Binder performance and testing

First step to the development of performance based criteria for bitumen resistance to low temperature cracking

Judita Gražulytė, Audrius Vaitkus
Road Research Institute, Vilnius Gediminas technical university, Vilnius, Lithuania

Abstract

The existing standardized method for the determination of bitumen behaviour at low (negative) temperatures is based on bitumen prismatic beam bending – bending beam rheometer (BBR). However, BBR very often underestimates the performance of modified bitumens and needs approximately 15 g of bitumen for one specimen what may become a concern evaluating recovered and aged bitumens. A dynamic shear rheometer test with 4 mm parallel plates (4-mm DSR), introduced by Western Research Institute (WRI) in 2015, seems superior to other bitumen tests and methods dedicated to bitumen behaviour at low temperatures. However, WRI proposed limiting criteria for bitumen resistance to low temperature cracking (relaxation modulus (G) and apparent relaxation rate (mr) at a specific loading time of 60 s) are based on the BBR limits, which often fails in evaluating bitumen resistance to low temperature cracking. In addition, existing high precision DSRs allow direct measurements of relaxation modulus. Therefore, this paper focuses on the algorithm for the development of performance based criteria that appropriately evaluate bitumen resistance to low temperature cracking. Furthermore, first results – the severity of low temperature cracking in 26 road sections and lowest asphalt surface temperatures determined on the basis of nearest road weather stations – are given in this paper.

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1. INTRODUCTION

Low temperature cracking is one of the most significant distresses in asphalt pavements. It appears when upon cooling the thermal stresses exceed the tensile strength of material. Typically, these cracks form in the transverse direction across the road and lead to a faster pavement deterioration and a lower driving comfort. Consequently, road administrations seek to prevent asphalt pavements from low temperature cracking and incorporate specific requirements for bitumen to ensure a long pavement lifetime.

Many tests and methods have been developed to evaluate bitumen performance at low temperatures in order to prevent asphalt pavements from low temperature cracking. However, they have one or more disadvantages, e.g. do not reveal actual bitumen behaviour at low temperatures, have low repeatability and reproducibility, hard to apply to recovered bitumen, are suitable only for virgin bitumen, results strongly depend on the specimen geometry and are highly affected by physical hardening and etc. [1]. Bending beam rheometer (BBR) test is the most popular standardised method (EN 14771, AASHTO T 313 and ASTM D6648) to evaluate bitumen behaviour at low temperatures (from 0 °C to −30 °C). Two limiting criteria, the flexural creep stiffness (S) and the change of this stiffness over loading time (m-value) at a specific loading time of 60 s, are used to determine the critical cracking temperature, i.e. the lowest temperature at which bitumen withstands induced thermal stresses. BBR was developed within the Strategic Highway Research Program at the end of 20th century [2], [3]. At that time, only virgin bitumens were used and thus modified bitumens were not incorporated in the test programme. Consequently, BBR criteria, S and m-value, often underestimate the performance of modified bitumens [4]–[6]. The other drawback of BBR is that the amount of bitumen needed to test its behaviour may become a concern evaluating recovered and aged bitumens. According to BBR procedure, at least four specimens (each of them needs approximately 15 g of bitumen) have to be tested in order to determine the critical cracking temperature.

A dynamic shear rheometer with 4 mm parallel plates (4-mm DSR), which was proposed by Western Research Institute in 2015, seems superior to other bitumen tests and methods dedicated to determining bitumen rheological properties at low temperatures [7]–[12]. The main principal of 4-mm DSR is based on using a sample with very small diameter (4 mm) to measure storage modulus (G'(ω)) at low temperatures (from 0 °C to -30 °C) which is later mathematically converted to relaxation modulus (G(t)). Two limiting criteria, relaxation modulus (G) and its slope (m_r) at a specific loading time of 60 s, have been developed on the basis of BBR criteria, flexural creep stiffness and m-value. Western Research Institute showed a strong correlation between 4-mm DSR and BBR limiting criteria [7] and it was proved by other research [13]. However, not all researchers have found such good comparisons between BBR and DSR data [9], [14]. It was revealed that relaxation modulus calculated by 4-mm DSR results lead to lower critical cracking temperatures than flexural creep stiffness measured by BBR and sometimes the difference between those two test methods may be more than 10 °C [9].

