BITUMEN AND ASPHALT CONCRETE REQUIREMENTS IMPROVEMENT FOR THE CLIMATIC CONDITIONS OF THE REPUBLIC OF KAZAKHSTAN

B.TELTAYEV & E.KAGANOVICH
JSC “Kazakhstan Highway Research Institute”
The Republic of Kazakhstan,
bagdatbt@yahoo.com

ABSTRACT

The report deals with issues of road bitumen non-conformity to Kazakhstan's sharp-continental conditions.

Based on the analysis of air and asphalt pavement maximum and minimum temperatures, in recent years the bitumen requirements for different country regions have been substantiated as well as zoning as to the performance temperatures has been developed. The results of investigating the high-temperature stability of a number of bitumens with J. Bari, M. W. Witczak correlation model as well as their low-temperature stability using BBR (bending beam rheometer) have shown that they meet the requirements only for a small part of the Republic’s territory.

In recent years, a number of polymer additives introduced both into bitumen and asphalt mix have been checked in situ: Kraton, Elvaloy, Sasobit, Butonal, TAFPACK-Super (TPS), TPS-F, etc. It has been found that at their introduction into bitumen, the low-temperature properties of polymer-modified bitumen either do not change or change insignificantly (for Elvaloy about 2°C per 1% of polymer) whereas their thermal resistance grows substantially: for each one percent of the introduced additive the increase is approximately by 6°C for Kraton, by 14°C for Elvaloy, and 9°C for Sasobit. These results are in good agreement with the actual pavement condition.

1. KAZAKHSTAN'S CLIMATIC DISTINCTIVE FEATURES

At present, the most part of roads of technical categories I-III in Kazakhstan is provided with asphalt pavements. It is well known that the asphalt concrete is the material with physical-mechanical and operational properties that are substantially dependent on temperature. That is why the climatic conditions of the region of operation, along with applied transport loads, govern the requirements both for the asphalt concrete and bitumen as a component that mostly determines the thermal resistance of asphalt concrete.

The climatic conditions of the Republic of Kazakhstan, having an area of 2717 square km and extending for 3000 km from the lower watercourse of the Volga river on the west to Altai on the east and for 1600 km from the Western Siberia lowland on the north to the Tyan-Shan mountain range on the south, are highly different. The analysis of the Republic basic meteorological stations' data for a long period has indicated that the mean minimum air temperature values vary over the range from -16°C on the west (the town of Aktau) to -39.4°C on the east (the town of Ust-Kamenogorsk) and from -17.8°C on the south (t. Shymkent) to -36°C on the north (t. Petropavlosk). The mean maximum temperature values are 36.2°C to 33.5°C from the west to the east and 37.1°C to 30.9°C from the south to the north, respectively. Therewith, the majority of the Kazakhstan regions, except for the southwest and extreme south ones, is characterized by the combination of low winter and high summer temperatures, which governs the sharp-continental climate. In addition to the above climatic peculiarities, it should be also noted that the climate in Kazakhstan is getting warmer more intensively, which was pointed out in the state program “Ecology of Kazakhstan for the period of 2010-2020: the rise in mean temperature on the territory of the country is on average two times higher than the world's values. Such data on the climatic conditions, even described briefly, show that it is necessary to take in to account their diversity, when substantiating the asphalt mix compositions and thermal stability of applied bitumens for separate regions, as well as to consider the fact that it is impossible to have a single solution for the country.

2. ZONING OF THE KAZAKHSTAN TERRITORY AS TO THE PAVEMENT PERFORMANCE TEMPERATURES

The necessity in differentiating the climatic conditions when choosing a bitumen for asphalt mixes is supported by various performance qualities of the asphalt pavements in different areas of the Republic. Along with this, the normative documents of the former USSR specified practically the same requirements for asphalt concretes in climatic zones IV-V, to which the Kazakhstan territory was attributed. These requirements were identical to those for asphalt concrete in road-climatic zones IV-V of the European part of the USSR with milder climate. It is evident that this situation arose from the fact that zoning was not based on the asphalt pavement performance.

