Case Studies in Construction Materials 11 (2019) e00238

Contents lists available at ScienceDirect

Case Studies in Construction Materials

journal homepage: www.elsevier.com/locate/cscm

Case study

Evaluating the effect of asphalt binder modification on the low-temperature cracking resistance of hot mix asphalt

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ARTICLE INFO

Article history:
Received 26 November 2018
Received in revised form 31 January 2019
Accepted 3 April 2019

Keywords:
Asphalt pavement
Polymer modification
Thermal stress
Low-temperature cracking
Tensile strength
Critical temperature

ABSTRACT

This study focused primarily on the effects of various polymer modifications on the low-temperature cracking performance of asphalt binders and resultant mixtures. Two air-blown bitumens were blended with four polymers with or without the addition of polyphosphoric acid (PPA). The low-temperature properties of the neat bitumens and the modified binders were characterized using bending beam rheometer (BBR). The prismatic samples of dense graded asphalt mixtures with the same content of different binders of 4.7% by weight were tested on direct tension at constant strain rate. The low-temperature cracking of the mixtures was also evaluated by tensile stress restrained specimen test (TSRST). The results indicated that the low-temperature parameters were dependent on base bitumen and on polymer modification. For all tested binders, the Superpave criterion E<300MPa appeared to be more restrictive than criterion m>0.30. Polymer modification showed significant benefits as compared to the corresponding base bitumen for direct tensile strength of asphalt mix at low temperatures. Addition of PPA reduced the strength at −30°C while raised at −20°C and −10°C. The BBR limiting binder stiffness temperature was close to the TSRST critical asphalt mix cracking temperature.

1. Introduction

Polymer modification of bitumen has received widespread attention since the 1980s in order to decrease bitumen susceptibility to high and low temperatures, allowing reduction in common pavement failure mechanisms as rutting and cracking. Bitumen modification has been commonly performed by addition of thermoplastic or elastomeric polymers. The overall objective of this study was to evaluate the low temperature cracking performance of asphalt mixtures with different modified binders [1,2].

Pavement with polymer modification exhibits greater resistance to rutting and thermal cracking, and decreased fatigue damage, stripping and temperature susceptibility. Polymers that have been most often used to modify asphalt include styrene–butadiene–styrene (SBS), styrene–butadiene rubber (SBR), Elvaloy, rubber, ethylene vinyl acetate (EVA), polyethylene, and others [1–3]. Several research groups around the world have worked on evaluating the benefits of polymer modification on pavement performance, and specifications for binders are still continually being developed. The incorporation of polymers into asphalt usually increased the price of the product between 60 and 100% [4].

Styrene–butadiene–styrene (SBS) is a block copolymer that increases the elasticity of asphalt. According to review by Becker et al. [4], it is probably the most appropriate polymer for asphalt modification, although the addition of SBS type block

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https://doi.org/10.1016/j.cscm.2019.e00238

copolymers has serious technical limitations. Although low temperature flexibility is increased, some authors claim that a decrease in strength and is observed at higher temperatures. Nonetheless, SBS is the most used polymer to modify asphalts.

To better understand the behaviour of SBS in asphalt binders, transmission electron microscopy was used [5]. Depending on the sources of asphalt and polymer, morphology varies: there can be a continuous asphalt phase with dispersed SBS particles, a continuous polymer phase with dispersed globules of asphalt, or two interlocked continuous phases. Formation of the critical network between the binder and polymer that increases the complex modulus, is an indication of resistance to rutting.

Styrene–butadiene–rubber (SBR) has been widely used as a binder modifier, usually as a dispersion in water (latex). The report of US Federal Aviation Administration describes the benefits of SBR modified asphalt in improving the properties of bituminous concrete pavement. Low-temperature ductility is improved, viscosity is increased, elastic recovery is improved and adhesive and cohesive properties of the pavement are improved [6]. According to Becker et al., SBR latex polymers increase the ductility of asphalt pavement [4], which allows the pavement to be more flexible and crack resistant at low temperatures, as found by the Florida Department of Transportation [7].

The DuPont website (http://www.dupont.com/products) describes Elvaloy as elastomeric terpolymer that chemically reacts with asphalt. As a result, problems with separation during storage and transportation are avoided. Pavements with Elvaloy have been in use since 1991. In 1995, Witczak et al. [8] studied the laboratory performance of asphalt modified with Elvaloy. The susceptibility of the mixtures to moisture damage was found to be greatly decreased by the addition of Elvaloy, but an Elvaloy in combination with granite had a significantly higher (poorer) fracture temperature than with diabase, limestone or granite aggregate treated with hydrated lime [8].

At the DuPont Institute, Babcock et al. [9] devised a lap shear test for high temperature binder properties. The results indicated that binder failure at temperatures above 6 °C tends to be cohesive failure, due the loss of integrity within asphalt.

Unfortunately, conclusion that around 6 °C and colder, failure occurs from loss of adhesion between the binder and aggregate does not look very comprehensive without considering the time effect. At the cooling rate of 2 °C/h that is similar to the rates experienced by pavements, the loading rate is of the order of 10–4 MPa/s [10] while at a lap shear test the loading rate is of the order of 10-1 MPa/s. A ten-fold decrease in stress rate shifts the strength vs. temperature curve to lower temperatures as much as around 7 °C [10]. Taking into account the stress rate, form the test results of Babcock et al. [9] it follows that a gradual transfer from cohesive to adhesive failure of asphalt concrete would be around minus 15 °C and colder, which sounds much more realistic than 6 °C.

The use of mineral acids in the asphalt-polymer compositions was described in some studies [11]. Polyphosphoric acid (PPA) is a polymer of orthophosphoric acid. The addition of mineral acid to the system widens the temperature range in which satisfactory performance from a given polymer asphalt composition can be achieved, hence reduces the amount of polymer additive that would otherwise be needed to modify the bitumen [12].

For asphalt pavement, one of the failure modes is low-temperature cracking. This occurs when the thermal stress induced at low temperatures exceeds the tensile strength of the asphalt concrete. Low-temperature cracking is a serious problem in cold areas, including Canada, north of the United States, Sweden, Norway, Russia, Kazakhstan, Ukraine, and other countries at extreme northern and southern latitudes. To reduce the risk of cracking, the binder should have good flexibility and high ability of stress relaxation at the lowest pavement temperature.

This study focused primarily on the effects of various polymer modifications on the low temperature cracking performance of asphalt binders and resultant mixtures.

2. Materials

2.1. Neat bitumens

In this paper neat bitumens of grades 100/130 and 130/200, satisfying the requirements of Kazakhstan standard ST RK 1373 [13] have been used. Bitumens have been produced by Pavlodar petrochemical plant from crude oil of Western Siberia (Russia) by method of direct oxidation. Main standard indicators for bitumens, determined in the laboratory of Kazakhstan Highway Research Institute (KazdorNII), are represented in Table 1.

Table 1
Main standard indicators of neat bitumens.

