Validation of high modulus asphalt concrete for low temperature conditions

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During most of the 1990s and in the beginning of 2000s, rutting of asphalt pavements was one of the biggest problem on most roads in Poland. One of proposed solutions was introducing of High Modulus Asphalt Concrete, an asphalt mixture first developed in France and made on the basis of hard grade bitumen. Since the beginning the Polish climate, which is much colder than in France, was the major concern during introducing of this technology. This paper presents the short summary of the 4 - year study conducted at the Department of Highway Engineering of Gdansk University of Technology. The first part presents results of laboratory tests. Five different laboratory-made asphalt concretes were tested: three high modulus asphalt concretes (with neat, polymer modified and multigrade bitumen) and two conventional asphalt concretes (both with neat bitumen). The second part of the paper presents results of field investigation of 80 road sections constructed with both high modulus and conventional asphalt concretes. Based on transverse low-temperature cracks index, a probabilistic model was developed to assess the probability of thermal cracking occurrence. On the basis of the research program the authors had given recommendations for usage of High Modulus Asphalt Concrete in Polish climate conditions, which are presented as a conclusion of the paper.

Keywords: High Modulus Asphalt Concrete; low temperature properties; field investigation; low temperature cracking

Introduction

Statement of research problem

Usage of the High Modulus Asphalt Concrete (HMAC), a French asphalt mixture made on the basis of hard grade bitumen, was one of the solution to the extensively rutting of asphalt pavements which occurred in Poland in the 1990s and the beginning of the 2000s. Usage of the very hard grade bitumen, such as 10/15 pen. and 15/25 pen., resulted in increased stiffness modulus of a mix, thus higher rutting resistance and longer fatigue life of asphalt layers. It was the main reason why many countries started research programs concerning introduction of this technology for their specific climatic conditions. In Poland, since the first usage of HMAC technology in the year 2002, climatic considerations were one of the main concern. Especially when some of the research (Vervaecke and Vanelstraete, 2008) showed inferior behaviour of hard grade bitumen and HMAC mixes in lower temperatures on the basis of BBR and TSRST tests.. Nevertheless this technology was commonly used in the years of 2010-2012 for major network motorways in Poland. The use of hard grade neat bitumen ended in extensive cracking of newly constructed pavements which was described in details by Judycki et al. (2015, 2016). One of the solution to this problem was the proposition to use crump rubber and fibre additives to improve the mechanical properties of asphalt mixtures (Moreno-Navarro et al. (2014)). Presently, one of the promising solution to the problem of thermal cracking is to use the highly modified bitumens in HMAC mixtures.

The problem described in this paper was to evaluate the low-temperature properties of HMAC mixtures used in Poland in comparison to commonly used conventional AC asphalt concretes, and answer the question is it possible to use HMAC technology in Polish climatic conditions. This problem is important as the road administration still strongly encourages to use HMAC mixtures for asphalt pavements.

Scope of the research program

The research program issued by the General Directorate of Public Roads and Motorways comprised of three major parts: a) laboratory evaluation of low-temperature mechanical properties of both types of mixtures, both normalized and non-normalized, b) computational analyses of thermal stresses which may appear in the pavement during the decrease of the temperature, and c) field investigation of constructed pavements with HMAC and conventional AC mixes. In this paper only selected results of low-temperature performance are presented. The detailed results of this research program are presented in the research report by Judycki et al. (2014). Up till now the only normalized laboratory test to evaluate the low-temperature properties of asphalt mixtures in Poland were Fraas and TSRST tests. None of them gave the correct links with the field performance. It was big problem as up till year 2014 there were no major contributions to describe even the low temperature behaviour of HMAC mixtures. During the research program authors done some preliminary test for evaluation of low-temperature properties of HMAC mixes, like Fracture Tests with different notch depths or determination of Master Curves from long time creep tests in low temperatures (later used in calculation of thermal stresses), which gave promising results to implement as normalized tests for new mixtures, before they could be admitted for common use.

