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

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Abstract

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

Keywords: High modulus asphalt concrete, low-temperature cracking, 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.

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

Grade of bitumen and stiffness of asphalt mix are very important but not the only factors, that influence the probability of occurrence of thermal cracks in a pavement. Among others, the most well-known influential factors are: climatic conditions, pavement age, chemical composition and properties of asphalt binder, mixture composition and its mechanical properties, and the quality of construction of pavement structure. Consideration of all these factors on the one hand would increase the accuracy and reliability of the analysis, but on the other hand would complicate or even make the analysis impossible. Nevertheless, data as pavement age, climatic conditions and structure are relatively easier to collect as compared to collection data on binders, asphalt mixtures and layers mechanical properties for particular road sections.

1.2. Objectives and scope

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

2. Field investigation

In many cases investigations of new road materials like HMAC are based on laboratory test results compared with data acquired from especially constructed trial sections e.g. [18,19] or compared with set of data after improvement of a specific element, like type of bitumen e.g. [20–23]. Such methods and their results, which are available in literature, have following limitations: the number of test section is very limited and located in one region, also the length of the sections is relatively short, trial test sections are constructed under strong supervision and high quality, most often deviating from the typical contract conditions, only single factors (like bitumen properties) are taken into account. Often, there are not available direct comparisons of high modulus asphalt concrete to conventional asphalt concrete.

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

A – the coldest – maximum depth of frost penetration equals h_z = 1,2 or 1,4 m, B – the medium – maximum depth of frost penetration equals $h_z = 1,0$ m,