Indicator	Measurement unit	Value of indicator	
		100/130	130/200
Penetration, 25 °C, 100 g, 5 s	0.1 mm	110	175
Penetration index PI	–	0.82	−0.2
Ductility: 25 °C	cm	135	85
0 °C		6.6	9.5
Softening point	°C	44.0	41,0
Fraas point	°C	−30,2	−29.9
Dynamic viscosity, 60 °C	Pa s	121.0	83.2
Kinematic viscosity, 135 °C	mm^2/s	329.0	323.0

2.2. Bitumens modified with polymers

Bitumens modified with polymers and additive of polyphosphoric acid (PPA) have been also used. Neat bitumens of grades 100/130, 130/200 have been used for modification, as well as the following polymers: Kraton (SBS), Calprene (SBS), Butonal NS198 (SBR) and Elvaloy 4170. Quantity of polymers and PPA, added to bitumens, are given in Table 2. Bitumens, modified with polymers, satisfy the requirements of Kazakhstan standard ST RK 2534 [14] and their main indicators are shown in Table 3. Data comparison of Tables 1 and 3 shows that in most cases bitumen modification with polymers and additive reduces considerably penetration and ductility, increases considerably softening point and increases Fraas point.

2.3. Asphalt concretes

Hot dense asphalt concretes and polymer asphalt concretes of type B, which satisfy the requirements of Kazakhstan standards [15] and [16] respectively, have been produced with the use of the following fractions of crushed stone: 5–10 mm (20%); 10–15 mm (13%) and 15–20 mm (10%). Crushed stone has been supplied from rock pit “Ozentas” (Almaty region, Kazakhstan). Sand of fraction 0–5 mm (50%) has been supplied from the plant “Asfaltobeton-1” (Almaty city, Kazakhstan) and activated mineral powder (7%) has been supplied from rock pit “Zhartas” (Zhambyl region, Kazakhstan).

Content of neat bitumens and bitumens modified with polymers in composition of all types of the asphalt concretes was the same and equal to 4.8% by weight of dry mineral material. Granulometric composition of mineral part has been also accepted as the same one for all types of asphalt concretes (Fig. 1).

3. Methods

3.1. Preparation of modified bitumens

Mixer of model IKA EUROSTAR 20 DIGITAL was used for preparation of modified bitumens in laboratory conditions. Frequency of shaft rotation for this mixing device is regulated automatically by microprocessor within the interval of 30 and

Table 2
Quantity of polymers and polyphosphoric acid added to bitumens.

Grade of bitumen	Name of polymer	Quantity, % by weight of neat bitumen	
		polymer	PPA
100/130	Kraton	4.0	–
	Calprene	4.0	–
	Butonal NS198	3.0	–
	Elvaloy 4170	1.4	–
130/200	Kraton	6.0	–
	Calprene	6.0	–
	Butonal NS198	3.5	–
	Elvaloy 4170	1.8	–
130/200	Kraton	5.5	0.02
	Calprene	5.5	0.02
	Elvaloy 4170	1.6	0.02
130/200	–	–	1.0

Table 3
Main standard indicators of modified bitumens.

Grade of bitumen	Name of polymer	Value of indicator			
		penetration, 25 °C, 100 g, 5 s (0.1 mm)	ductility, 25 °C (cm)	softening point (°C)	Fraas point (°C)
100/130	Kraton	60	43.5	76.0	−30.3
	Calprene	58	42.5	73.0	−23.7
	Butonal NS198	83	51.0	58.0	−27.4
	Elvaloy 4170	86	38.3	63.5	−29.1
130/200	Kraton	74	45.0	75.5	−24.7
	Calprene	63	55.0	79.0	−27.5
	Butonal NS198	110	150.0	61.5	−32.1
	Elvaloy 4170	105	48.0	60.5	−24.1
130/200	Kraton + PPA	79	47.0	58.0	−21.7
	Calprene + PPA	76	82.0	75.0	−20.6
	Elvaloy 4170 + PPA	118	87.0	60.5	−27.9
130/200	PPA	75	49.5	63.0	−20.5

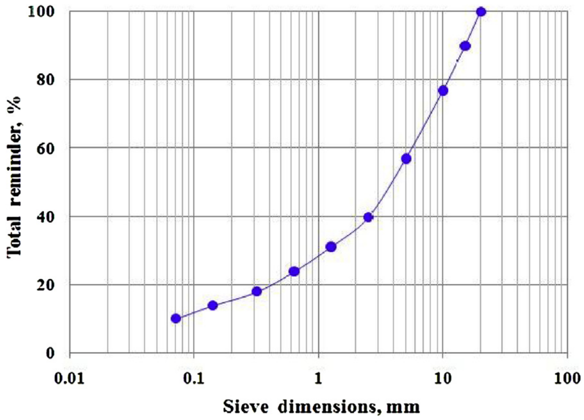

Fig. 1. Granulometric curve of mineral part of the asphalt concretes.

2000 rotations per minute. Shaft rotation frequency has been regularly compared with the target one and it is automatically corrected at deviation. This ensures constant rotation rate even at binder viscosity variation.

Preparing of modified bitumens by the mixing device was performed in the following sequence. First, neat bitumens were heated up to the temperature of 175–180 °C in the mixing device, then polymer was gradually added in bitumen during mixing. Full mixing time was 2 h. Bitumens modified with polymer Elvaloy after mixing (duration for 2 h) were kept at the mixing temperature (175–180 °C) for 12 h. In case of adding of PPA bitumen with polymer (SBS or Elvaloy) has been mixed for 1.5 h, then PPA was added and the compound has been mixed for 0.5 h more.

3.2. Short-term aging

Short-term aging of the bituminous binders in the vertical rolling thin film oven has been performed under the standard of ST RK 1224-2003 [17], which models the bitumen aging during preparing of an asphalt concrete mix, its transportation, laying and compaction. The samples of the bituminous binders were in the oven at the temperature of 163 °C for 75 min.

3.3. Long-term aging

Long-term aging of the bituminous binders in the special pressure aging vessel has been performed under the standard of ASTM D 6521-08 [18], which models the bituminous binder aging during operation of the asphalt concrete pavement. The samples of the bituminous binders, after the short-term aging, were in the vessel under the pressure of 2070 kPa and at the temperature of 100 °C for 20 h.

3.4. Bending beam rheometer

Testing of the bituminous binders at low temperatures has been performed by bending beam rheometer (BBR) under the standard of AASHTO T 313-08 [19] after double (short-term and long-term) aging. The samples of the bituminous binders for the tests had the shape of a beam with dimensions of $6.25 \times 12.5 \times 125$ mm. Before testing the samples have been kept at the tested temperature for 60 min. In the beginning of the test the load, equal to 980 mN, has been applied automatically for 1 s and it has been kept as the constant one for the following 240 s. The maximum deflection of the middle of the beam has been measured automatically.

3.5. Preparation of asphalt concrete mixes

A preparing of asphalt concrete mixes was performed in a laboratory mixer of the company InfraTest (Germany). The mixer with capacity of 30 litres has constant shaft rotation rate, equal to 60 rotations per minute. Opening and closing of the upper cover of the mixer occurs automatically by an electric engine. The cover has an observation window, which allows observing of the process for mixing. The vessel of the mixer can bend forward by an electric engine to unload the prepared asphalt concrete mix.

Preparing of asphalt concrete mixes (both with neat bitumens and with modified bitumens) has been performed in the following sequence. First, stone material (crushed stone and sand) was heated in a drying oven up to the temperature of 180 °C. Then the laboratory mixing device was heated up to the temperature of 190 °C and the heated stone material was added in it and mineral powder and bitumen (neat or modified) were gradually added in the stone material.

Temperature of the prepared asphalt concrete mix with the neat bitumens was 150–155 °C under the requirements of the standard ST RK 1225 [15], and the temperature for preparing of asphalt concretes with polymers is adopted equal to 160–170 °C.