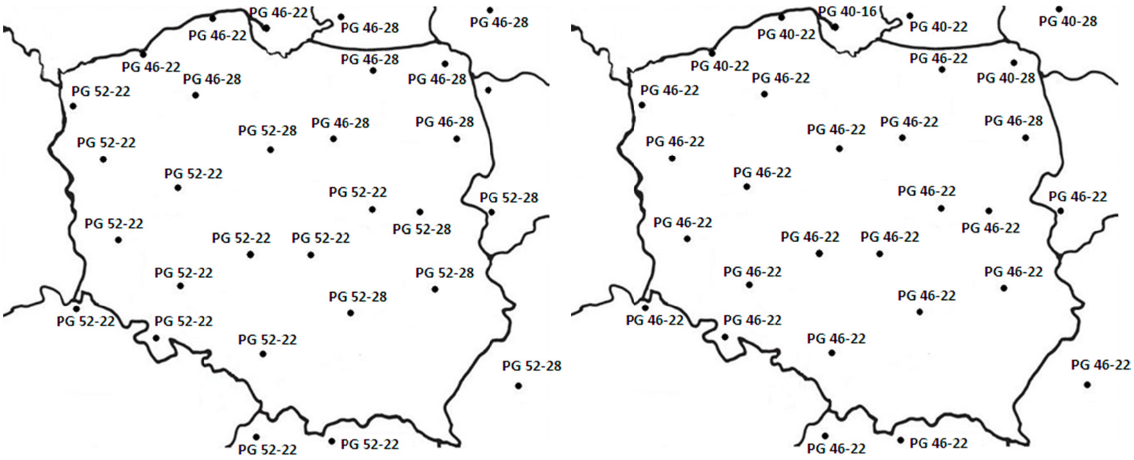
Polish climate conditions

Poland is located in temperate transitional climate zone in Europe. Its territory is crossed by air masses from both the Atlantic Ocean and the heart of the Eurasian landmass. The continental impact increases gradually with a move from the west to the east boundary of Poland. During the research project the following data from 18 meteorological stations located on national roads in Poland were collected: air temperature, road surface temperature, temperature 5 cm below the surface, hourly temperature gradient, period of time when temperature is lower than -10, -15 or -20°C. Analyzed data was recorded in the period from 2003 to 2013. It was determined that the lowest winter pavement temperature in the assessed period was equal to -24,2°C (26 January 2010, station Podborze located in the north-east part of Poland) and the longest period in which the surface temperature was continuously below -20°C lasted 18 hours.

The fastest recorded temperature drop in asphalt layers equaled to 3,1°C/h.

Determination of required Performance Grade (PG) for Polish climate conditions

According to the conducted survey in most cases only two types of bitumen were used in HMAC in Poland: neat 20/30 pen. and polymer-modified PmB 25/55-60. Rarely, at the early stage of HMAC application, bitumens modified with polyethylene and other additives which increased the stiffness of the bitumen. Studies made by Radziszewski et al. (2011) determined that Performance Grade (PG) for both bitumens 20/30 pen. and polymer-modified PmB 25/55-60 is PG 82-10. Performance Grades for binder and base courses were determined using SUPERPAVE method (1995) on the basis of the 30 years of temperature data from weather stations located in major cities in Poland. The data was collected from National Climatic Data Center (NCDC) servers. The analyses showed that the required Performance Grade for bitumen ranges from PG46-22 to PG52-28 for binder courses and from PG40-16 to PG46-28 for base courses (Figure 1). These values were determined with 98% level of confidence. Therefore, bitumens typically used in HMAC mixes are not appropriate, and evidently too hard for Polish climate conditions, what may increase the number of low-temperature cracks. But on the other hand, the analysis showed that commonly used neat bitumens in Poland (35/50 and 50/70 pen.) are also not sufficient to answer the climatic conditions.



(a) (b)

Figure 1. Required Performance Grade for: (a) binder course, (b) base course, confidence level: 98%

Laboratory investigation

Tested materials

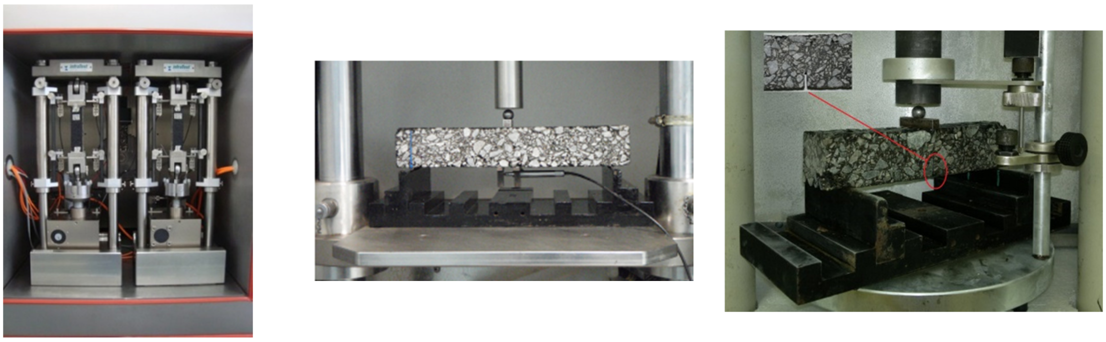
For the purpose of the research program five different mixtures were designed according to the Polish Technical Requirements (GDDKiA, 2012): three types of HMAC mixtures and two conventional AC mixtures. Basic information about tested mixtures are presented in Table 1.