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

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

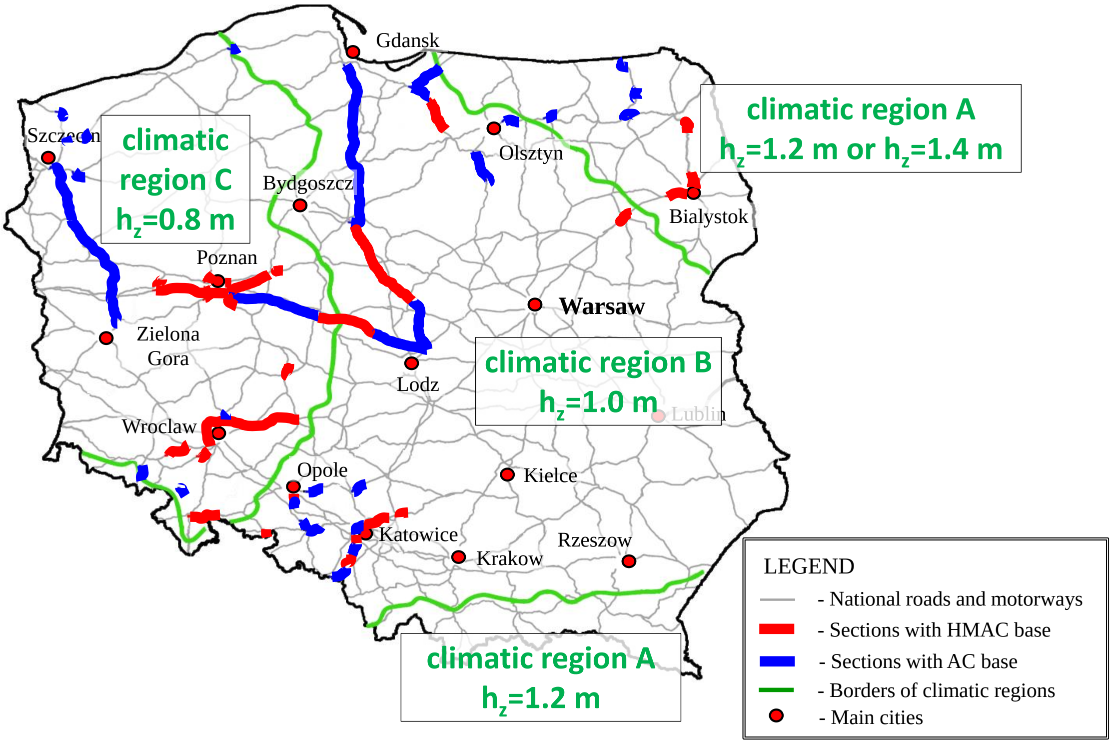

Figure 1. Localization of road sections included in the field investigation

The field investigation consisted of visual assessment of pavement distresses including cracks, ruts, roughness and surface condition and it was conducted in accordance with the Polish standardized method SOSN *Evaluation of pavement condition system* [24], supplemented if necessary by the *American Distress Identification Manual* [25]. The condition of the top of wearing course was observed and it was next rated in relation to what was the material used in the base course underneath, either HMAC or AC. However for the analysis presented in this article, solely information about low-temperature cracks is presented. Cracks which originated from other causes than low-temperature, like fatigue cracks or cracks which occurred near bridges, culverts, manholes etc. were excluded from the analysis. The low-temperature cracks were identify as single transverse cracks that were visible on the surface of each investigated section. The possibility of occurrence of reflective cracks from cement treated layers was excluded due to the fact that subbase layers directly under the asphalt layers were made from unbound aggregate.

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

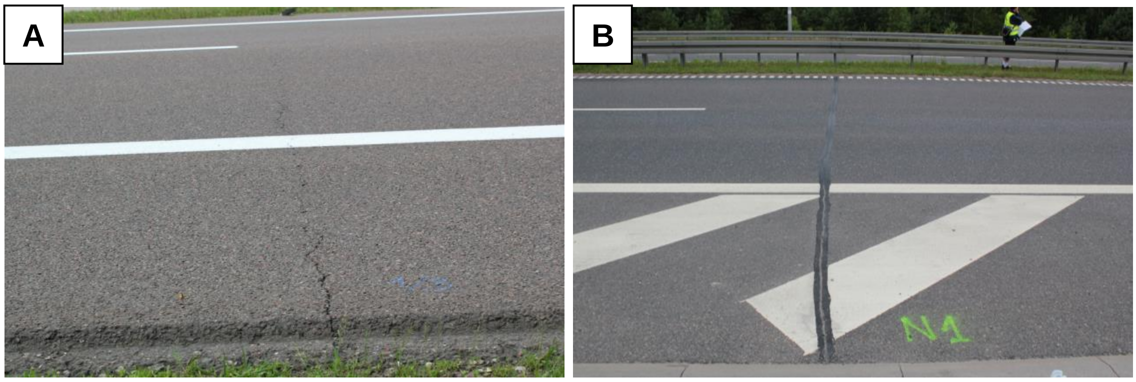

Figure 2. Examples of low-temperature cracks a) not repaired b) repaired

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

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

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

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

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 - 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

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

3. Selected results from field investigations

The field investigations were conducted during three consecutive years from 2012 to 2014. Results showed in Figures 3-5 and further statistical analysis are based on the investigations from 2014. The percentage of road sections classified into particular groups of cracks intensity, according to observations in 2014, are presented in the Figure 3. Figures 4 and 5 present effect of climatic region and pavement age, respectively. The results showed in Figures 3 – 5 indicate evident effect of the asphalt base type on the intensity of low-temperature cracks. Figure 6 shows the increase of cracked pavements with HMAC base courses in consecutive years of observations. Figures 3 – 6 show that number of low-temperature cracks is:

