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Evaluation of low temperature properties of rubberized asphalt mixtures

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Abstract

The paper presents low-temperature test results of asphalt mixtures designed with use of bitumen modified by crumb rubber and also SBS polymer. Laboratory tests were conducted on two types of asphalt mixtures for wearing course – stone matrix asphalt (SMA 8) and porous asphalt (PA 8). This paper presents results of the following laboratory tests at low temperatures: TSRST test, three point bending creep test, fracture toughness test and assessment of physical hardening. It was found that test results of asphalt mixtures with use of polymer-rubber modified bitumen showed high resistance to low temperature cracking in all tests conducted. In some cases use of polymer-rubber modified bitumen even increased resistance to low temperature cracking in comparison with standard SBS polymer modified bitumen. The additional advantage is that usage of crumb rubber allows to reduce the amount of added polymers with respect to the standard SBS polymer modified bitumen.

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Keywords: crumb rubber modification; polymer-rubber modified bitumen; low temperature tests; TSRST test; three point bending test; fracture toughness test; physical hardening.

1. Introduction

The use of tyre rubber in asphalt mixtures has started to be popular in 1960’s as a result of its elastic properties which had the potential to improve skid resistance, durability and resistance to low temperature cracking of asphalt

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mixtures. The additional benefit of rubber-modification in asphalt mixtures was using recycled waste tires. The crumb rubber has been used to modify asphalt mixtures mainly by employing two different processing methods, as described by Presti [1]. The first method is the "wet process", whereby crumb rubber is blended with hot bitumen to produce a rubberized bitumen binder. The second method is the "dry process" where the course rubber particles are added to the asphalt mixture as an aggregate. Both of the described methods usually take place in plant site during production process of asphalt mixture. It is also possible to use at the same time the crumb rubber and polymer such as SBS copolymer during one process of binder modification, (Król et al. [2]). The new bitumen modified by SBS copolymer and crumb rubber (CR) was developed in Gdańsk refinery. The process of production of polymer–rubber modified bitumen at the refinery was described by Świeczko-Żurek et al. [3]. New polymer-rubber modified bitumen 45/80-55 CR fulfils all requirements set for polymer SBS modified bitumen PmB 45/80-55 according to the European Standard PN-EN 14023. The main advantage is that usage of crumb rubber allows to reduce the amount of added polymers with respect to the standard polymer modified bitumen.

Low temperature cracking starts at the surface of asphalt pavement and progresses down with time, as a result of low winter temperatures and drop of ambient temperature. Asphalt pavements are subjected to high cooling rates and low temperatures action. As a result tensile stresses develop in asphalt layer due to its shrinkage. When these thermal stresses exceed the fracture strength of the asphalt pavement layer, transverse thermal cracking develops. Several studies have investigated the low-temperatures properties of binders and asphalt mixtures with the use of crumb rubber modified bitumen (Ghavibazoo and Abdelrahman [4]; Troy, Sebaaly and Epps [5]; Sebaaly, Gopal and Epps [6]; but the effects of crumb rubber modification were highly dependent on the bitumen source and type. Studies have shown that stiffness $S(t,T)$ of bitumen and as a result also of the asphalt mixture will decrease because of the lower stiffness of the rubber at low temperatures (up to -20°C).

This paper presents the low-temperature performance of asphalt mixtures made with the use of bitumen modified with both SBS polymer and crumb rubber. Obtained results were compared with the performance of mixtures made with the use of bitumen modified only with SBS polymer. The low-temperature tests were conducted at the Gdansk University of Technology by Judycki et al. [7] within a framework of greater research program sponsored by one of the leading Polish refineries.

2. Materials

Laboratory tests were conducted on two types of asphalt mixtures for wearing course – stone matrix asphalt (SMA 8) and porous asphalt (PA 8). Aggregate skeleton was designed in compliance with Polish Technical Guidelines WT-2 2010 [8]. For each type of mixture one optimum bitumen content was selected based on laboratory tests results for typical SBS modified bitumen. The composition of mixtures and type of used bitumen are presented in Table 1.

Table 1. Composition of tested asphalt mixtures.

		Type of Mixture			
Property		SMA8	SMA8 CR	PA8	PA8 CR
Aggregate	Passes # [mm]				
	11,2	100		100	
	8	94,2		91,2	
	5,6	41,2		13,4	
	2	25,6		6,7	
	0,125	11,9		4,8	
	0,063	9,7		4,1	
	type of aggregate	gneiss, granodiorite and limestone		gneiss, granodiorite and limestone	
Bitumen	optimum content [%]	7,0		6,5	
	type of bitumen	45/80-55 PmB	45/80-55 CR	45/80-65 PmB	45/80-65 CR

Four types of bitumens were selected for low-temperature tests: two polymer-rubber modified bitumens: 45/80-55 CR, 45/80-65 CR and as reference two SBS polymer modified bitumens: 45/80-55 and 45/80-65. Standard properties of bitumens used in this research are shown in Table 2.