Table 1. Properties of tested asphalt mixtures

Properties	High Modulus Asphalt Concretes (HMAC)			Conventional Asphalt Concretes (AC)	
Mix designation	HMAC 20/30	HMAC 25/55-60	HMAC 20/30 MG	AC 16W 35/50	AC 16W 50/70
Mix designed for	Binder and base courses	Binder and base courses	Binder and base courses	Binder course	Binder course
Type of binder	Neat 20/30 pen.	PmB 25/55-60	20/30 Multigrade	Neat 35/50 pen.	Neat 50/70 pen.
Binder content, % by wt.	5,0	5,0	5,0	4,6	4,6
Fraction passing 2 mm, %	32,0	32,0	32,0	27,4	27,4
Fraction passing 0.063 mm, %	7,3	7,3	7,3	5,5	5,5
Voids content, %	3,6	3,5	3,5	4,3	4,2
Voids filled in aggregate, %	76,9	77,3	77,3	71,8	72,4

Selected test methods and test results

Low-temperature laboratory tests comprised of both: normalized tests (according to PN-EN standards) and non-normalized tests developed in Gdansk University of Technology. This study presents only selected results of the following laboratory tests (Figure 2): Thermal Stress Restrained Specimen Test (TSRST), three point bending tests and fracture toughness test. For all presented laboratory test the specimen were cut using laboratory saw from 300x300x50 mm or 300x300x40 mm asphalt concretes plates compacted acc. To EN 13108-20 standard. Before the compaction all of the mixes were subjected to short term ageing according to AASHTO R30 standard.



(a) (b) (c)

Figure 2. Laboratory test used for low-temperature performance analysis (a) TSRST test (b) three point bending test (c) fracture toughness test

Thermal Stress Restrained Specimen Test (TSRST)

TSRST test was conducted according to PN-EN 12697-46 standard. For each of the tested mixtures three prismatic specimens (40x40x160mm) were prepared. The results of the TSRST test: the fracture temperature and thermal stresses induced at the temperature of -20°C and at the moment of specimen fracture, are presented in Figure 3.

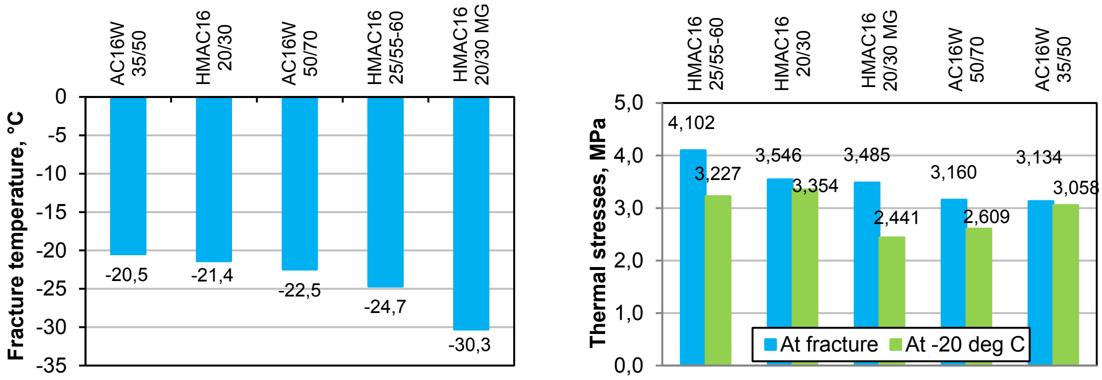


Figure 3. TSRST test results for tested

The lowest fracture temperature was measured for HMAC 20/30 pen. multigrade bitumen, while the highest fracture temperatures were measured for conventional AC 16W 35/50 and HMAC with 20/30 pen. neat bitumen. What was to expect the highest thermal stresses for measured at -20°C and at specimen fracture were developed for two HMAC mixtures – with 20/30 pen. neat and 25/55-60 PmB bitumen, due to hard grade of the used bitumens. But on the other hand, every HMAC mixture showed improved mechanical response, as their strength during fracture is from 10 up to 30% higher than for conventional AC. And for PmB mixture, even with greater developed thermal stresses it gives better performance in low temperatures. It is also worth to notice very good behaviour of the HMAC with 20/30 pen. multigrade bitumen. Even with very hard bitumen (20/30 pen.) it obtained the lowest fracture temperature and the lowest thermal stress induced at -20°C.