A road network without or at least minimal number of low temperature cracks can be achieved only if reliable and performance based criteria for bitumen resistance to low temperature cracking are developed. For this purpose, the asphalt pavements performance regarding low temperature cracking and the properties of binders used to produce those asphalt mixtures have to be analysed. The experimental programme should also involve the analysis of modified bitumens. Nowadays existing high precision DSRs allow direct measurements of relaxation modulus, thus relaxation test at low temperatures with 4-mm DSR should be considered as a prime test for the evaluation of bitumen behaviour at low temperatures.

The main objective of this paper is to give an algorithm for the development of performance based criteria that appropriately evaluate bitumen resistance to low temperature cracking. In addition, severity of low temperature cracking in 26 road sections and the lowest temperatures measured in the nearest road weather stations at surface of asphalt pavements are discussed.

2. ALGORITHM FOR THE DEVELOPMENT OF PERFORMANCE BASED CRITERIA

To determine performance based criteria for bitumen resistance to low temperature cracking is vital to analyse actual bitumen properties depending on the severity of low temperature cracking. Taking this as well as 4-mm DSR test advantages over BBR test and the possibility of measuring relaxation modulus directly with DSR into consideration, an algorithm for the development of performance based criteria that appropriately evaluate bitumen resistance to low temperature cracking was created and is given in Figure 1.

The algorithm consists of three stages. In the first stage, the severity of low temperature cracking is identified. A representative number of road sections with different performance and pavement age has to be selected. In addition, the possibility to confuse low temperature cracks with reflection cracks has to be eliminated. Thus, only newly constructed road sections as well as rehabilitated ones (those in which all asphalt layers have been replaced) may be involved in the analysis.

In the second stage, the lowest asphalt surface temperature to which pavement was exposed for each analysed road section is determined. From the perspective of low temperature cracking this temperature leads to failure, i.e. development of low temperature cracks. The lowest surface temperature of asphalt pavement in a specific site may be determined from the analysis of asphalt surface temperatures measured in the nearest road weather stations (RWSs). However, the distance and different climate conditions between site and RWS have to be evaluated.

In the third stage, asphalt pavement cores are drilled from all analysed road sections to recover bitumen. If pavement suffers from low temperature cracking, cores are taken close to this crack. In addition, bitumen is recovered only from the top 15 mm of cores. These aspects allow to reveal bitumen properties at the crack and assess faster bitumen oxidation, which occurs at the upper part of the pavement. The recovered bitumen from each road section is tested at a specific critical temperature by relaxation test with 4 mm DSR. Test temperature is selected according to results from the second algorithm stage. Measured relaxation modulus and its slope at a specific loading time of 60 s are then compared to the severity of low temperature cracking which was identified in the first algorithm stage. From those comparisons, performance based criteria for bitumen resistance to low temperature cracking are determined.