Table 4
Mix design characteristics of the asphalt concretes.

Name of polymer	Value of characteristics			
	air voids, %	voids in mineral aggregate, %	density, g/cm^3	water saturation, % by volume
Bit 100/130	3.8	15.7	2.39	3.3
Bit 130/200	4.2	16.9	2.38	3.7
Bit 130/200+PPA	3.9	12.8	2.39	1.6
Bit 100/130+ Kraton	3.5	15.4	2.40	2.3
Bit 130/200+ Kraton	3.3	15.1	2.40	2.5
Bit 130/200+ Kraton + PPA	3.5	13.3	2.41	1.7
Bit 100/130+ Calprene	3.2	15.5	2.40	2.2
Bit 130/200+ Calprene	3.2	14.8	2.41	1.8
Bit 130/200+ Calprene + PPA	3.1	13.3	2.41	1.8
Bit 100/130+ Elvaloy	3.4	15.1	2.40	2.5
Bit 130/200+ Elvaloy	3.4	15.0	2.40	2.0
Bit 130/200+ Elvaloy + PPA	4.9	16.3	2.40	3.0
Bit 100/130+ Butonal	3.5	15.6	2.40	2.6
Bit 130/200+ Butonal	3.7	15.3	2.40	2.8
Bit 130/200+ Butonal + PPA	–	–	–	–

Mix design characteristics of the asphalt concretes are shown in Table 4.

3.6. Production of asphalt concrete samples

Asphalt concrete samples in the shape of a rectangular prism with dimensions of 5 × 5 × 50 mm (Fig. 2, right) have been prepared in the following way. First, asphalt concrete samples, using the sector compactor (model CRT-RC2S, Cooper, Nottingham, UK) (Fig. 3), have been prepared in the shape of a rectangular slab (Fig. 2, left) under standard EN 12697-33 [20]. Then asphalt concrete samples have been cut from them in the shape of rectangular prisms.

3.7. Testing of asphalt concretes

Testing of asphalt concretes at three low temperatures (−10 °C, −20 °C and −30 °C) has been performed under two schemes [21] in a special device called TRAVIS, produced by the company InfraTest (Germany). Device TRAVIS represents by itself a thermal chamber with the fixed equipment inside, which allows performing the asphalt concrete sample test at direct tension.

Fig. 2. Asphalt concrete samples: in the shape of a square slab with dimensions 305 × 305 × 50 mm (left); in the shape of a rectangular prism with dimensions 5 × 5 × 50 mm (right).

Fig. 3. Sector compactor.

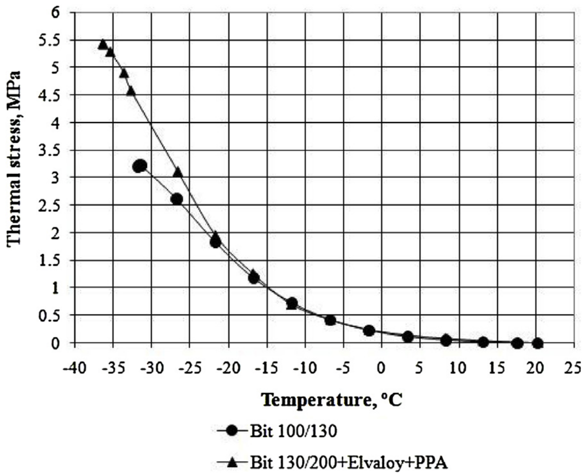

Fig. 4. Dependence of thermal stresses on temperature in the asphalt concrete samples.

According to the first scheme an asphalt concrete sample is deformed with constant rate (1 mm/min) till its failure. A computer fixes stress and strain at the moment of sample failure.

At testing under the second scheme, which is called the thermal stress restrained specimen test (TSRST), the temperature of the asphalt concrete sample, starting from 20 °C, is decreased with constant rate (10 °C/hour) till sample failure. Non-realized thermal strain occurs in the asphalt concrete sample at the temperature decreasing due to impossibility of free deformation of the sample. This strain causes the appearance of thermal stress in the sample. If the temperature decreasing in the sample occurs continuously, the value of thermal stress in it increases in time. At some time moment, when accumulated thermal stress in the sample reaches the critical value σ_{cr}, the sample failure occurs. The temperature, at which the sample failure occurred, is called the critical temperature T_{cr}.

As an example Fig. 4 represents dependences of thermal stress on temperature for two asphalt concrete samples. The first asphalt concrete sample has been prepared with the use of neat bitumen of grade 100/130, and the second one with bitumen of grade 130/200, polymers Elvaloy and PPA.

As it is seen from the figure, at linear increasing of non-realized thermal strain the thermal stress in the asphalt concrete sample is increased nonlinearly. Thermal stress is increased in the same way for the samples of both types of the asphalt concrete till the temperature of -22 °C, and with further temperature decrease the asphalt concrete, prepared with the use of modified bitumen, shows high low temperature strength (higher for 68.4%) and lower (nearly for 5 °C) critical temperature.

4. Results and discussion

4.1. Bituminous binders

4.1.1. Low temperature characteristics of bituminous binders

Indicators of low temperature resistance of bituminous binders - stiffness S and m-value at load duration of 60 s, determined on BBR, are represented in Figs. 5 and 6. Technical specifications of Superpave require that bituminous binder stiffness at calculated minimal temperature and at load duration of 60 s should not exceed 300 MPa, and m-value should not be lower than 0.3 [22]. As relaxation ability of bituminous binders is decreased with the temperature reduction [23,10,24], practically the lower temperature is the less m-value for all binders. However, m-value is higher than the required minimal value for all tested binders even at the temperature of −36 °C. Binder stiffness is increased with the temperature reduction. Stiffness for all tested binders at the temperatures of −24 °C and −30 °C is considerably lower than the acceptable maximum value, and only non-modified bitumen of grade 130/200 and bitumen of grade 100/130 with polymer Calprene satisfy the requirement of Superpave at the temperature of −36 °C.

Many researchers specify that the modification of bitumens with polymers, as a rule, improve their rheological properties [25–30]: stiffness of bitumens is decreased [25–29] and resistance to low temperature cracking is increased [26]. However, some authors also express their opinion that the effect of the modification of the bitumens with polymers depend on the base bitumen, character and content of a polymer [25,26,30]. The work [30] reads that modification with polymer in some cases does not show the essential effect.

As we can see (Figs. 5 and 6), really, some polymers do not show the essential effect at some temperatures compared with the base pure bitumen.

It is not difficult to understand that the temperature, which corresponds to maximum allowable value of stiffness on Superpave, i.e. the temperature when the binder stiffness is equal to 300 MPa, can be an important characteristic of low temperature resistance for bituminous binders. We call this temperature as a critical one for binder and specify it as T_{Bcr}.