Bending tests

The three point bending tests used in this research program were developed by Judycki (1990) and improved by Pszczoła and Judycki (2009). Specimens in form of beams 50x50x300 mm were tested in two different loading conditions – with constant rate of deformation and with constant load (creep test). Bending tests with constant rate of deformation were conducted for the temperature range from 0°C up to -30°C. For each mixture ultimate strains, flexural strengths were determined. Creep bending tests were conducted at three temperatures: -20°C, -10°C and 0°C. On the basis of the creep tests stiffness master curves, Burgers rheological model parameters and relaxation times for each mixture were determined. Results of bending tests are presented in Figures 4 and 5. Exemplary Burgers model parameters determined on the basis of creep tests, at the temperature of -10°C, are presented in Table 2.

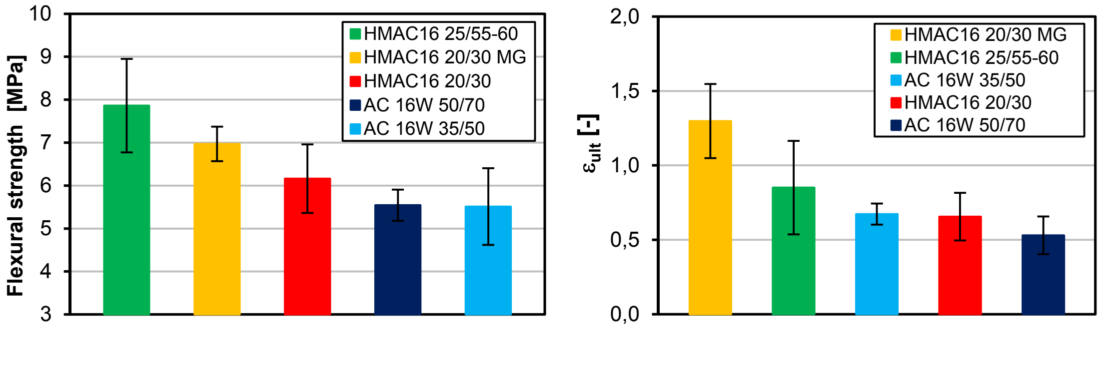


Figure 4. Flexural strength and ultimate strain ε_{ult} at -30°C

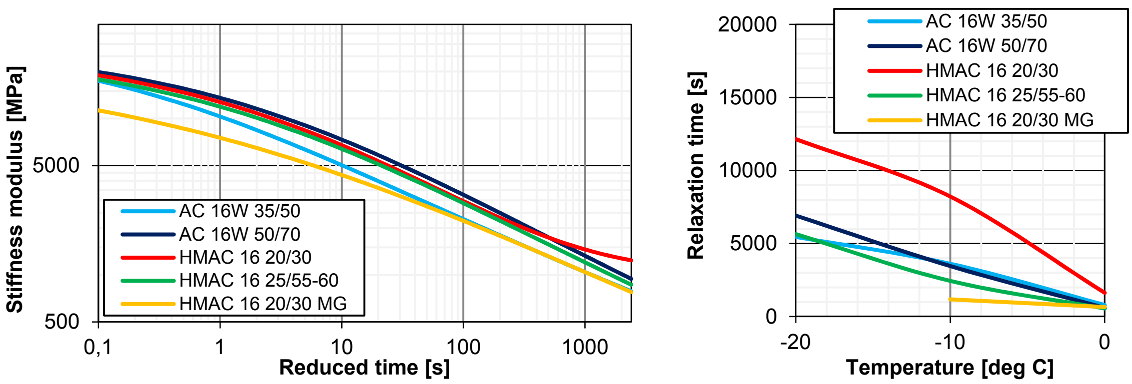


Figure 5. Master curves (T_{ref} = 0°C) and relaxation time obtained from creep test