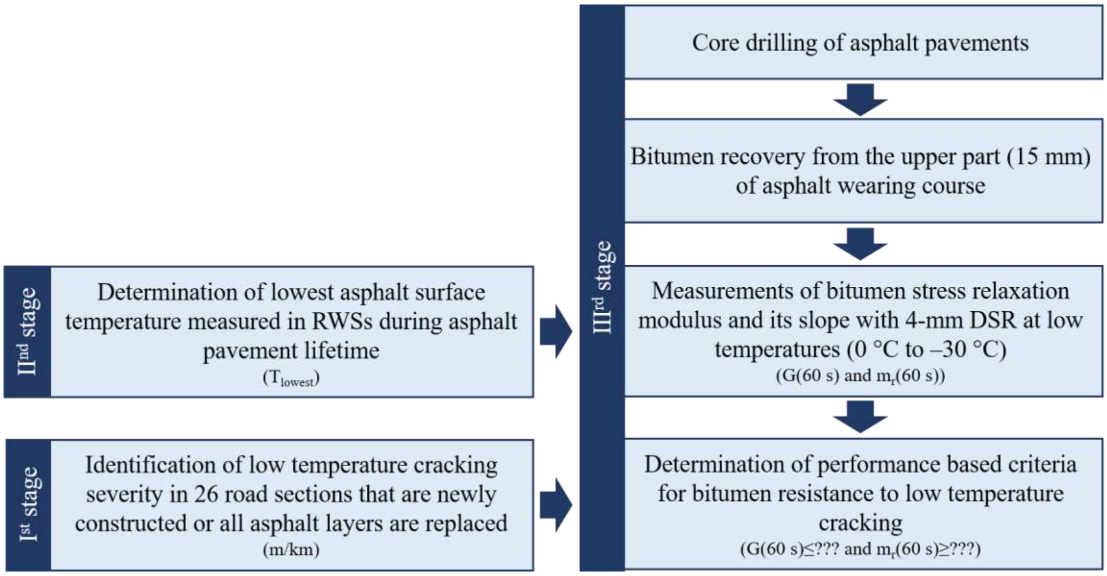

Figure 1: Algorithm for the development of performance based criteria for bitumen resistance to low temperature cracking

3. EXPERIMENTAL RESEARCH

An experimental plan to determine the performance based criteria for bitumen resistance to low temperature cracking was created on the basis of algorithm given in the second section. 26 newly constructed or rehabilitated road sections in Lithuania were selected for the analysis and testing. In the selected rehabilitated road sections all asphalt layers had to be replaced. It eliminated the possibility to confuse low temperature cracks with reflection cracks, which are formed in the old asphalt layers and progressively reflects in the newly constructed asphalt layers. Road sections were selected according to:

- road significance (it was sought that national significance main and national roads would be involved in the analysis);
- severity of low temperature cracking (it was sought that road sections suffering from low temperature cracking and without this type of cracking would be involved in the analysis);
- pavement age (it was sought that pavement age would not be more than 12 years);
- bitumen type used to produce asphalt mixture for wearing course (it was sought that different bitumens (especially polymer modified bitumens) would be involved in the analysis);
- geographical location (it was sought that at least in the three road sections the maximum frost depth would be higher than 1.5 m).

All selected road sections are given in Figure 2 and Table 1. Each selected road section was indexed by number from 1 to 26.