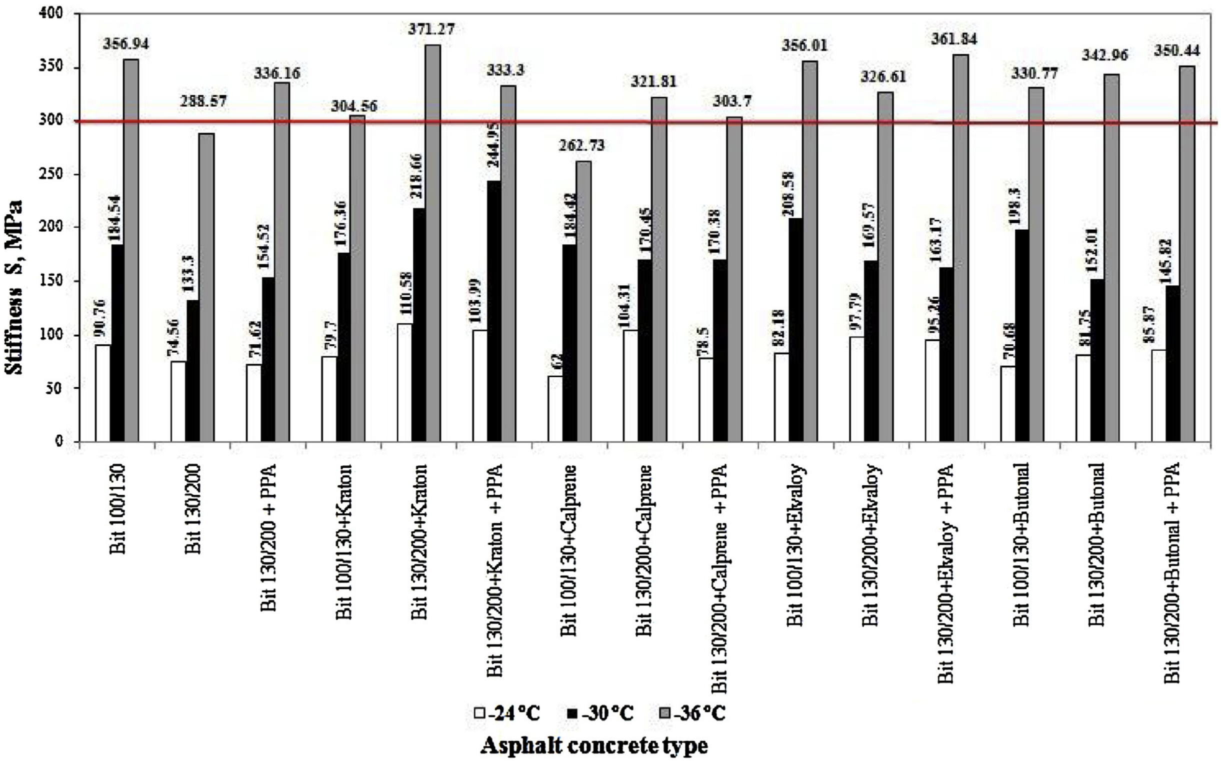

Fig. 5. Bituminous binder stiffness at low temperatures.

Fig. 7 shows how critical temperature T_{Bcr} is determined according to the measurement results of binder stiffness on BBR. And Fig. 8 represents the values of critical temperature for binders T_{Bcr}, determined by the above method. As it is seen, it is found that critical temperature values for bituminous binders are within the range of -32.2 °C and -38.2 °C. Meanwhile, for the majority of tested bituminous binders, except for some binders (bitumen of grade 130/200 with polymer Kraton and PPA, bitumen of grade 130/200 with polymer Kraton, bitumen of grade 130/200 with polymer Butonal), the critical temperature varies within relatively narrow limits (from 33.8 °C to 36.7 °C).

4.2. Asphalt concretes

4.2.1. Deformation with constant rate

Fig. 9 represents bar graphs, constructed under the test results of various types of the asphalt concretes on the scheme of deformation with constant rate at the temperatures of −10 °C, −20 °C and −30 °C. As it is seen practically all tested asphalt concretes, except for asphalt concrete with bitumen of grade 130/200 and polymer Kraton, showed close strength at temperatures −10 °C. Alongside of approximately similar strength values for all other asphalt concretes, essentially low strength of the asphalt concrete with bitumen of grade 130/200 and polymer Kraton can be explained by individual defects in the asphalt concrete samples. Thus, one can draw conclusion regarding the fact that the difference in strength values at tensile is not considerably reasonable at the temperature of −10 °C for the considered types of asphalt concretes.

It is clearly seen (Fig. 9), that the difference in strength values for the asphalt concretes becomes more distinct with the temperature reduction. The lower test temperature is the more the difference of tensile strength for various types of asphalt concretes.

The following asphalt concretes have high strength compared with the conventional asphalt concrete of grade 100/130 at the temperature of −20 °C with appropriate growth: with bitumen of grade 130/200 with polymer Kraton and PPA (15%), with bitumen of grade 130/200 with polymer Calprene and PPA (18%), with bitumen of grade 100/130 and polymer Elvaloy (14%), with bitumen 130/200 and polymer Elvaloy (25%) and with bitumen of grade 130/200 and polymer Butonal (22%).

The following asphalt concretes showed considerably high strength at the temperature of −30 °C, compared with the conventional asphalt concrete: with bitumen of grade 100/130 and polymer Kraton (38%), with bitumen of grade 100/130 and polymer Calprene (33%), with bitumen of grade 100/130 and polymer Elvaloy (43%), with bitumen of grade 130/200 and polymer Butonal (63%).

The experimental results we obtained comply with the results of other researchers [31,32] and our previous data [33,34]. The works [31,32] determine that the modification with polymers can effect essentially on the asphalt concrete strength. In

