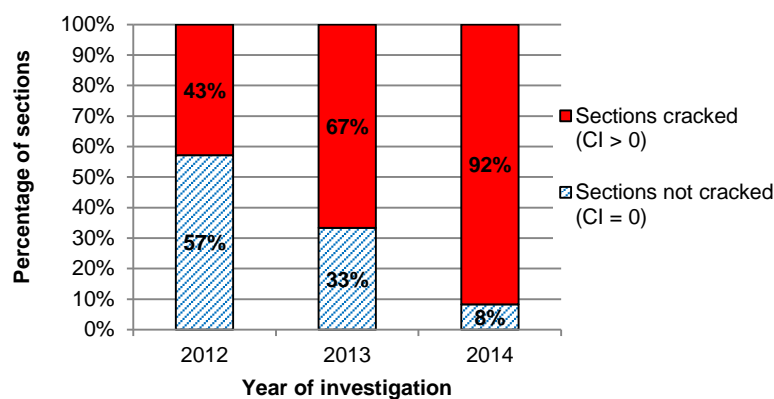


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215 Figure 5. Intensity of cracking in pavements with HMAC and AC base courses in

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, β_{0g} ,
240 β_1, \dots, β_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 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
$$OR = \frac{p_0(Y \leq g)/p_0(Y > g)}{p_1(Y \leq g)/p_1(Y > g)} \quad (2)$$

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 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 X₁ changes from X₁=0 (AC
 291 base) to X₁=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_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).

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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