Before specimen compaction, every type of asphalt mixture was subjected to the short-time ageing according to AASHTO R30-02 standard specification.

Table 2. Standard properties of bitumen according to PN-EN 14023 standard for SBS polymer modified bitumen.

Property	Type of bitumen			
	45/80-55 PmB	45/80-55 CR	45/80-65 PmB	45/80-65 CR
Penetration in 25°C, 0,1 mm, acc. PN-EN 1426	43	53	52	45
R&B Temperature, °C, acc. PN-EN 1427	60	55	72	76
Dynamic viscosity, Pa·s, acc. PN-EN 12596				
90°C	35,321	19,058	43,728	81,833
135°C	1,225	0,859	1,813	1,947
160°C	0,373	0,303	0,596	0,563

3. Methods of research

Low-temperature laboratory tests were the main part of the whole research and comprised both normalized tests (according to PN-EN standards or technical requirements) and non-normalized tests developed or improved in Gdansk University of Technology. This study presents results of the following laboratory tests:

- TSRST, according to PN-EN 12697-46,
- Three point bending creep test,
- Fracture toughness test,
- And assessment of physical hardening process.

Each of the laboratory test was conducted for all four asphalt mixtures: SMA8, SMA8 CR, PA8 and PA8 CR. Conducted test are presented on figure 1 and their procedures are described in details in subsections below.

(a) (b) (c)

Fig. 1. Laboratory test used for the purpose of low-temperature performance analysis (a) TSRST test (b) three point bending test (c) fracture toughness test.

TSRST test

TSRST test was conducted according to PN-EN 12697-46 (2012) standard. For each of the tested mixtures three beam specimens (40x40x160mm) were prepared. Each specimen was placed in test frame and after a conditioning period was subjected to temperature gradient of 10°C per hour. Test starts at a temperature of +20°C and ends after cracking of the specimen. During the whole test, thermal stress inducted into asphaltic beam is measured. Apart from continuous values of thermal stresses the main results of the TSRST test are: critical temperature at which the specimen was destroyed and maximum induced thermal stress.

Bending test

The three point bending test used in laboratory tests was developed by Judycki [9,10] and improved by Pszczoła and Judycki [11]. Later it was adapted to run in Nottingham Asphalt Tester. The bending test consisted of 2 phases: in the first phase beams were subjected to constant static load for a time of 2400 seconds; in the second phase beams were left unloaded for a time of 1200 seconds . The applied load depended on the temperature in which the test was conducted and type of mixture (SMA or PA) tested. Load values were assigned as 20% to 30% of the flexural strength. For all beams the test temperatures were -20°C, -10°C and 0°C. For the basic three point bending test specimens were conditioned in selected temperature for the time of 4 hours before the test. The strain at the bottom of the specimen was measured with a LVDT sensor. In each temperature 3 beams (size 50×50×300 mm) of each mixture were tested.

Fracture toughness test

The second method of assessing the resistance to low temperature cracking was performed basing on the fracture mechanics theory. Fracture toughness was evaluated with the use of semi-circular bending test performed according to standard PN-EN 12697-44. The original test methodology described by the standard PN-EN 12697-44 was modified basing on literature review (Li, Marasteanu [12], Elseifi et al. [13], Szydlowski, Judycki [14]). Standard method included in standard PN-EN 12697-44 is based on determining the resistance of asphalt mixtures to fracture K_{IC}, which is calculated on the basis of maximum force recorded during bending of the specimen. For further classification of mixtures in terms of fracture properties, an additional value of the J-integral was measured, which characterizes the critical strain energy release rate.

The semi-circular specimen was subjected to vertical load applied at constant rate by laboratory press. The specimen was supported by metal frame that allowed to obtain three-point bending load configuration. During the test, load and vertical displacement were continuously recorded. The displacement rate was 1 mm/min. Specimen and loading frame during the test were placed in thermostatic chamber of the press to maintain constant desired test temperature of -20°C.

On the basis of the value of maximum load recorded at the corresponding vertical displacement critical stress intensity factor, K_{IC} was calculated. Strain energy to failure was calculated as the area under the graph F(d) and from the analysis of the graph that illustrate relationship between deformation energy and depth of the notch. From the graph of the function U(a) equations of linear regression were determined in which the slope of the function is the derivative dU/da - the change of strain energy with the change of notch depth.