Table 2. Parameters of Burgers rheological model at -10°C for tested mixtures

Type of mixture	Burger's model parameters			
	E_1 [MPa]	E_2 [MPa]	η_1 [MPa·s]	η_1 [MPa·s]
AC 16W 35/50	15 609	3 901	55 355 791	783 953
AC 16W 50/70	14 703	3 453	50 311 400	640 611
HMAC 20/30	16 338	4 437	128 667 390	1 000 705
HMAC 25/55-60	13 417	4 017	32 637 170	798 762
HMAC 20/30 MG	7 048	5 520	8 699 462	1 097 785

Presented test results showed very good low-temperature performance of HMAC mixtures with polymer modified and multigrade bitumens – the highest values of flexural strengths and ultimate strains at low temperatures (bending with constant rate of deformation test) and the lowest values of relaxation times, Burgers model parameters and stiffness modulus (creep test). The opposite situation was visible for HMAC mixture with 20/30 pen. neat bitumen. While its flexural strength was slightly higher than for conventional ACs, all other ratings indicated its poor low-temperature performance. As in the TSRST test, the performance of conventional ACs was between HMAC mixtures with neat 20/30 pen. bitumen and 25/55-60 PmB bitumen.

Fracture toughness test

The third selected method of assessing the resistance to low-temperature cracking was performed basing on the fracture mechanics theory. Fracture toughness was evaluated at the temperature of -10°C with the use of single edge notch beam. Test method was chosen based on literature review (Artamendi, Khalid (2006), Elseifi et al. (2012), Szydlowski, Judycki (2014)). The used displacement rate was 1 mm/min., as it was assumed, that this rate better describe the development of low-temperature cracking. The resistance of asphalt mixtures to fracture was measured with use of two parameters - K_{IC} and J_C-integral. The K_{IC} parameter was calculated from the maximum force recorded in the bending test. The J_C-integral was calculated from the energy induced in bending test up to the peak load and characterizes the critical strain energy release rate. Selected results of the Fracture Toughness test are presented in Figure 6.

High values of K_{IC} and J_C-integral indicate higher resistance to fracture. While values of K_{IC} did not change very significantly for all tested mixtures, the J_C-integral presented significant differences. The highest resistance to fracture was obtained for the

HMAC with 20/30 pen. multigrade bitumen, while HMAC with 20/30 pen. neat bitumen showed the worse low-temperature performance. Conventional ACs presented better performance than HMAC with 20/30 pen. neat bitumen.

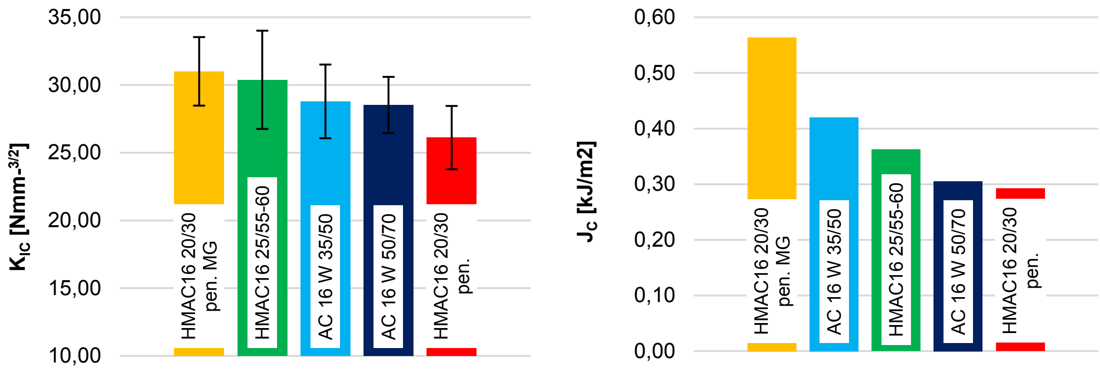


Figure 6. Results of the fracture toughness test – K_{IC} and J_C-integral (temp. -10°C)

Field investigation

The field investigation was conducted during three consecutive years (2012-2014) on 80 road sections: 33 constructed using HMAC and 47 constructed using conventional AC in binder and/or base courses. The selected road sections were localized in all climatic zones of Poland (Figure 7). Their age ranged from 1 to 12 years. All these sections were constructed under normal contract conditions and have been in normal service and maintenance. Each section was characterized by: location, type of road (provincial, national or motorway), climatic zone, pavement structure, pavement age, 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 provincial roads. 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 range from 1 km to 63 km.