With the road network development, increased asphalt pavement length, and need to improve the transport-operational indices, it has become obvious that such zoning is necessary for substantiating the requirements for bitumen and asphalt concrete depending on the pavement performance temperature.

For this purpose, methods for determining the design minimum and maximum pavement temperatures have been analyzed on the basis of long-term meteorological observation data. It has been found that at present there exist several methodical approaches [1, 2, 3]. Table 1 gives the results of determining the asphalt pavement design temperatures by Superpave method [1] with the use of formulae proposed by Ya. N. Kovalyov [2] and B. B. Teltayev [3].

Table 1. Design temperatures determined by different methods

Location of meteorological station	Maximum design pavement temperature determined according to			Minimum design pavement temperature determined according to		
	[1]	[2]	[3]	[1]	[2]	[3]
Astana	64	68	50	-29	-37	-37
Almaty	69	64	53	-21	-26	-31
Atyrau	68	78	55	-23	-30	-31
Ust-Kamenogorsk	64	62	51	-33	-41	-38

The analysis of the above table indicates that data obtained on the basis of Superpave research results and those from experimental studies performed by Kazakhstan specialists are close to each other.

In the subsequent analysis, the design values of pavement maximum and minimum temperatures have been defined by Superpave specification formulae that are currently considered as more substantiated and checked.

The maximum design temperature values have been determined by formula:

$T_{max} = (T_{air}-0.00618Lat^2+0.2289Lat+42.2)\ (0.9545)-17.18,$ (1)

where
T_{max} – maximum design pavement temperature at a depth of 20 mm, °C;

T_{air} – mean of absolute maximum air temperature for 7-day period, °C;

Lat – geographic latitude.

The design values of pavement minimum temperature T_{min} have been found from the following empirical formula depending on minimum air temperature T_{air}:

$T_{min}=0.859\ T_{air}+1.7^0C,$
(2)

Maximum and minimum design pavement temperatures defined from the data of 20 main meteorological stations located on the Republic's territory with the use of Superpave Specifications are presented in Table 2.

Table 2. Design temperature values for asphalt pavements on the Kazakhstan territory

Meteorological station location	Pavement design temperatures, ° C		Meteorological station location	Pavement design temperatures, ° C	
	T max	T min		T max	T min
t. Astana	51,9	-36,4	t. Karaganda	53,2	-34,4
t. Aktau	58,5	-23,4	t. Kostanai	52,7	-37,3
t. Aktobe	55,6	-37,5	t. Kyzylorda	59,4	-28,9
t. Almaty	55,9	-24,1	t. Pavlodar	52,4	-38,8
t. Aralsk	60,1	-32,5	t. Petropavlovsk	49,4	-38,6
t. Arkalyk	54,3	-35,9	t. Semei	53,6	-39,8
t. Atyrau	58,5	-31,7	t. Taldykorgan	57,3	-33,6
t. Balkhash	54,0	-33,0	t. Uralsk	55,5	-35,0
t. Taraz	58,2	-27,5	t. Ust-Kamenogorsk	53,5	-42,0
t. Zhezkazgan	57,3	-37,2	t. Shymkent	58,6	-22,9

On the basis of Table 2 data, zoning of the Kazakhstan territory as to the asphalt pavement performance temperatures has been developed (Figure 1).