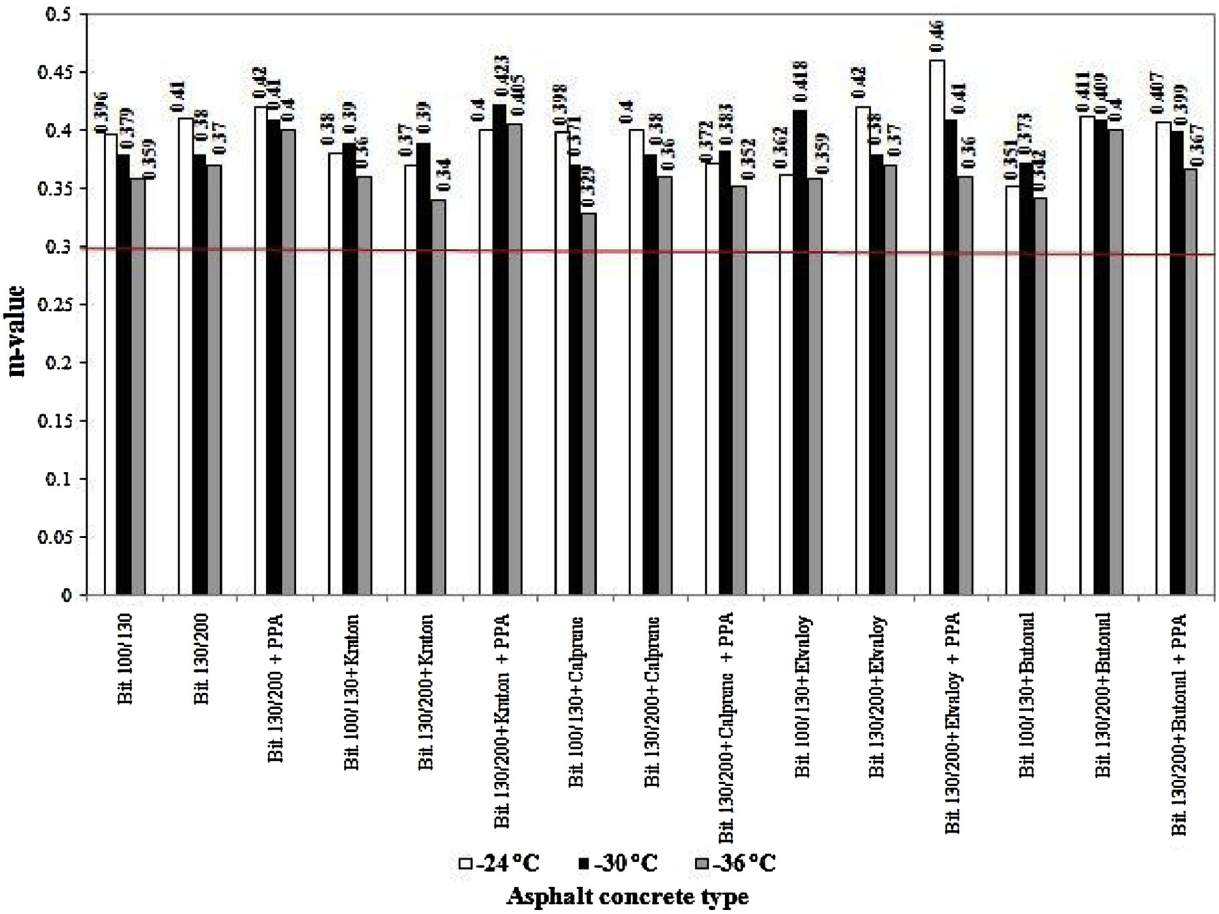

Fig. 6. Bituminous binder m-value at low temperatures.

addition, it is known that the asphalt concrete strength within the range of negative temperatures depends greatly on a temperature [31–33] and it is also affected greatly by the binder properties and volumetric indicator of a mix [23,24].

Our results also show that the asphalt concrete strength depends greatly on a temperature and polymer type (different binder properties and volumetric characteristics of mixes).

Test results, set forth above, show that modification of less viscous bitumen (grade 130/200) with polymers increase considerably the asphalt concrete strength compared with more viscous non-modified bitumen of grade 100/130; additive

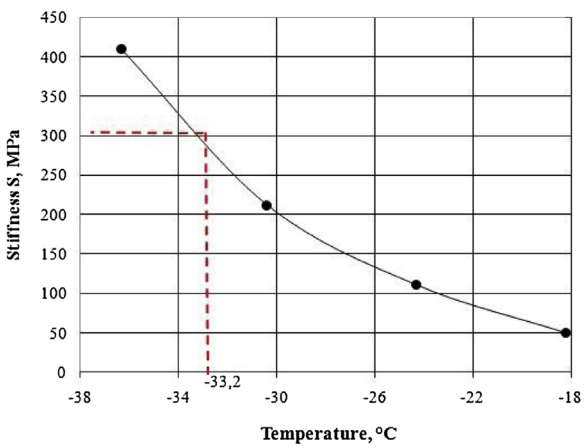

Fig. 7. Determination of critical temperature T_{Bcr} for binders.

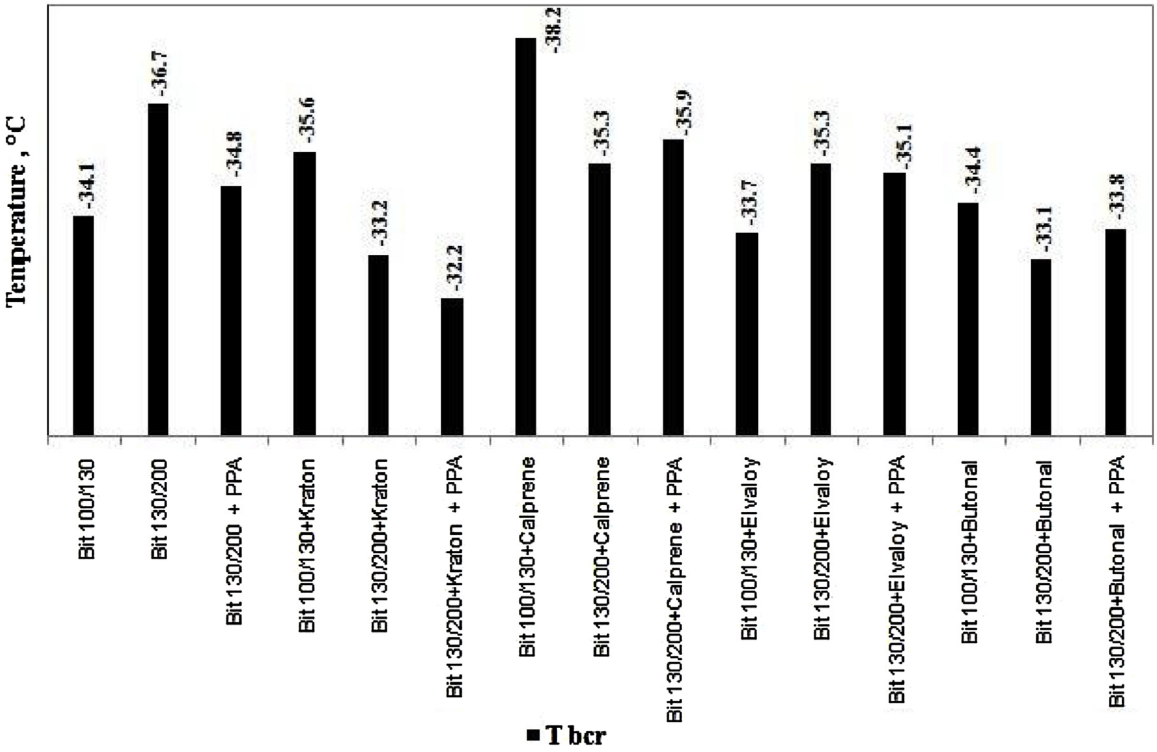

Fig. 8. Critical temperatures for bituminous binders T_{BCr}.