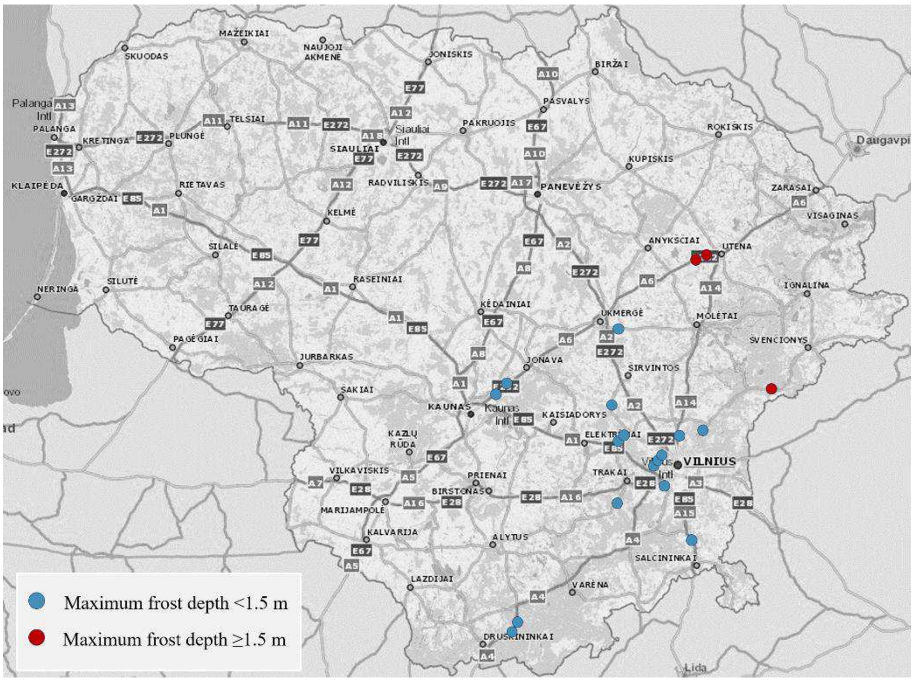

Figure 2: Selected road sections for experimental research

Table 1. In the experimental research analysed road sections

Index of road section	Road No.	Road section, km		Section length, km	Direction[1)]	Construction/ rehabilitation year	Asphalt mixture of wearing course	Bitumen
		start	end					
1	A15	30.30	40.42	10.12	L+R	2012	SMA 11 S	PMB 48/80-55
2	A6	19.00	24.00	5.00	R	2011	SMA 11 S	PMB 45/80-55
3	A6	48.00	50.00	2.00	L+R	2010	SMA 11 S	PMB 45/80-55
4[2)]	A6	137.35	142.00	4.65	L+R	2010	SMA 11 S	PMB 45/80-55
5[2)]	A6	142.00	149.00	7.00	L+R	2015	SMA 11 S	PMB 45/80-55
6	A4	113.00	116.00	3.00	L+R	2007	AC 11 VS	PMB 45/80-55
7	A4	117.00	122.00	5.00	L+R	2006	AC 11 VS	70/100
8	A14	11.00	16.00	5.00	L	2009	SMA 11 S	PMB 45/80-55
9	A14	11.00	16.00	5.00	R	2009	SMA 11 S	PMB 45/80-55
10	102	16.20	21.82	5.62	L	2016	SMA 11/8 S	PMB 45/80-55
11	102	16.20	21.82	5.62	R	2016	SMA 11/8 S	PMB 45/80-55
12[2)]	102	56.00	59.00	3.00	L+R	2009	SMA 11 S	PMB 45/80-55
13	108	1.00	6.00	5.00	L+R	2017	SMA 8 S	PMB 45/80-55
14	108	6.00	10.00	4.00	L+R	2008	SMA 8 S	PMB 45/80-55
15	108	29.00	33.00	4.00	L+R	2017	SMA 11 S	PMB 45/80-55
16	116	17.00	20.00	3.00	L+R	2007	SMA TM 0/8	PMB 45/80-55
17	220	13.38	15.70	2.32	L+R	2012	AC 11 VN	70/100
18	115	2.43	4.00	1.57	L+R	2017	SMA 8 N	PMB 45/80-55
19	Vilnius western bypass. 1st phase				L	2011	SMA 11 S	PMB 45/80-55
20	Vilnius western bypass. 1st phase				R	2011	SMA 11 S	PMB 45/80-55
21	Vilnius western bypass. 2nd phase				L	2013	SMA 11 S	PMB 45/80-55
22	Vilnius western bypass. 2nd phase				R	2013	SMA 11 S	PMB 45/80-55
23	Vilnius western bypass. 3rd phase				L	2016	SMA 11 S	PMB 45/80-55
24	Vilnius western bypass. 3rd phase				R	2016	SMA 11 S	PMB 45/80-55
25	A19	1.00	7.00	6.00	L+R	2013	SMA 11 S	PMB 45/80-55
26	A19	1.00	7.00	6.00	L+R	2013	SMA 11 S	PMB 45/80-55

Notes: [1)] L – left side of the road; R – right side of the road;
[2)] Road sections, in which maximum frost depth ≥1.5 m

This paper provides the results from the first and second stages of algorithm given in the second section and focuses on the identification of low temperature cracking severity in 26 representative road sections and the lowest asphalt surface temperatures measured during those asphalt pavements lifetime.

3.1. Identification of low temperature cracking severity

Severity of low temperature cracking in the selected road sections was determined in spring 2018 by conducting visual assessment. All cracks that were in the transverse direction across the road and at least 0.15 m in length as well as at least 1 mm in width were assumed as low temperature cracks (Figure 3). Cracks that appeared because of inadequate joint sealing were not counted. The length of each low temperature crack was recorded. In the analysis the low temperature cracking severity in each road section was expressed as m/km assuming road width equal to 9 m.