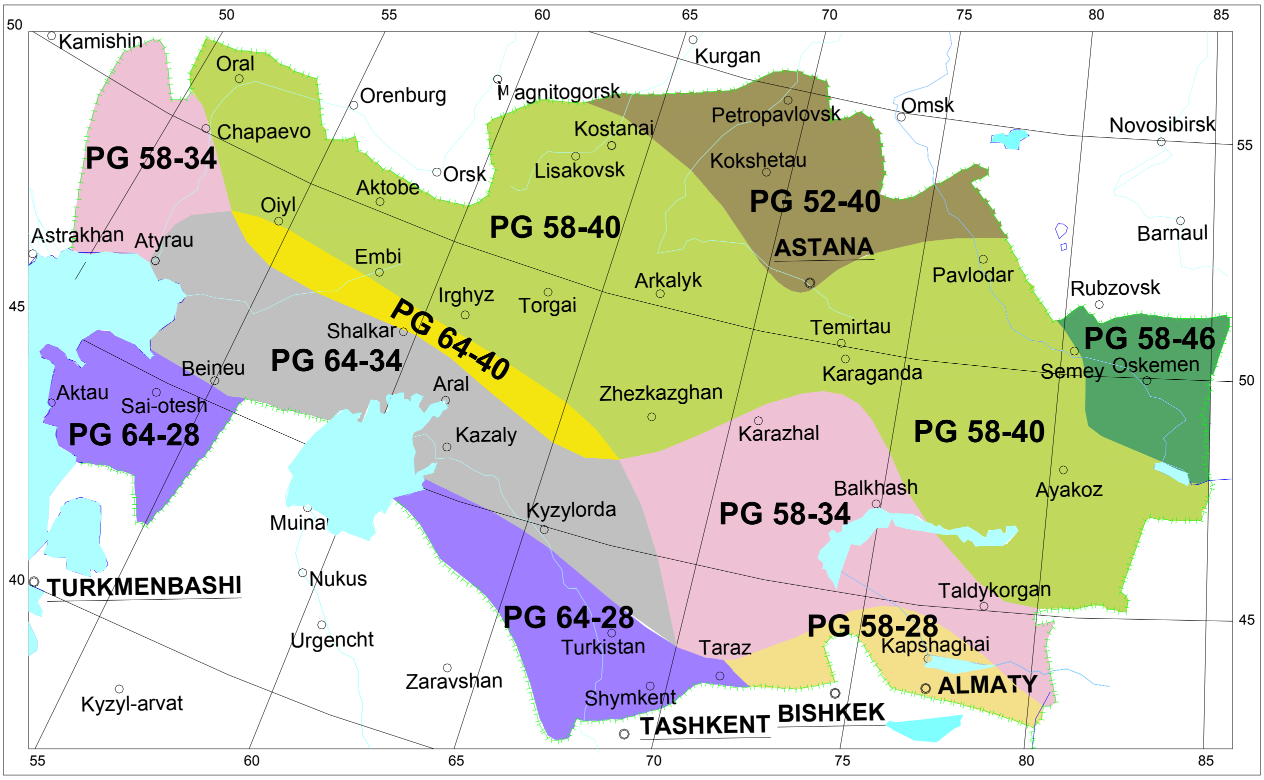

Figure 1. Zoning of the Kazakhstan territory as to the asphalt pavement performance temperatures

3. EVALUATION OF BITUMEN THERMAL RESISTANCE AS TO DIFFERENT CRITERIA

According to Superpave Specifications, the compliance with the requirements for characteristics defined by means of specially developed devices (dynamic shear rheometer, rotational viscometer, bending beam rheometer, and direct tension test device) at temperatures approaching the design ones is the criterion for choosing a bitumen for asphalt mixtures.

In connection with the fact that many laboratories of the Kazakhstan road organizations are not furnished or furnished inadequately with the equipment for such binder tests, an attempt was undertaken to accept the standard indices characterizing the bitumen thermal stability as the estimation ones with some degree of conventionality. As such indices the following ones have been accepted: ring and ball softening temperature T_{soft} after ageing according to ST RK 1224-2003 [4], which characterizes the plastic deformation stability of bitumen and thus asphalt concrete at high summer temperatures, and Fraas brittle temperature T_{brit} also after ageing according to CT RK 1224-2003, which defines the crack resistance at low winter temperatures.