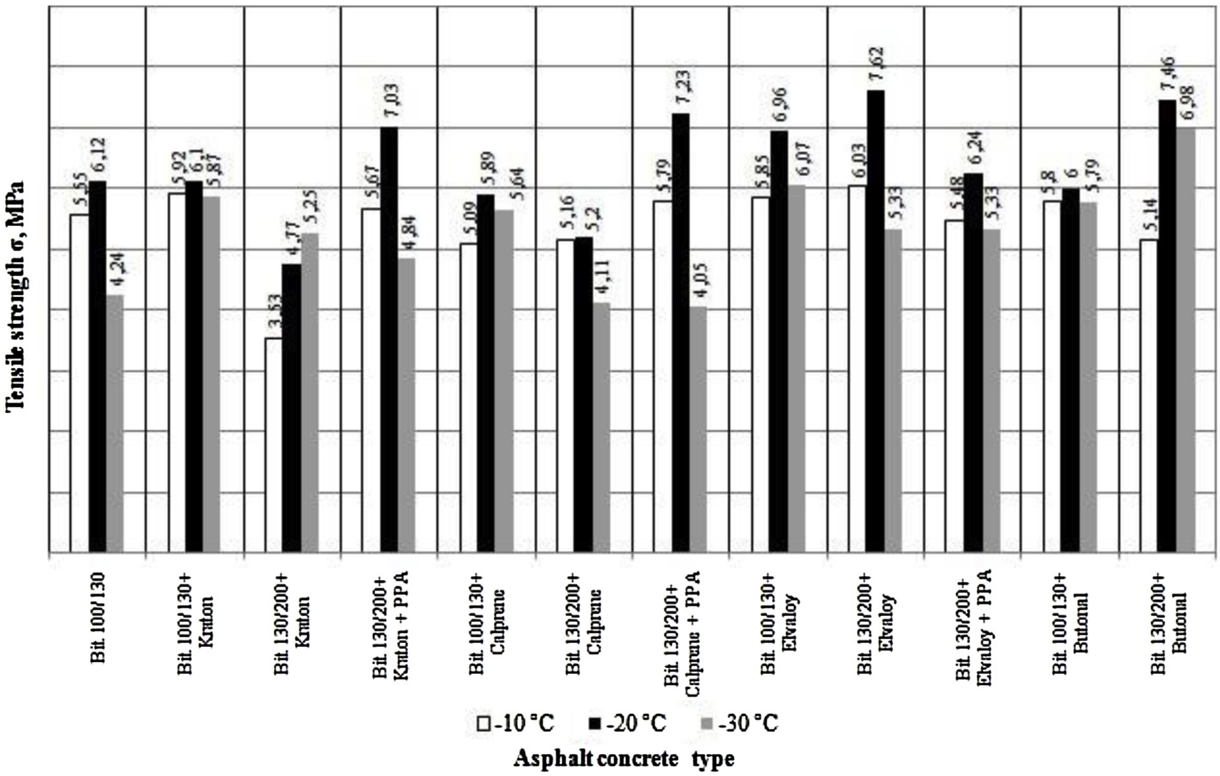

Fig. 9. Tensile strength of asphalt concretes at low temperatures.

PPA to bitumen of grade 130/200 modified with polymers Kraton and Calprene increases an asphalt concrete strength for 15% and 18% respectively at the temperature of −20 °C compared with the conventional non-modified bitumen of grade 100/130; asphalt concretes, containing PPA, showed comparably low strength at the temperature of −30 °C. Only the asphalt concrete with polymer Butonal showed high strength in case of less viscous bitumen of grade 130/200, whereas the asphalt concretes with other polymers (Kraton, Calprene и Elvaloy) had high strength in case of more viscous bitumen of grade 100/130.

4.2.2. Thermal stress restrained specimen test

Bar graphs, constructed according to the test results of asphalt concretes on scheme TSRST and showing distribution according to types of the asphalt concretes are represented in Figs. 10 and 11. As it is seen, modification of bitumen with polymers and additive PPA increase characteristics of low temperature resistance of the asphalt concretes. Meanwhile, critical temperature (Fig. 10) is increased by 2.2 °C (bitumen of grade 130/200 + polymer Kraton + PPA) and 4.9 °C (bitumen of grade 130/200 + polymer Elvaloy + PPA) compared with the conventional asphalt concrete with bitumen of grade 100/130.

It is found out that effect of bitumen modification with polymers and addition of PPA on an asphalt concrete strength is strongly expressed in the values of critical stress (Fig. 11). Practically with all types of the asphalt concretes occurs the following sequence in the critical stress increase for them: more viscous bitumen of grade 100/130→ less viscous bitumen of grade 130/200 → bitumen of grade 100/130 + polymer → bitumen of grade 130/200 + polymer → bitumen of grade 130/200 + polymer + PPA. For example, critical stress increase for the asphalt concretes with bitumen of grade 100/130 + polymer Elvaloy, with bitumen of grade 130/200 + polymer Elvaloy and with bitumen of grade 130/200 + polymer Elvaloy + PPA was 33%, 72% and 81% respectively compared with the asphalt concrete with non-modified bitumen of grade 100/130.

Other researchers also note that modification with polymers can improve essentially the low temperature characteristics of the asphalt concretes [31,33,34]. Critical stress can be increased up to 60–70 % [31], and the critical temperature – up to 6–7 °C [32]. Meanwhile, the impact of bitumen type and aggregate [34] and polymer [31,33] is an essential one. As it is seen, the results we obtained comply well with the results of other researchers.

4.2.3. Comparison of critical temperatures for bituminous binders and asphalt concretes

Careful analysis of the bar graphs in Figs. 8 and 10 shows that critical temperature values of bituminous binders T_{Bcr} and critical temperature of relevant asphalt concretes T_{cr} are very close to each other. For visual reference the bar graph of critical temperature values for bituminous binders T_{Bcr} and relevant asphalt concretes T_{cr} is shown in Fig. 12. As it is seen really the values of corresponding critical temperatures proved to be very similar. It is stated that except for three cases (bitumen of grade 100/130 with polymers Kraton, Calprene and Butonal) variation of T_{Bcr} from T_{cr} for all other twelve binders does not

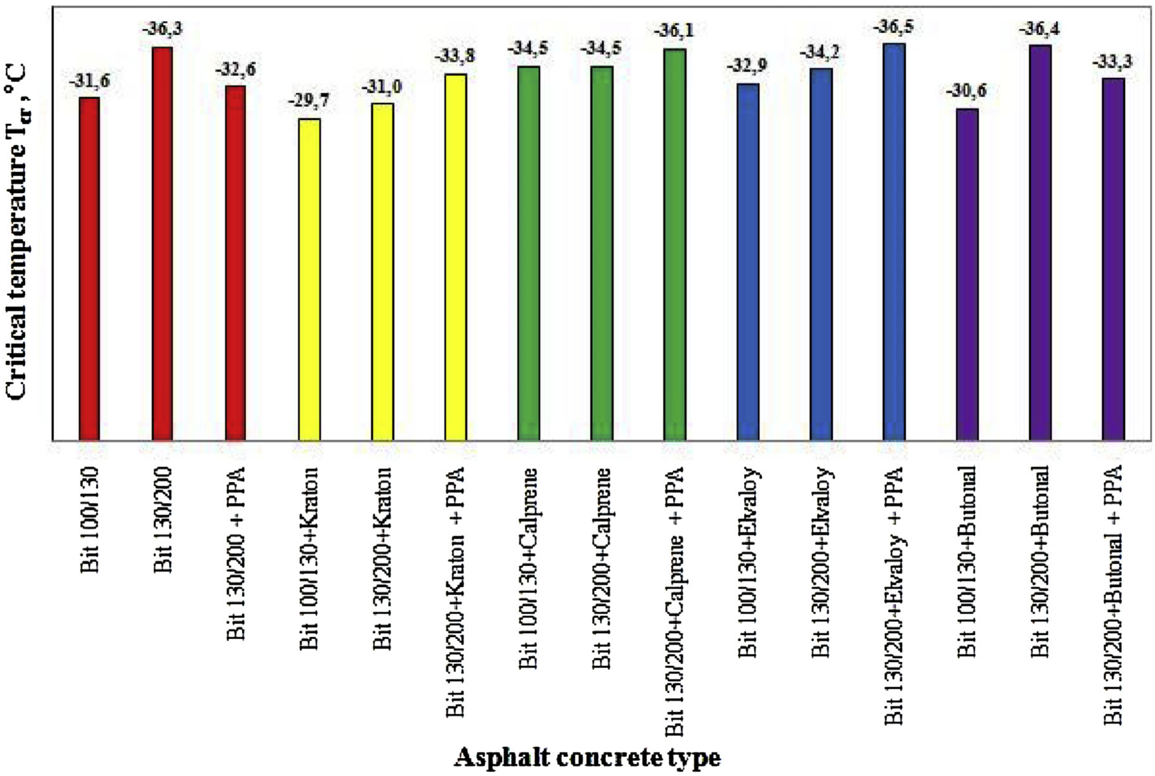

Fig. 10. Critical temperatures of asphalt concretes T_{cr}.