Physical hardening investigation

Physical hardening is one of many important aspects which influence thermal cracking of asphalt mixtures. It was found (Blokker, Van Hoorn [15], Struik [16], Anderson et al. [17]) that during maintaining constant low temperature the stiffness modulus of tested asphalt specimen increases with the duration of conditioning period. The same behavior was also found for some asphalt mixtures under short time of loading (Hesp et al. [18], Baglieri et al. [19], Judycki [20]), especially in the case of SMA mixtures. One of the part of presented research program was to investigate if the same behavior is also visible in the case of long time loading. For this purpose authors had chosen three point bending creep test. Used methodology was almost the same as presented in point 3.2. To measure the change of stiffness moduli in long time creep, additional beams were prepared from the same batch. Conditioning of specimen differed in the aspect of the period of time for which the specimens were subjected to the temperature of the test. In basic test period of time was equal to 4 hours. In extended test for the purpose of physical hardening the period of time was extended to 120 hours.

4. Test results

Results of TSRST test are presented in table 3. As it could be seen the results obtained both in group of SMA8 mixtures and PA8 mixtures are similar for typical SBS modified bitumen and CR modified bitumen. The difference in both of fracture temperature and maximum thermal stresses are similar to the tolerances of the TSRST test for the single test. In the case of SMA8 mixture, the CR modified bitumen was slightly better. The opposite situation was obtained for the PA8 mixture in which the SBS modified mixture was slightly better.

Table 3. Results of TSRST test.

Mix type	Fracture temperature		Maximum thermal stress at the moment of fracture	
	Mean [°C]	St.dev. [°C]	Mean [MPa]	St.dev. [MPa]
SMA8 45/80-55 CR	-27,8	1,29	3,890	0,240
SMA8 45/80-55	-25,8	1,36	3,917	0,565
PA8 45/80-65 CR	-29,1	0,79	1,205	0,040
PA8 45/80-65	-31,4	0,50	1,165	0,062

Three-point bending test results are presented in two different approaches: as a master curve of mean values of stiffness modulus (presented in the Fig. 2.) and as a Burgers rheological model parameters (presented in table 4). As for the PA8 mixtures, in both approaches, both CR modified and SBS modified bitumen obtained results were very similar. Some differences are visible in the viscosity parameters of Burgers model in the temperature of -20°C. But it should be taken into account that, in the case of PA8 mixture with SBS modified bitumen, part of the viscosity results were rejected. It was caused by very small flow during the test, and as a result in very high rejected values of viscosity.

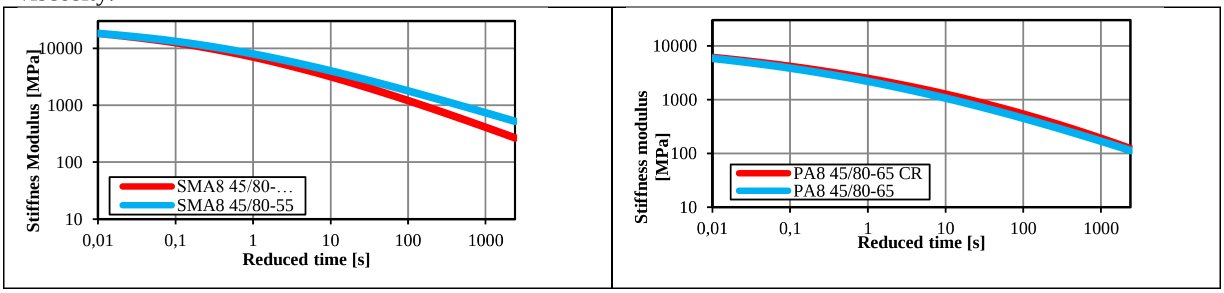

Fig. 2. Master curves of tested asphalt mixtures developed on the basis of three point bending creep test, reference temperature 0°C.

Table 4. Mean values of Burger's model parameters.

Temp. [°C]	Burger's model parameters	SMA8		PA8	
		45/80-55 CR	45/80-55	45/80-65 CR	45/80-65
0	E_1 [MPa]	5 714	5 802	2 281	2 000
	E_2 [MPa]	767	1 364	329	328
	η_1 [MPa·s]	1 032 619	2 393 693	538 905	447 603
	η_2 [MPa·s]	166 533	271 244	68 390	63 438
-10	E_1 [MPa]	11 325	10 943	3 373	3 079
	E_2 [MPa]	1 833	3 185	829	527
	η_1 [MPa·s]	12 536 969	16 302 694	2 871 632	2 660 394
	η_2 [MPa·s]	406 449	559 783	130 071	117 390
-20	E_1 [MPa]	15 583	17 771	3 911	4 505
	E_2 [MPa]	5 917	6 300	941	1 852
	η_1 [MPa·s]	76 181 403*	243 163 549	13 012 448*	109 779 649
	η_2 [MPa·s]	1 422 685	1 719 587	317 827	857 877

* test results without creep or with large deviations from mean value were omitted.