Figure 3: Low temperature cracking

3.2. Determination of lowest surface temperature of asphalt pavements

Road weather stations (RWSs) are installed adjacent to the roads at specific locations and provide real-time, accurate and local-specific data (Figure 4). RWSs measure asphalt surface temperature with DST111 remote surface temperature sensor every 15 min. The sensor is installed at 5.0–5.5 m height and the average measuring distance is 10 m. According to the manufacturer, DST111 is superior to conventional infrared sensors since has a unique correction of the error caused by the emissivity of the road surface, negating the need for emissivity adjustment. Currently, more than 100 RWSs are installed in Lithuania. It covers the whole area and provides representative results. As a result, the lowest surface temperature of asphalt pavement that each analysed road section suffered was determined from the analysis of asphalt surface temperatures measured in the nearest road weather stations (RWSs).

To reveal more accurate results, in most cases 2–3 RWSs that are less than 50 km away from the specific road section were selected for the analysis. At all, data recorded from 2006 to 2018 in 13 RWSs were analysed. The lowest asphalt surface temperature measured during each winter in each RWS was determined. Finally, the lowest (crucial) asphalt surface temperature that each analysed road section suffered was established from those data.

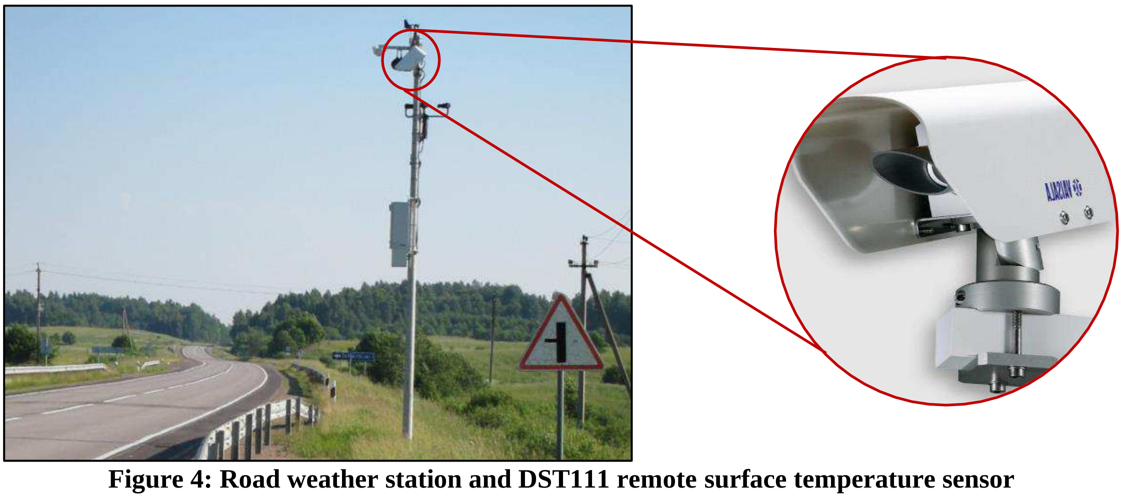

Figure 4: Road weather station and DST111 remote surface temperature sensor

4. RESULTS AND DISCUSSION

4.1. Severity of low temperature cracking

Determined severity of low temperature cracking in the selected 26 road sections is given in Table 2. 9th section, which was constructed / reconstructed in 2009, revealed the highest severity of low temperature cracking (28.4 m/km), while 10 road sections in age from 1 year to 7 years (1st, 2nd, 10th, 11th, 13th, 15th, 18th, 21st, 22nd and 24th section) perform without low temperature cracks.