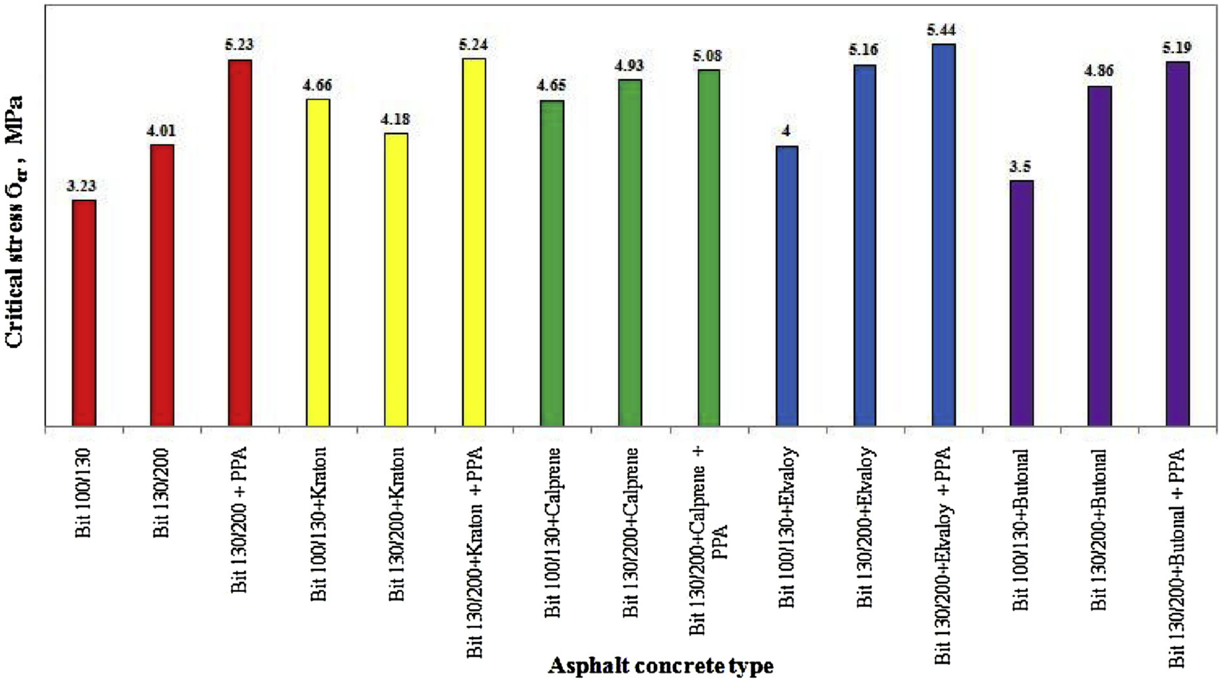

Fig. 11. Critical stress of asphalt concretes σ_{cr}.

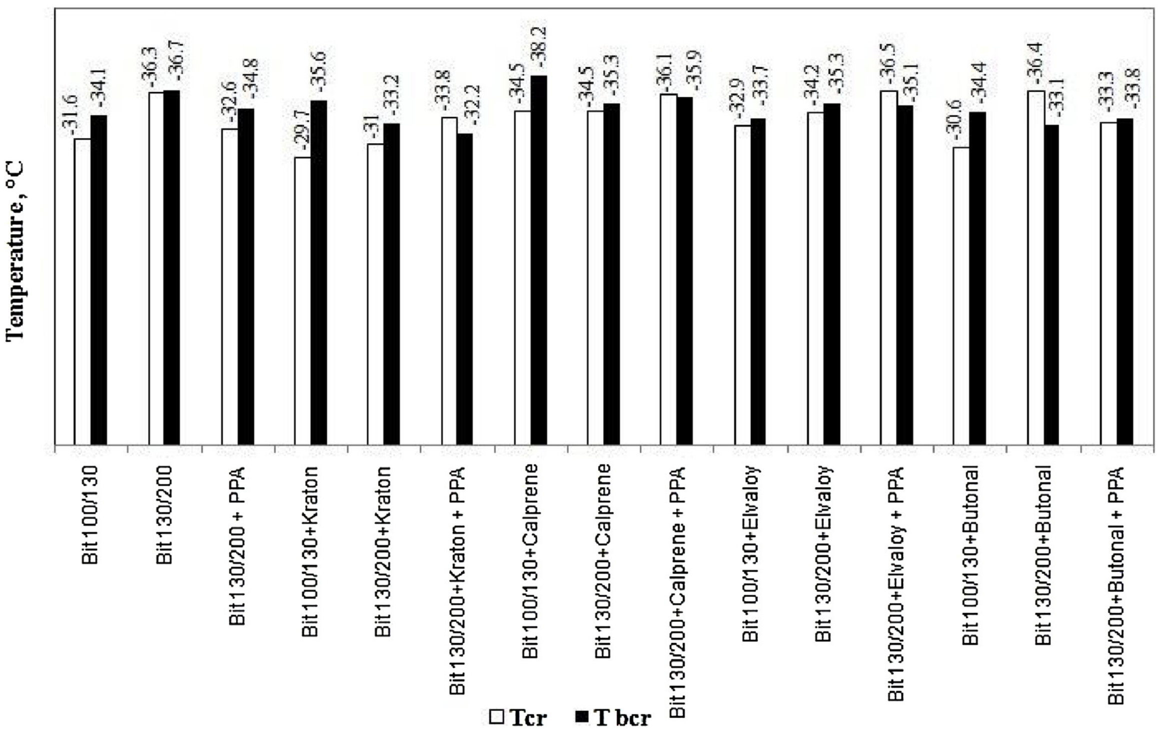

Fig. 12. Critical temperature values of bituminous binders and relevant asphalt concretes.

exceed 10%. The existence of good correlation between critical temperatures of bituminous binders and relevant asphalt concretes has been mentioned by other researchers as well [30,34]. Such sufficiently good similarity of two critical temperatures can be still improved with the quantity increase of parallel samples for bituminous binders and asphalt concretes during testing.

5. Conclusion

- All tested neat and modified bitumens at all test temperatures (−24 °C, −30 °C and -36 °C) showed m-value more than the required minimal value, equal to 0.3. This fact gives the idea that in case of blown bitumens the m-value criterion of Superpave does not work.
- Stiffness of all tested bituminous binders at the temperatures of −24 °C and −30 °C is considerably lower than the acceptable maximum value, equal to 300 MPa. And at the temperature of −36 °C only neat bitumen of grade 130/200 and bitumen of grade 100/130 with polymer Calprene satisfy the requirements of Superpave.

Critical temperature values, at which binder has acceptable maximum stiffness (300 MPa), are within the range of −32.2 °C and −38.2 °C.

- At deformation with constant rate at the temperature of −10 °C all tested asphalt concretes showed practically similar strength: 5.1–6.0 MPa. The difference in strength values for various types of asphalt concretes becomes more evident with temperature reduction.

Modification of a bitumen with polymers and adding of PPA gave positive effect at the temperature of −20 °C. At a lower temperature (−30 °C) only modification of bitumen with polymers shows positive effect. And joint addition of PPA to them in all cases shows the negative effect, excluding the effect of modification with polymers.