In so doing, the condition $T_{soft}>T_{max}$, where T_{max} is the design maximum pavement temperature from formula (1), is taken as the basic criterion of the asphalt pavement resistance to high-temperature plastic deformations whereas the condition $T_{brit}<T_{min}$, where T_{min} is the design minimum pavement temperature from formula (2), is accepted as the criterion of the asphalt pavement resistance to low-temperature cracking. It should be noted that when choosing the composition of polymer-modified bitumen binder on the basis of SBS blockpolymers worked out in Russia [2], the similar criteria are accepted with

the difference that the design values of maximum and minimum pavement temperatures are determined by Ya. N. Kovalyov's formulae while the brittle and softening temperatures are defined for the initial bitumen. We think that considering the bitumen thermal resistance after ageing with due regard to the performance temperature allows to simulate the real conditions more adequately: the asphalt concrete and bitumen perform under the actual service conditions after heating the bitumen to the working temperature, preparing a mixture in the mixer, etc, that is after ageing, and the brittle temperature results determined after heating (Table 3) indicate that it increases to a variable degree (4 to 11.3%) for bitumens of different manufacturers.

Table 3. Change in bitumen brittle temperature after their ageing

Serial number	Bitumen grade manufacturing plant	Bitumen brittle temperature, °C		increase of t_{brit}, %
		initial	after ageing	
1.	BND 80/120 Orsk plant	-27.3	-26.2	4.0
2.	BDU 100/130 Ukhta plant	-26.7	-24.5	8.0
3.	BND 60/90 Saratov plant	-24.2	-21.6	10.7
4.	BND 90/130 Ufa plant	-22.4	-21.4	4.5
5.	BND 90/130 Ryazan plant	-21.7	-19.8	8.3
6.	BND 90/130 Novokuibyshev plant	-26.6	-25.6	3.7
7.	BND 60/90 Salavat plant	-25.0	-23.7	5.2
8.	BND 60/90 Syzran plant	-22.1	-19.6	11.3
9.	BND 90/130 Syzran Plant	-25.6	-24.5	4.3

These criteria for choosing a binder to ensure the asphalt concrete performance under the particular climatic conditions appear as logically correct. Table 4 presents the results of four bitumen tests performed by one specialist using 7 devices of different design and various manufacturers.

Table 4. Brittle temperature values (°C) obtained using different Fraas devices

Bitumen manufacturer	T_{brit} values, ^{0}C, determined with						
	ATKh -024	ATKh -30	ATKh - 20	Pikhta-72M	Manual device 1	Manual device 2	ATKh (using a smoothing iron)
1. Almaty plant	-29.9	-31.8	-25.5	-24.0	-20.6	-24.2	-29.5
2. Pavlodar plant	-25.6	-25.8	-24.5	-20.5	-17.8	-19.7	-27.4
3. Ukhta plant	-23.7	-27.7	-29.8	-20.7	-17.5	-23.0	-23.9
4. Yanos	-26.3	-30.0	-28.0	-22.7	-17.9	-20.9	-26.2

The analysis of data in the table shows that variation in the results obtained for one bitumen tested by the same specialist is in the range of 0.4 to 41.2 whereas deviation from the average value is 22-26%. This situation with Fraas method for determining the bitumen brittle temperature makes one to admit that Superpave method for determining the low-temperature binder characteristics with the use of bending beam rheometer (BBR) is now preferable. Therefore during the subsequent studies the low-temperature resistance of bitumens was determined with BBR and their resistance to high summer temperatures – with M. W. Witczak – Bari correlation model [5].

Indices of physical-chemical properties of the bitumens studied are given in Table 5.

Figures 2 and 3 present the relationships between the complex shear modulus of the above bitumens and their temperatures in the initial state (before ageing) and in the state after RTFOT (5) ageing, respectively.

As can be seen, for all the bitumens considered the complex shear modulus-temperature relationship is nonlinear. With a rise in temperature the value of complex modulus decreases. Stiffness of bitumens manifests itself at relatively not high temperatures. For instance, in the temperature range of 52°C to 64°C, as expected, BND 60/90 viscous bitumens in the initial state show the highest stiffness. The complex shear modulus – temperature relationships of BND 90/130 are located lower than the corresponding plots of BND 60/90 bitumens (Figure 2).