Table 2. Severity of low temperature cracking in spring 2018

Index of road section	Construction / rehabilitation year	Pavement age	Asphalt mixture of wearing course	Bitumen	Severity of low temperature cracking, m/km
1	2012	6	SMA 11 S	PMB 45/80-55	0.0
2	2011	7	SMA 11 S	PMB 45/80-55	0.0
3	2010	8	SMA 11 S	PMB 45/80-55	4.5
4[1)]	2010	8	SMA 11 S	PMB 45/80-55	9.7
5[1)]	2015	3	SMA 11 S	PMB 45/80-55	3.5
6	2007	11	AC 11 VS	PMB 45/80-55	15.0
7	2006	12	AC 11 VS	70/100	6.3
8	2009	9	SMA 11 S	PMB 45/80-55	18.9
9	2009	9	SMA 11 S	PMB 45/80-55	28.4
10	2016	2	SMA 11/8 S	PMB 45/80-55	0.0
11	2016	2	SMA 11/8 S	PMB 45/80-55	0.0
12[1)]	2009	9	SMA 11 S	PMB 45/80-55	20.3
13	2017	1	SMA 8 S	PMB 45/80-55	0.0
14	2008	10	SMA 8 S	PMB 45/80-55	13.5
15	2017	1	SMA 11 S	PMB 45/80-55	0.0
16	2007	11	SMA TM 0/8	PMB 45/80-55	22.5
17	2012	6	AC 11 VN	70/100	11.6
18	2017	1	SMA 8 S	PMB 45/80-55	0.0
19	2011	7	SMA 11 S	PMB 45/80-55	21.2
20	2011	7	SMA 11 S	PMB 45/80-55	21.2
21	2013	5	SMA 11 S	PMB 45/80-55	0.0
22	2013	5	SMA 11 S	PMB 45/80-55	0.0
23	2016	2	SMA 11 S	PMB 45/80-55	2.0
24	2016	2	SMA 11 S	PMB 45/80-55	0.0
25	2013	5	SMA 11 S	PMB 45/80-55	1.5
26	2013	5	SMA 11 S	PMB 45/80-55	0.8

Notes: [1)] Road sections, in which maximum frost depth ≥1.5 m

Figure 5 shows a comparison between the severity of low temperature cracking and the pavement age. All analysed road sections are resistant to low temperature cracking or severity is lower than 3.5 m/km during first five years. However, from the 6th years pavement performance may change. For example, 2nd and 20th sections are the same age (7 years), but perform differently: 2nd section after 7 years is still resistant to low temperature cracking, while in 20th section the severity of low temperature cracking is 21.2 m/km. It should be noted that in 17 of 26 analysed road sections the severity of low temperature cracking was lower than 10 m/km independently of pavement age.

Dependency of low temperature cracking severity on asphalt mixture and bitumen was also analysed. However, any correlation or tendency was not observed between them. In addition, any effect of maximum frost depth higher than 1.5 m on low temperature cracking was not revealed.