- Test results of the asphalt concretes on scheme of thermal stress restrained specimen test showed that bitumen modification with polymers and adding of PPA increase characteristics of low temperature resistance for the asphalt concretes.
- It was stated that values of critical temperature of bituminous binders and critical temperature of relevant asphalt concretes are practically similar.
- It is recommended to use bitumen of grade 100/130 with polymers Kraton, Calprene, Butonal NS 198 and Elvaloy 4170 in the regions with minimal temperature till −24 °C, bitumen of grade 130/200 with polymers Calprene, Butonal NS 198 and Elvaloy 4170 in the regions with minimal temperature till −30 °C and bitumen of grade 130/200 with polymers Butonal NS 198, Elvaloy 4170, Calprene + PPA, Elvaloy + PPA in the regions with minimal temperature till −36 °C.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgements

This study was funded by the Road Committee of the Ministry for Investments and Development of the Republic of Kazakhstan (Agreement No. 36 dated July 21, 2016).

References

[1] G. King, et al., Additives in asphalt, J. Assoc. Asph. Pav. Technol. A 68 (1999) 32–69.
[2] Y. Yildirim, Polymer modified asphalt binders, Constr. Build. Mater. 21 (1) (2007) 66–72.
[3] J. Zhu, B. Birgisson, N. Kringos, Polymer modification of bitumen: advances and challenges, Europ. Polym. J. 54 (2014) 18–38.
[4] Y. Becker, M.P. Mendez, Y. Rodriguez, Polymer modified asphalt, Vis. Technol. 9 (1) (2001) 39–50.
[5] J.S. Chen, M.C. Liao, M.S. Shiah, Asphalt modified by styrene–butadiene–styrene triblock copolymer: morphology and model, J. Mater. Civ. Eng. 14 (3) (2002) 224–229.
[6] R. Bates, R. Worch, Styrene-Butadiene Rubber Latex Modified Asphalt, Federal Aviation Administration, Engineering Brief 39, Washington, DC, 1987.
[7] R. Roque, B. Birgisson, M. Tia, B. Kim, Z. Cui, Guidelines for the Use of Modifiers in Superpave Mixtures: Executive Summary and Volume 1 of 3 Volumes: Evaluation of SBS Modifier. State Job 99052793, Florida Department of Transportation, Tallahassee, FL, 2004.
[8] M.W. Witczak, I. Hafez, X. Qi, Laboratory Characterization of Elvaloy Modified Asphalt Mixtures, I – Technical Report, University of Maryland, College Park, Maryland, 1995.
[9] G.B. Babcock, R.J. Statz, D.S. Larson, Study of asphalt binders using lap shear bonds, Proceedings of the Annual Conference – Can. Tech. Asph. Assoc. 43 (1998) 1–15.
[10] B. Teltayev, B. Radovskiy, Predicting thermal cracking of asphalt pavements from bitumen and mix properties, Road Mat. Pav. Des. 19 (8) (2017) 1832–1847.
[11] J. Bukowski, J. Youtcheff, T. Harman, The Use and Performance of Asphalt Binder Modified with Polyphosphoric Acid (PPA), TechBrief, Office of Pavement Technology, 2012 FHWA-HIF-12-030.
[12] Transportation Research Circular E-C160, Polyphosphoric Acid Modification of Asphalt Binders, TRB, Washington D.C, 2012.
[13] ST RK 1373-2013, Bitumens and Bituminous Binders. Oil Road Viscous Bitumens. Technical Specifications, Astana, (2013) .
[14] ST RK 2534-2014, Bitumens and Bituminous Binders. Oil Modified Road Bitumens. Technical Specifications, Astana, (2014) .
[15] ST RK 1225-2013, Hot Mix Asphalt for Roads and Airfields. Technical Specifications,Astana, (2013) .
[16] ST RK 1223-2013, Polymer Asphalt Concrete Road Airfield Mixes and Polymer Asphalt Concrete. Technical Specifications, Astana, (2013) .
[17] ST RK 1224-2003, Bitumens and Bituminous Binders. Methods for Determination of Resistance to Aging Under Impact of Heating and Air Environment. Technical Specifications, Astana, (2003) .

[18] ASTM D 6521-08, Standard Practice for Accelerated Aging of Asphalt Binder Using Pressurized Aging Vessel (PAV), (2008) .
[19] AASHTO T 313-08, Standard Test Method for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR), (2008) .
[20] EN 12697-33, Bituminous Mixtures. Test Methods for Hot Mix Asphalt, Part 33, Specimen Prepared by Roller Compactor, European Committee for Standardization, Brussels, 2003.
[21] EN 12697-46, Bituminous Mixtures. Test Methods for Hot Mix Asphalt, Part 46. Low Temperature Cracking and Properties by Uniaxial Tension Tests, (2004) .
[22] Superpave series 1, Performance Graded Asphalt Binder Specification and Testing, Asphalt Institute, Lexington, 2003.
[23] B. Teltayev, B. Radovskiy, Low temperature cracking problem for asphalt pavements in Kazakhstan, Proceedings of the 8th RILEM International Conference on Mechanisms of Cracking and Debonding in Pavements 1 (2016) 139–145.
[24] B. Radovskiy, B. Teltayev, Viscoelastic Properties of Asphalts based on Penetration and Softening Point, Springer International Publishing AG, 2018.
[25] V. Mouillet, J.-Ch. Molinengo, F. Durrieu, J.-P. Planche, Effect of aging on the low temperatures cracking properties of bituminous binders: new insights from bending beam rheometer measurements, Proceedings of the 5th International RILEM Conference "Cracking in Pavements. Mitigation, Risk Assessment and Prevention" (2004) 351–356.
[26] J.-P. Planche, D. Lesueur, M.L. Hines, G. King, Evaluation of elastomer modified bitumens using SHRP binder specifications, Proceedings of the Euroasphalt and Eurobitumen Congress, (1996) , pp. 1–17.
[27] S. Aflaki, N. Tababaee, Proposals for modification of Iraninan bitumen to meet the climatic requirements of Iran, Const. Build. Mat. 23 (2009) 2141–2150.
[28] S. Aflaki, P. Hajikarimi, Implementing viscoelastic rheological methods to evaluate low temperature performance of modified asphalt binders, Const. Build. Mat. 36 (2012) 110–118.
[29] M.A. Javid, Effect of polymer modification on rheological properties of asphalt, J. Civ, Eng. Res. 6 (3) (2013) 55–60.
[30] X. Lu, U. Isacsson, J. Ekblad, Influence of polymer modification on low temperature behavior of bituminous binders and mixtures, Mat. Struc. 10 (2003) 652–656.
[31] F. Orald, H.Di Benedetto, B. Eckmann, J.-C. Vaniscote, Low temperature failure behavior of bituminous binders and mixes, Transportation Research Board Annual Meeting CD, (2004) .
[32] Y. Tan, L. Zhang, H. Xu, Evaluation of low temperature performance of asphalt paving mixtures, Cold Reg. Sci. Technol. 70 (2012) 107–112.
[33] B. Teltayev, Evaluation of low temperature cracking indicators of hot mix asphalt pavement, Int. J. Pav. Res. Technol. 5 (2014) 343–351.
[34] D. Jung, T. Vinson, Thermal stress restrained specimen test to evaluate low temperature cracking of asphalt-aggregate mixtures, Transp. Res. Rec. 1417 (1993).