In the case of SMA8 mixture, differences are visible in the case of higher temperatures. As it is visible in figure 2, mixture with CR modified bitumen shows lower stiffness moduli for reduced time from 10 to 2400 second. In the case of lower temperatures (-10°C and -20°C) mixtures with both bitumen showed similar behaviour. But taking into account Burgers model parameters, SMA8 mixture with CR modified bitumen showed slightly better low temperature performance – lower or similar stiffness moduli and lower viscosities.

Figure 3 presents relationship between strain energy $U(a)$ and notch depth. Equations of linear regression that were used to calculate the value of the integral J_C are also presented.

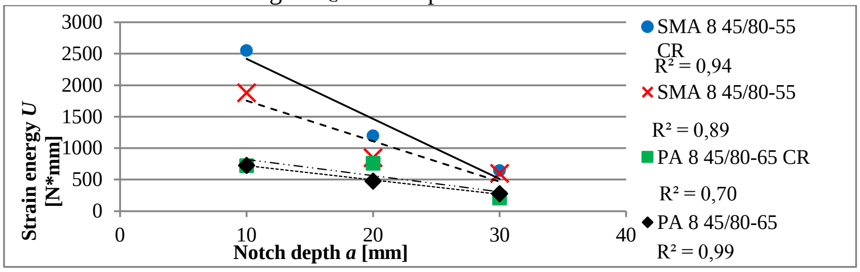

Fig. 3. Relationship between strain energy and the notch depth.

Summary of the test results of fracture toughness are shown in Table 5 and Figure 4.

Table 5. The results of fracture toughness test at -20°C, the average values from four specimens.

Type of asphalt mixture	a [mm]	F_{max} [N]	U [N*mm]	σ_0, [N/mm^2]	K_{IC}, [N*mm$^{-3/2}$]	dU/da, [N]	J_C, [kJ/m^2]
	10	10696	2550.4	1.4	38.2		
SMA 8 45/80-55 CR	20	7942	1198.9	1.1	40.9	-95.23	1.90
	30	5138	645.7	0.7	35.6		
	10	10870	1882.4	1.4	38.8		
SMA 8 45/80-55	20	7110	851.6	0.9	36.6	-64.19	1.28
	30	5264	598.6	0.7	36.5		
	10	4795	723.5	0.6	17.1		
PA 8 45/80-65 CR	20	2800	440.4	0.4	14.4	-25.67	0.51
	30	1701	210.2	0.2	11.8		
	10	5220	728.7	0.7	18.6		
PA 8 45/80-65	20	2968	479.6	0.4	15.3	-22.58	0.45
	30	1517	277.2	0.2	10.5		

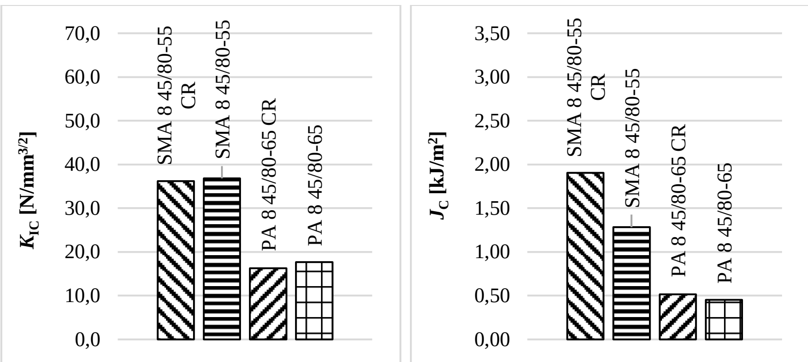

Fig. 4. Fracture toughness K_{IC} (average of three notch depth) and J-integral of investigated asphalt mixes.

Figure 5 presents example results of physical hardening phenomenon investigation. Obtained results didn't show strait correlations. Only mixture SMA8 with SBS modified bitumen presented even increase of stiffness modulus in all test temperatures – about 20-30% increase of stiffness modulus in comparison to 4h of conditioning. In the case of PA8 mixture with SBS modified bitumen, the increase of stiffness modulus was visible in temperatures of 0 and -10°C. In -20°C results were similar for both times of conditioning.