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

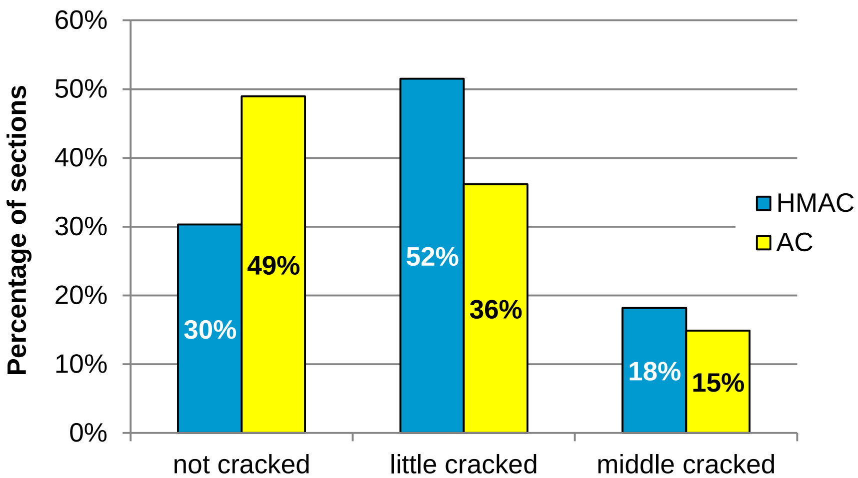

Figure 3. Percentage of sections with HMAC and AC pavement base courses in three groups of cracks intensity, according to observations in 2014

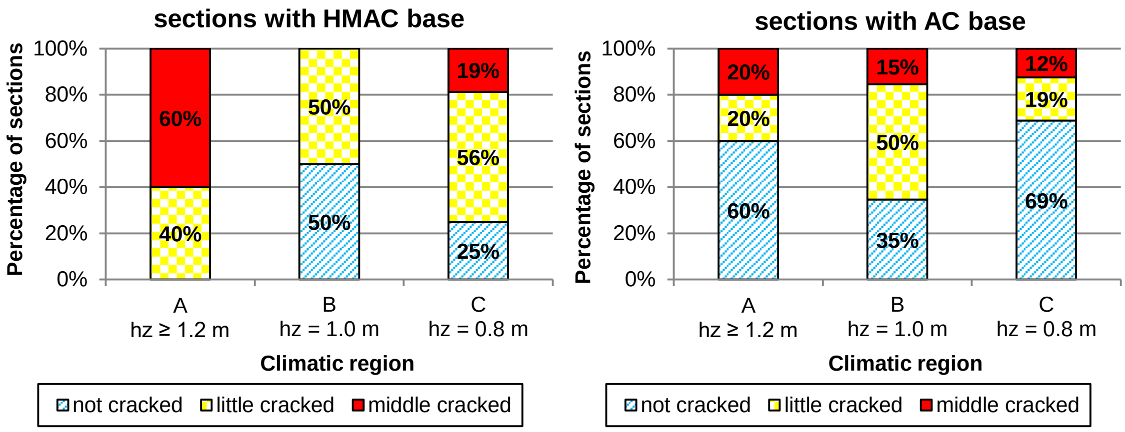

Figure 4. Intensity of cracking in pavements with HMAC and AC base courses in relation to depth of frost penetration (h_z) in regions A, B, and C in Poland (2014)