This is explained by the fact that at such temperatures bitumens have not reached the viscous-elastic state yet. With further rise in temperature the bitumens begin quickly transfer into the liquid state. At a temperature of 82°C all the bitumens practically are in the liquid state and characterized by low values of the complex shear modulus approaching zero.

It can be noticed that the ageing process has a different effect on each bitumen. So, after RTFOT ageing, BND 60/90 bitumen produced by the Almaty plant and BND 90/130 bitumens produced by the Pavlodar and Ukhta plants practically have the same complex shear modulus-temperature relationships (Figure 3). Thereby, their complex modulus values after ageing at 52°C were 1.9 to 3.5 times higher as compared with those in the initial state. BND 60/90 bitumen of the Pavlodar plant manufacture remained the most stable at high temperatures both before and after ageing (Figure 4) with a 2.8 fold increase in the maximum shear modulus after ageing.

BND 90/130 bitumen produced by the Almaty plant was the softest one after ageing. Among all the bitumens examined, precisely this one is characterized by the lowest value of complex shear modulus after ageing within the accepted temperature interval with a 1.4 fold maximum increase in the complex modulus (Figure 5).

Table 5. Indices of physical-chemical properties of the bitumens studied

Index name	Values of bitumen indices				
	BND 90/130 Almaty plant	BND 90/130 Pavlodar plant	BND 90/130 Ukhta plant	BND 60/90 Almaty plant	BND 60/90 Pavlodar plant
Bitumen number	**1**	**2**	**3**	**4**	**5**
Needle penetration depth, 0.1 mm					
- at 25°C	102	105	109	86	71
- at 0°C	42	32	29	25	25
Ductility, cm					
- at 25°C	116.8	127	98.5	105	74
- at 0°C	5.5	4.9	5.7	4.0	3.7
Softening point, °C	48	45	49	49.5	50
Brittle temperature, ^{0}C	-31.6	-26.4	-27.3	-24.9	-27.1
Penetration index	+0.19	-0.64	+0.41	+0.70	-0.08
Dynamic viscosity at 60°C, Pa·s	157.5	137.2	111.7	226.0	337.8
Kinematic viscosity at 135°C, mm^2/s	256.9	252.8	203	313	362.8
Ageing resistance at 163°C in 3.2 mm course -change in softening point, °C	3.0	4.0	1.0	4.0	4.0
-change in mass, %	0.23	0.20	0.30	0.16	0.16
-needle penetration depth, %	69.6	67.0	66.6	68.3	70.0

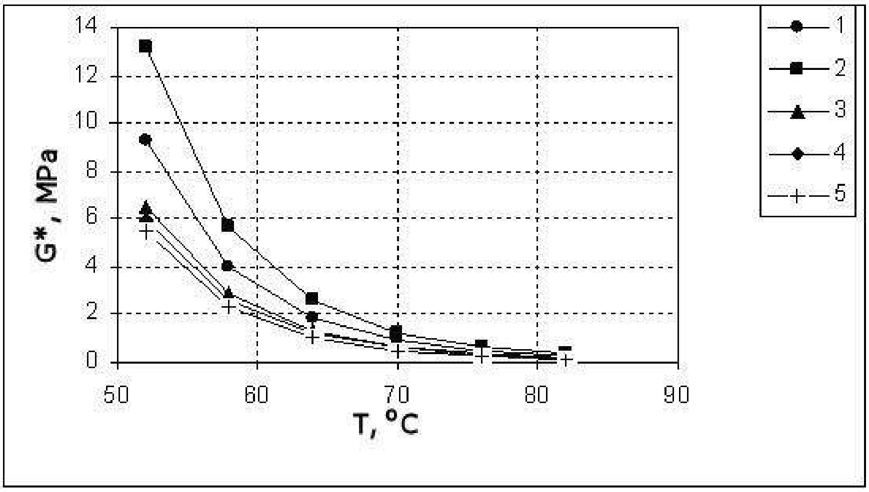

Figure 2 - Complex shear modulus-temperature relationship in the initial state of bitumens