The field investigation consisted of visual assessment of pavement distresses including cracks, ruts, roughness and surface condition and was conducted in accordance with the Polish standardized method SOSN (GDDKiA, 2002), supplemented if necessary by the American Distress Identification Manual (Miller, Bellinger (2003)). The low-temperature cracks were counted and characterized by the cracking index CI - the average number of low-temperature cracks per one kilometer. For further analysis following four cracking intensity categories were used: not cracked (CI = 0), little cracked (0 < CI ≤ 2), middle cracked (2 < CI ≤ 10) and heavy cracked (CI > 10). Detailed methodology of field investigation, data analysis and complete results were described in details by Judycki et al (2014) and Ryś et al. (2017).

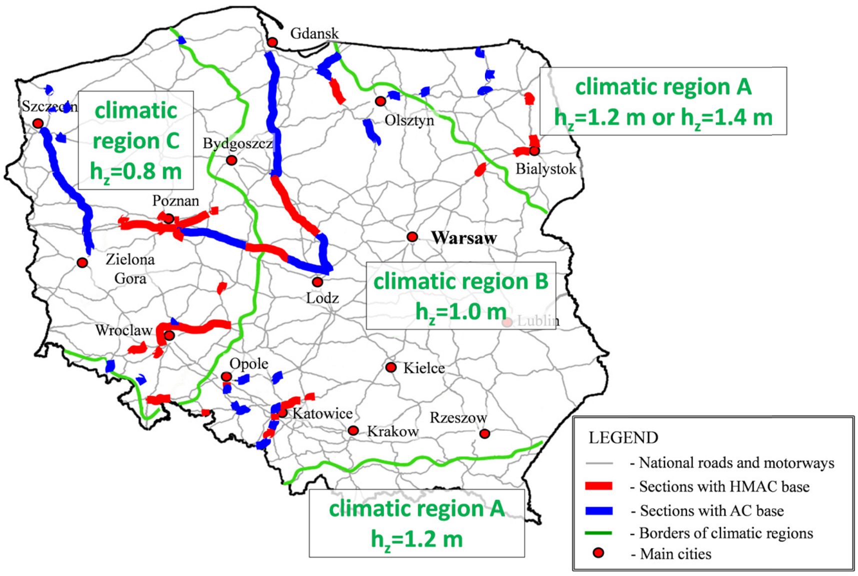


Figure 7. Localization of road sections included in the field investigation, h_z stands for depth of frost penetration; climatic zones : A – coldest, B – middle and C - warmest

Results showed in Figures from 8 to10 are based mostly on the investigations from 2014, with the exception of right chart of the Figure 8, which presents the increase of the cracked sections with HMAC in consecutive years of field investigation. The number of not cracked sections in the both charts slightly differs, as for the left chart only sections assessed for three consecutive years were taken into consideration (sections under construction in 2012 or assessed only in 2014 were excluded in this case). Figures 9 and 10 present effect of climatic region and pavement age, respectively.

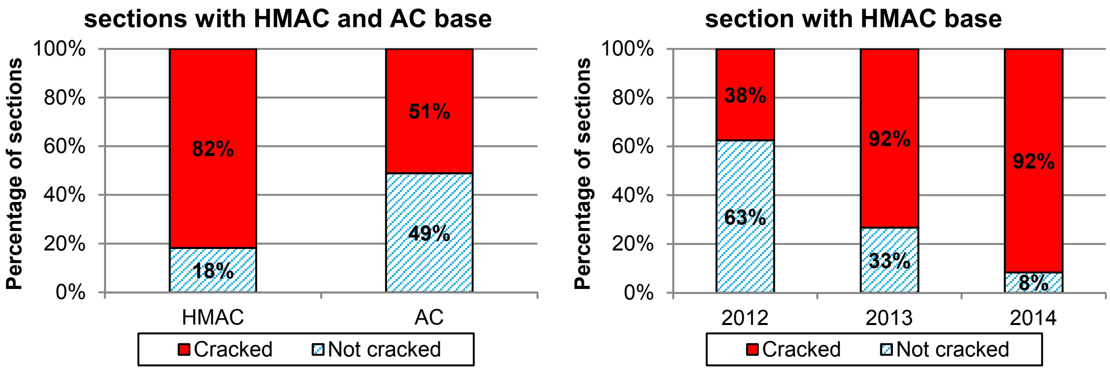


Figure 8. Percentage of cracked sections with HMAC and AC pavement base courses according to observations in 2014 (left chart); The increase of cracked pavements with HMAC base courses in consecutive years (2012-2014) of observations (right chart)