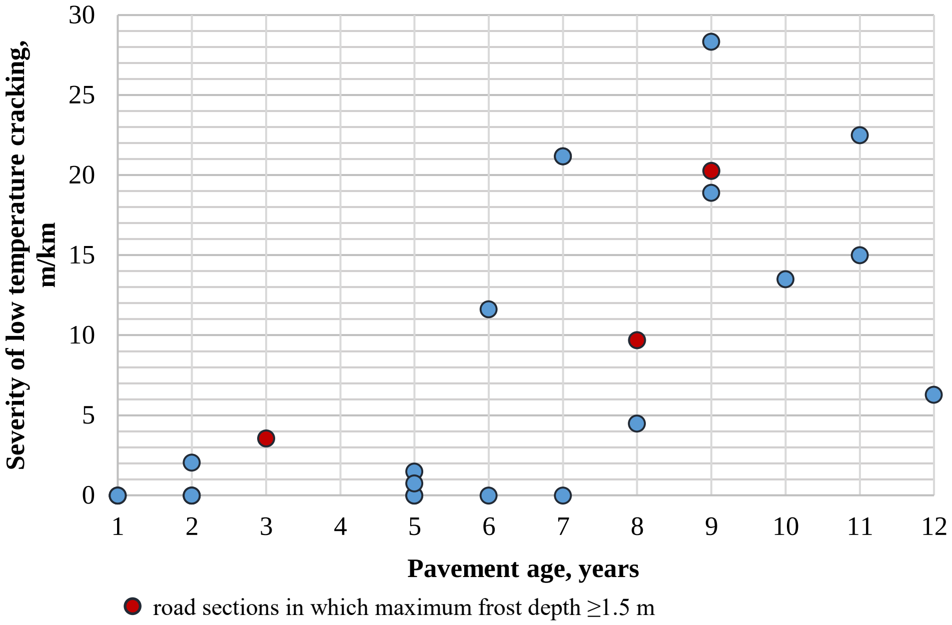

Figure 5: Severity of low temperature cracking depending on the pavement age

4.2. The lowest surface temperature of asphalt pavements

Determined the lowest surface temperatures of asphalt pavements in the selected 26 road sections are given in Table 3. 12th section was exposed to the lowest surface temperature (–25.6 °) among analysed road sections in 2011–2012 winter, while the highest one (–15.6 °C) was recorded in 18th section in 2017–2018 winter. Analysis of lowest surface temperatures of asphalt pavements and winters, when those temperatures were recorded, showed that 2011–2012 winter was the severest. 11 of 12 sections (91.7%), which were operated in 2011–2012 winter, experienced the lowest surface temperature in this winter. In 3rd section, which was constructed / rehabilitated in 2010, the lowest surface temperature (–18.3 °C) was determined in 2015–2016 winter. This may be caused by errors in measuring asphalt surface temperature in RWS "Pageležiai", which is the nearest RWS, in 2010–2012 winter.

Table 3. The lowest surface temperature of asphalt pavement

Index of road section	Construction / rehabilitation year	RWS		The lowest surface temperature of asphalt pavement, °C	Winter, when the lowest surface temperature was recorded
		No.	title		
1	2012	386	Tartokas	–21.4	2013–2014
2	2011	682	Rumšiškės	–23.4	2011–2012
3	2010	1241	Pageležiai	–18.3	2015–2016
4[1)]	2010	408	Svėdasai	–21.8	2011–2012
5[1)]	2015	1125	Daugailiai	–17.5	2016–2017
6	2007	105	Druskininkai	–23.2	2011–2012
7	2006	105	Druskininkai	–23.2	2011–2012
8	2009	101	Bukiškės	–25.0	2011–2012
9	2009	101	Bukiškės	–25.0	2011–2012
10	2016	1101	Bukiškės	–19.3	2016–2017
11	2016	1101	Bukiškės	–19.3	2016–2017
12[1)]	2009	136	Pabradė	–25.6	2011–2012
13	2017	308	Vievis	–17.0	2017–2018
14	2008	141	Maišiagala	–24.1	2011–2012
15	2017	1132	Maišiagala	–16.7	2017–2018
16	2007	141	Maišiagala	–24.1	2011–2012
17	2012	2481	Gudeliai	–20.5	2016–2017
18	2017	1135	Ukmergė	–15.6	2017–2018
19	2011	681	Vilnius	–24.1	2011–2012
20	2011	681	Vilnius	–24.1	2011–2012
21	2013	4021	Galvė	–21.6	2016–2017
22	2013	4021	Galvė	–21.6	2016–2017

23	2016	1101	Bukiškės	–19.3	2016–2017
24	2016	1101	Bukiškės	–19.3	2016–2017
25	2013	4021	Galvė	–21.6	2016–2017
26	2013	4021	Galvė	–21.6	2016–2017

Notes: [1)] Road sections, in which maximum frost depth ≥1.5 m

Figure 6 shows a comparison between the severity of low temperature cracking and the lowest surface temperature of asphalt pavements determined on the basis of the nearest RWSs data. An analysis of those data showed that in all cases at asphalt surface temperatures lower than –23.4 °C the severity of low temperature cracking is higher than 13 m/km. However, if asphalt surface temperature is up to –20.5 °C, asphalt pavements are either resistant to low temperature cracking or severity is minimal (lower than 4.5 m/km).