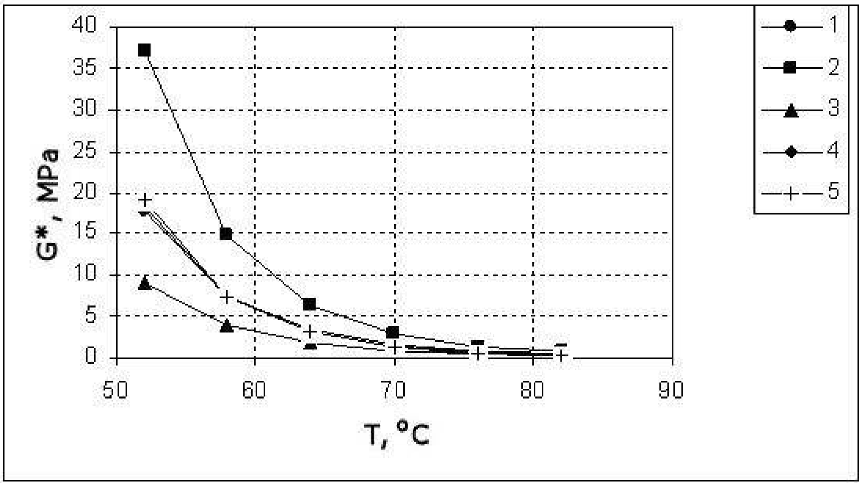

Figure 3 - Complex shear modulus-temperature relationship after RTFOT bitumen ageing

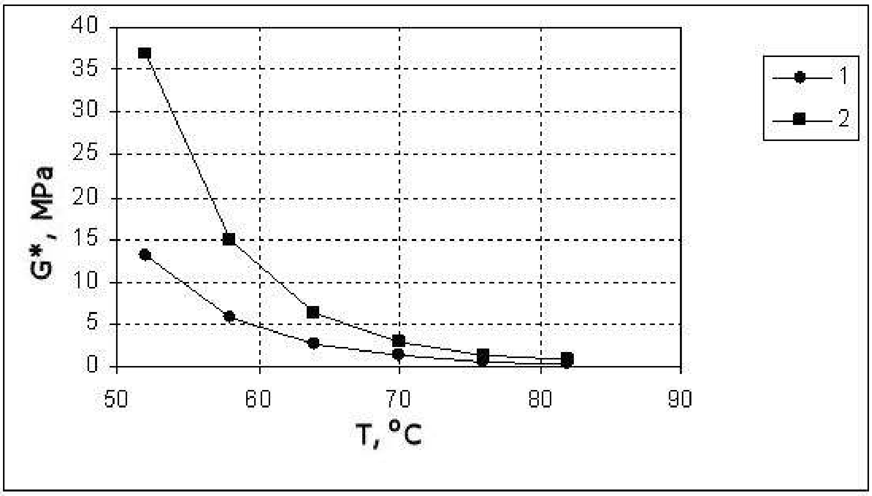

Figure 4 - Complex shear modulus-temperature relationship for BND 60/90 bitumen produced by the Pavlodar plant in the initial state and RTFOT+PAV ageing