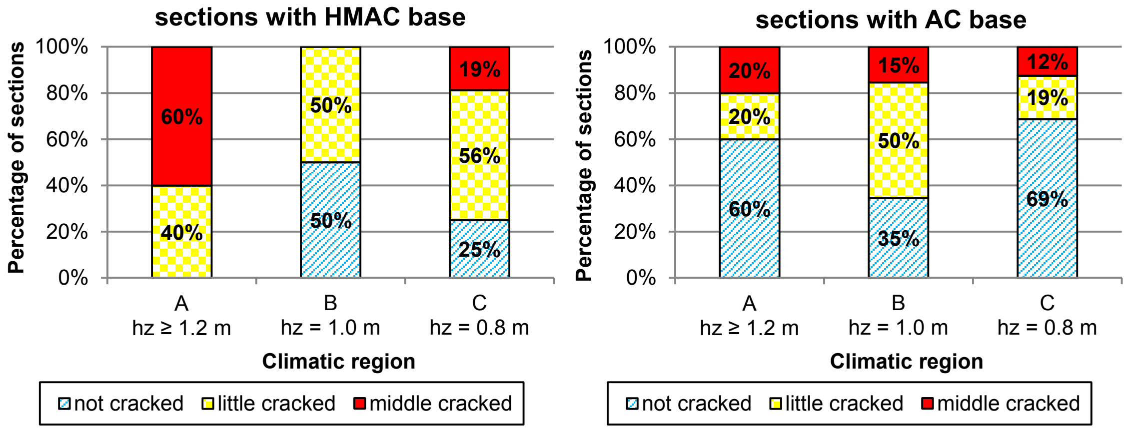


Figure 9. The intensity of low-temperature cracking in pavements with HMAC and AC base courses in relation to depth of frost penetration (h_z) (acc. to observation from 2014)

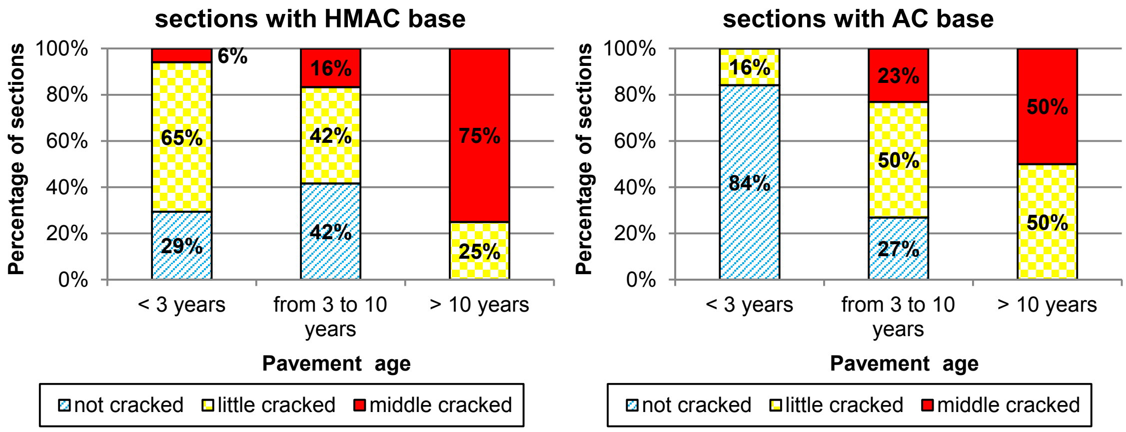


Figure 10. Intensity of cracking in pavements with HMAC and AC base courses in relation to age of pavements (acc. to observation from 2014)

Presented results indicate evident effect of the asphalt base type on the intensity of low-temperature cracking. The number of low-temperature cracks was higher for HMAC in comparison with conventional AC, higher in colder regions, higher for older pavements and increased in consecutive years of observation. What was interesting, also on sections with HMAC mixture with PmB bitumen (which were in this study included in all HMAC sections), the cracks appeared more often than on section with conventional AC, what is on the contrary to the laboratory test results. On the basis of the field investigation results from 2014, statistical model for assessment of risk of cracking was developed. Its creation and detailed results are presented in separate article (Ryś et al. (2016)). The model indicated 2,5 times greater odds that the pavements with HMAC will crack at low temperature as compared with conventional AC mixtures, all other factors being the same.

Analysis of the results

Laboratory tests of susceptibility of HMAC mixtures to low-temperature cracking were the most work consuming and the extensive part of the conducted research. Five different test methods were used for assessment. Up till now, none of the used method is commonly accepted for assessment of low-temperature performance. Even if there are standards, as for the TSRST test, only test methodology is described, without any quantitative requirements for low-temperature susceptibility assessment. Nevertheless on the basis of conducted laboratory tests it can be stated that:

- The lowest resistance to low temperature cracking was shown by HMAC with 20/30 pen. neat bitumen. This mixture presented the worst or the second worst results in all conducted laboratory tests.