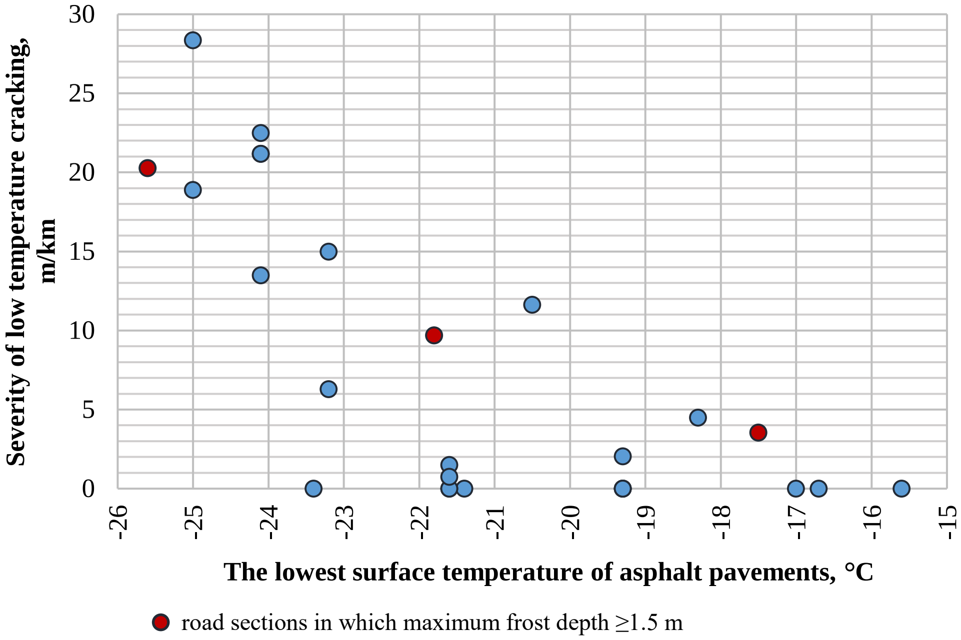

Figure 6: Severity of low temperature cracking depending on the lowest surface temperature of asphalt pavements

5. CONCLUSIONS

Low temperature cracking in asphalt pavements can be solved or at least minimized by using performance based criteria. In this paper an algorithm for the development of performance based criteria for bitumen resistance to low temperature cracking was created. Identification of low temperature cracking severity, determination of the lowest surface temperature of asphalt pavements, core drilling, bitumen recovery (from the top 15 mm of asphalt layer) and testing with 4–mm DSR are crucial steps in the development of these criteria.

Experimental research showed that asphalt pavements are resistant to low temperature cracking during first five years. Otherwise, only some cracks (3.5 m/km) may appear. While from the 6^{th} years pavement performance may significantly change and severity of low temperature cracking may reach more than 25 m/km. This may be influenced that winters during first five years were milder than in 6^{th} years. It is worth mentioning that any correlation between severity of low temperature cracking and asphalt mixture type, bitumen type and maximum frost depth was not revealed.

An analysis of asphalt surface temperatures recorded in 13 road weather stations from 2006 to 2018 showed that 2011–2012 winter was the severest and led to the lowest surface temperature of asphalt pavements in 91.7% analysed road sections that operated in 2011–2012 winter.

Dependency of low temperature cracking severity on the lowest surface temperature of asphalt pavements in 26 road sections revealed that in all cases asphalt surface temperatures lower than –23.4 °C are critical and lead to severity of low temperature cracking of 13 m/km and higher. However, at asphalt surface temperatures up to –20.5 °C, asphalt pavements are either resistant to low temperature cracking or severity is minimal (lower than 4.5 m/km).

The implemented first and second stages of created algorithm is the first step to the development of performance based criteria for bitumen resistance to low temperature cracking. Further, asphalt pavement cores will be taken and recovered bitumen will be tested at specific low temperatures by relaxation test with dynamic shear rheometer using small diameter (4 mm) plates. Finally, test results will be compared with severity of low temperature cracking in asphalt pavements and performance based criteria for bitumen that ensure asphalt pavement performance without or limited amount of cracks will be determined.

Measurement accuracy of asphalt surface temperature will directly affect performance based criteria, thus it is recommended to find out if there is a significant difference between asphalt surface temperatures measured by RWSs and other measuring techniques, e.g. sensors installed in pavement surface.

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