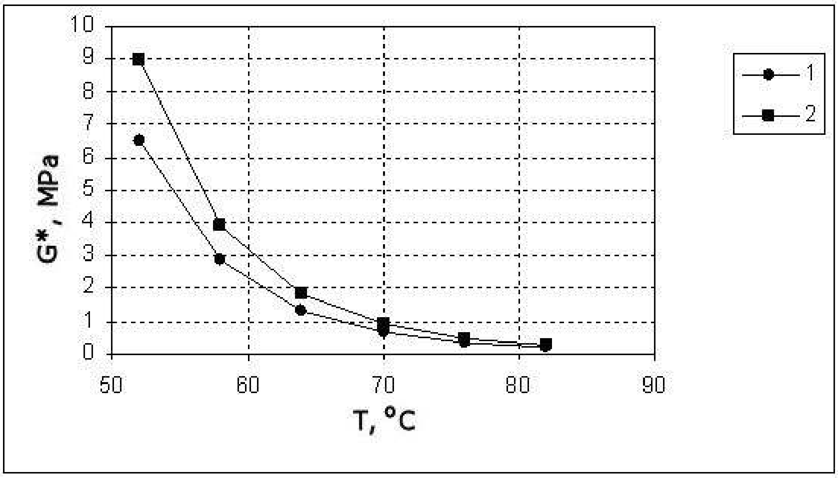

Figure 5 - Complex shear modulus-temperature relationship for BND 90/130 bitumen produced by the Almaty plant in the initial state and after RTFOT+PAV ageing

The relationship between bitumen phase angle (both in the initial state and in the state after ageing) and temperature is of nonlinear character as well. With a rise in temperature the value of phase angle increases (Figure 6). It has been found that within a temperature interval of 52°C to 82°C the phase angle of bitumens under consideration changes from 74°C to 89°C. This points out that with the rise in temperature, the bitumens that are in the mechanical state of elastic-viscous deformability, at a temperature of 52°C, begin to show the viscous properties rather than the elastic ones. The ageing process results in a reduction of the phase angle on average by 2° for all the bitumens.

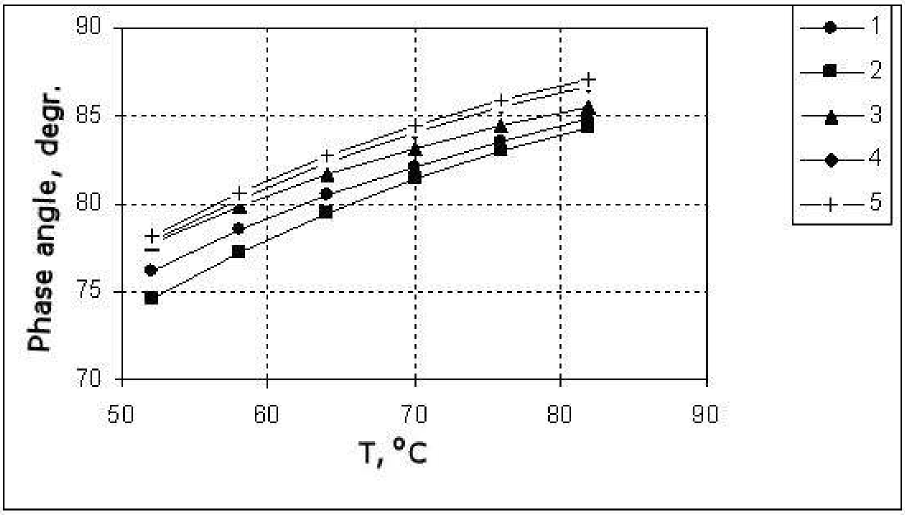

Figure 6 - Phase angle-temperature relationship after RTFOT ageing of bitumens

As is known, the basic engineering requirements of the Superpave system are given for high-speed traffic road sections (mainline sections) with the total number up to 10 million equivalent axle design load applications per one traffic lane for the whole service life of a road pavement [1]. If the total number of design axle load applications is within 10 to 30 million, it is necessary to raise the binder grade by one scale. In cases when the total number of design axle load applications exceeds 30 million, the binder grade should be selected by two scales higher. For the road sections with slow traffic (for example, road intersections) the binder should be also chosen higher by one more grade.

The design axle load accepted in the USA is 80 kN. In Kazakhstan in 2005, in the flexible road pavement design for roads of the Republic and international significance a load of 130 kN was taken as the design one. The coefficient of equivalence for the design axle action is determined by formula (3):

$$S = \left(\frac{Q_{130}}{Q_{80}}\right)^{4,4}, \qquad (3)$$

where Q80, Q130 are the axle design loads accepted in the USA and Kazakhstan, which are equal to 80 kN and 130kN, respectively.