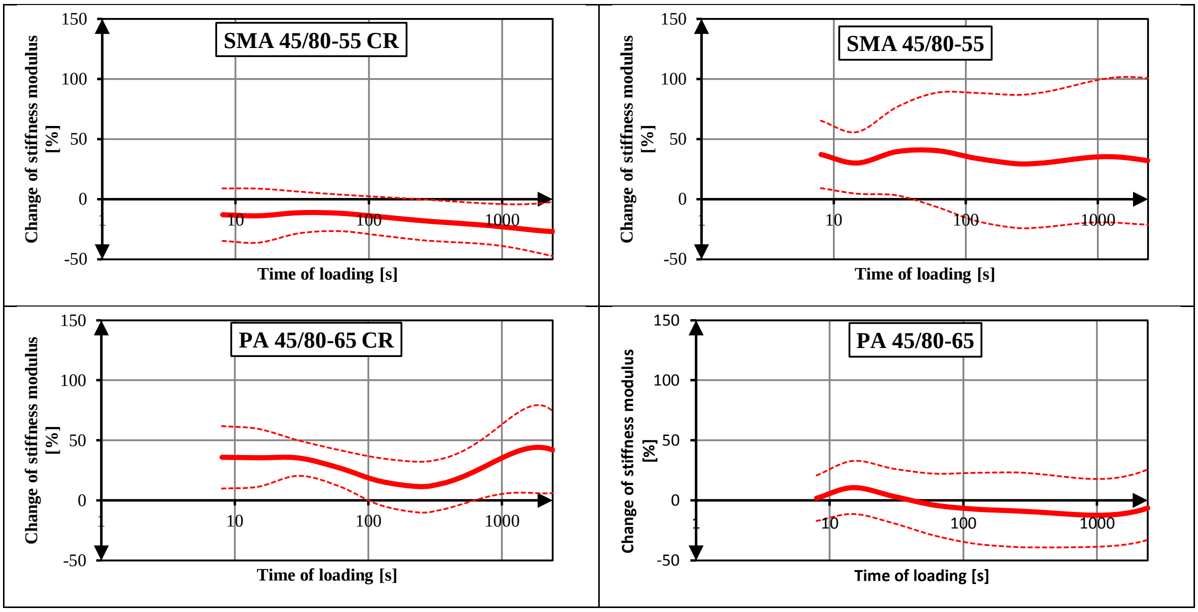

Fig. 5. Change of stiffness modulus in three point bending creep test, after 120h of conditioning in temperature -20°C.

In the case of mixtures with CR modified bitumen, results obtained from three point bending test varied. Only in one temperature (-20°C for PA8 mixture and -10°C for SMA8 mixture) physical hardening was visible – results showed from 20 to 40% increase in stiffness modulus. In remaining temperatures both mixtures presented from 10 to 20% decrease in stiffness modulus.

5. Conclusions

Presented test results for SMA8 and PA8 mixtures with SBS and CR modified bitumen allows to form following conclusions:

1. New polymer-rubber modified bitumen 45/80-55 CR fulfils all requirements set for polymer SBS modified bitumen PmB 45/80-55 according to the European Standard PN-EN 14023. The main advantage is that use of crumb rubber allows to reduce the amount of added polymers with respect to the standard polymer modified bitumen.
2. Mixtures made with the usage of CR modified bitumen and typical SBS modified bitumen presented similar test results in all conducted test results. Small differences are visible only in the case of SMA8 mixture for single results (J_C-integral of fracture toughness test and results of three point bending test in temperature 0°C).
3. TSRST test results showed high resistance to low temperature cracking in the case of PA8 mixtures (-31°C) and average resistance to low temperature cracking in the case of SMA8 mixtures (-25°C). Both types of bitumen presented similar performance for each type of asphalt mixture.

4. Master curves obtained from three point bending creep test showed similar results for PA8 mixtures with both type of bitumen. In the case of SMA8 mixtures, slightly better performance in higher temperatures presented mixture with typical SBS modified bitumen.
5. Burgers model parameters obtained from three point bending creep test were similar for PA8 mixtures with both types of bitumen. In the case of SMA8 mixture, better results were obtained for the mixture with CR modified bitumen.
6. Fracture toughness test showed similar results for both type of bitumen. Only difference is visible in J-integral for SMA8 mixtures - CR modified bitumen showed slightly better performance.
7. Only for SMA8 mixture with SBS modified bitumen showed visible results of physical hardening phenomenon. Results obtained for the rest of specimen were varied – in most cases mixtures with CR modified bitumen showed decrease of stiffness modulus in 2 of 3 test temperatures. Physical hardening phenomenon for long time load needs further investigation.

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