- The highest resistance to low-temperature cracking was shown by HMAC with 20/30 pen. multigrade bitumen. While multigrade bitumen presented very good performance in all conducted tests, in Poland it is produced in very limited amount and it was never used for HMAC layers in field conditions. Before its admittance for wide practical usage, long term test sections should be constructed and assessed with special attention.
- HMAC with 25/55-60 PmB bitumen, depending on the conducted test method, obtained the second or the third best resistance to low-temperature cracking. It could be assumed, that utilizing polymer modified bitumen in HMAC instead of neat hard grade bitumen, can result in lower risk of low-temperature cracking.

Obtained results from all conducted tests are with agreement with the results of relaxation times determined in bending creep test. The longest relaxation times at lower temperatures indicates that the highest thermal stresses will be induced for the HMAC with 20/30 pen. neat bitumen.

Also the used test methods should be assessed taking into account their credibility for assessment of low-temperature performance of asphalt mixes and asphalt layers. According to the authors the most credible is bending creep test developed and successfully used at the Gdansk University of Technology. Its results, including rheological properties, allow to grade the performance of the tested mixtures and can be used in more sophisticated analyses, such as calculations of thermal stresses induced by cooling. Fracture toughness test gave promising results, but it was its first usage in Poland and it still needs further improvement and correlations with field results. The TSRST test is now standardized and widely used but still has two disadvantages. Firstly, its cooling condition - the rate of cooling of 10^{o}C/h is unrealistic and several times greater than extreme rate of cooling occurring in field. Secondly, the TSRST test standards does not specify any conditions for evaluation of a mix low-temperature performance.

On the field sections with HMAC low-temperature cracks were observed more often and with higher intensity in comparison to the sections with conventional ACs. On more than 80% of sections with HMAC low-temperature cracks were observed, regardless of pavement age and climatic zone, whereas only on 52% of field section with conventional AC low-temperature cracks appeared. Also the age of pavement and climatic zone had strong impact on intensity of cracking. The highest number of non-cracked sections was observed in the group of the newest sections localized in the warmest zone of Poland, regardless of used type of asphalt mixtures. Created statistical logistic model showed that a road section with HMAC has 2,5 times higher odds to be classified as a cracked section, than a road section with conventional AC. It also confirmed that the risk of cracking increase with the increase of the pavement age and decrease of the mean temperature of the climatic zone.

Conclusions and recommendations

After conducting wide range of laboratory tests, computational analyses and field investigations the authors prepared the following list of short conclusions and recommendations regarding the usage of HMAC for Polish climatic conditions:

(1) The usage of 20/30 pen. neat bitumen in HMAC binder and base courses should be put on hold, regardless of the climatic zone, due to very high risk of low-temperature cracking.

(2) For heavily trafficked road sections, with high probability of rutting – i.e. slow-traffic lanes, high slopes, parking lots for heavy vehicles, it is possible to use HMAC with polymer modified / multigrade bitumen, but it is not recommended.

In that case, due to minimization of low-temperature cracking, HMAC with 25/55-60 PmB bitumen or 20/30 pen. multigrade bitumen can be used for the binder course and se conventional asphalt mixtures should be used for the remaining asphalt courses, as their resistance to rutting is sufficient. But it is recommended to use either cement concrete pavement or pavement with all asphalt layers made from conventional asphalt concretes.

(3) For all other cases, not mentioned in the second point, the usage of HMAC should be put on hold. Even with the usage of polymer modified or multigrade bitumen the risk of low-temperature cracking will be not eliminated. In the long run, after long-term ageing, the stiffness of the HMAC layers will significantly increase, due to the hard grade of the used bitumen. It is recommended to use conventional asphalt mixtures with the usage of the softer bitumen chosen on the basis of climatic conditions. Nevertheless, special attention must be put to the resistance to permanent deformation of all mixtures.

(4) SUPERPAVE specification for bitumen should be implemented taking into consideration Polish climatic conditions. Up till now, they are still used only as informational.

(5) Field investigation of road sections constructed with the usage of HMAC should be continued, to assess the long-time performance, especially in the case of polymer modified and multigrade bitumen, as up till now there are only single road sections were constructed using these bitumen.

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