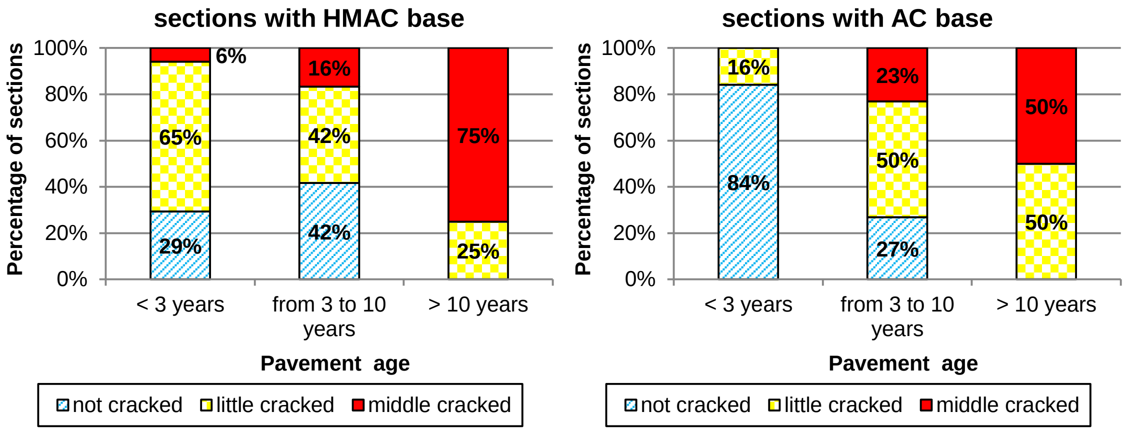

Figure 5. Intensity of cracking in pavements with HMAC and AC base courses in relation to age of pavements (2014)

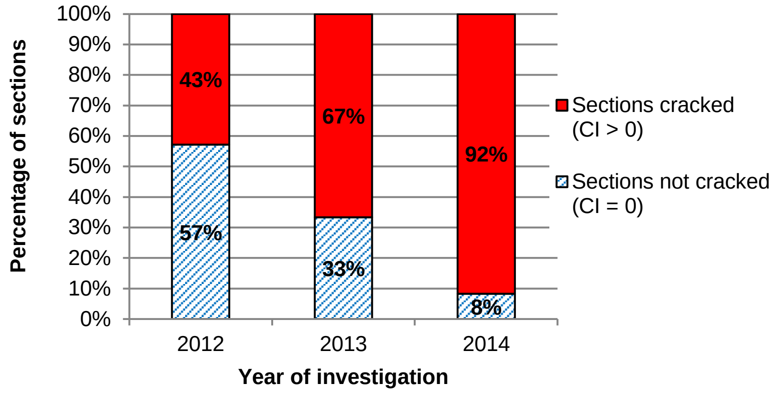

Figure 6. The increase of cracked pavements with HMAC base courses in consecutive years of observations

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

4.1. General data on used statistical method

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

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

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

where: Y – response (dependent) variable, $p(Y \le g)$ – the probability of a particular outcome, $p(Y > g)$ – the probability of the complement of a particular outcome, β_{0g}, β_1.., β_n – parameters of regression model, X_1, ..., X_n – dependent variables, g = 1,.. k-1.

4.2.Statistical model

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

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

In the analysed case, response variable Y represents a category of cracks intensity. The basis of classification is cracking index for a given road section obtained from field investigation. Each section was classified into one of k = 3 categories of cracks intensity, as it is presented in Table 3. Heavy cracked sections (Y = 4) did not occur on evaluated road sections thus they are not listed in Table 1 and were excluded from the further analysis.

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 ≤ 2
3	Middle cracked	2 < CI ≤ 10

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

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	

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

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

4.3.Interpretation of the statistical model

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

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

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

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

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	95% confidence interval 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

The following example illustrates how the odds ratios should be interpreted. Let us consider that the type of base expressed by variable X_1 changes from $X_1=0$ (AC base) to $X_1=1$ (HMAC base) the odds ratio is equal to 2.45 (see Table 4). Two groups of road sections: cracked (Y>1) and not cracked (Y=1) are compared. According to the formula (2) it can be stated that pavements with HMAC bases with 2.45 times higher odds will belong to the groups of cracked pavements than pavements with conventional AC bases. The remaining results of odds ratio should be interpreted as follows:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

5. Summary and conclusions

(1) The presented analysis was based on the field investigations carried out on 80 selected road sections in Poland, of total length of about 1 300 km. The sections were constructed under normal contract conditions and were in normal way used by traffic. The intensities of low-temperature cracking for pavements with high modulus asphalt concrete HMAC and conventional asphalt concrete AC base were determined and compared.

(2) In order to include several effects, such as base type - high modulus asphalt concrete HMAC as compared with conventional asphalt concrete AC, pavement

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

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

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

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

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

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