We found from formula (1) that S=8.47. This means that one passage of 130kN axle load in respect of the destruction action on the road pavement is equivalent to 8.47 passages of 80 kN axle load. Thus, 1.181 million and 3.542 million passages of 130 kN axle load correspond to the total numbers of passages of 80 kN axle load, equal to 10 million and 30 million.

The analysis of reconstruction projects of roads with the road pavement structures designed for 130 kN load has shown that the total number of design axle loads substantially exceeds 3.542 million during the design service life. This requires to specify the grades of bitumen binder by two scales higher than the basic ones determined by the map (Figure 1).

On the basis of the analysis of Kazakhstan territory zoning as to the performance conditions and the results of high-temperature bitumen stability studies, with regard to the foregoing about the relative number of design axle passages, it has been established that only the Pavlodar plant bitumen of BND 60/90 grade can provide the rut resistance of asphalt pavement over the larger part of the Kazakhstan territory.

To study the behavior of bitumens under the low-temperature conditions, BND 90/130 bitumens of two Kazakhstan (Almaty and Pavlodar) plants were tested using bending beam rheometer (BBR). Figure 7 presents bitumen maximum flexural tensile deformation versus temperature. As can be seen, with lowering the temperature the bitumen deformation decreases according to the nonlinear relationship. As the temperature lowers, there takes place a drop in the rate of deformation reduction. At a temperature of 12°C, the deformability is more for the Pavlodar plant bitumen the deformation of which is 1.5 times higher than that of the Almaty plant bitumen, while at -27...-28°C they both show the same deformability (deformation is $0.6\text{-}0.8 \times 10^{-3}$). In the range from -12°C to -27...-28°C the deformation of the Pavlodar bitumen decreases by 19 times whereas that of the Almaty bitumen – by 17 times.

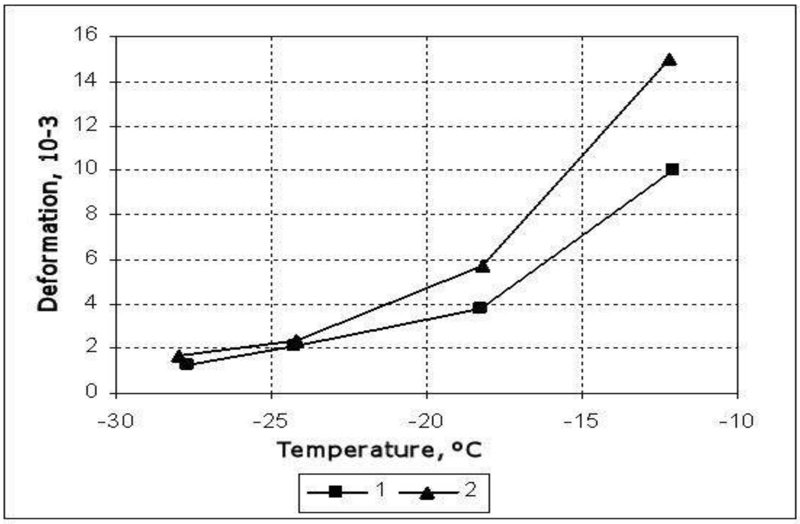

Figure7 - Maximum flextural deformation-temperature relationship for bitumen samples

The relationships of change in bitumen stiffness (Figure 8) show that the Almaty bitumen is stiffer than the Pavlodar one. The stiffness of bitumens also depends nonlinearly on temperature. In contrast to the change in deformation, the rate of decrease in bitumen stiffness becomes lower with the temperature rise. Thereby, the maximum values of bitumen stiffness occur at the lowest temperatures while the minimum ones – at the highest temperatures over the interval considered. At a temperature (-27...-28)°C the values of stiffness for the Pavlodar and Almaty bitumens are equal to 229 MPa and 174 MPa, respectively, whereas at -12°C they are 29 MPa and 21 MPa, respectively, that is the difference in bitumen stiffness values grows with temperature lowering.

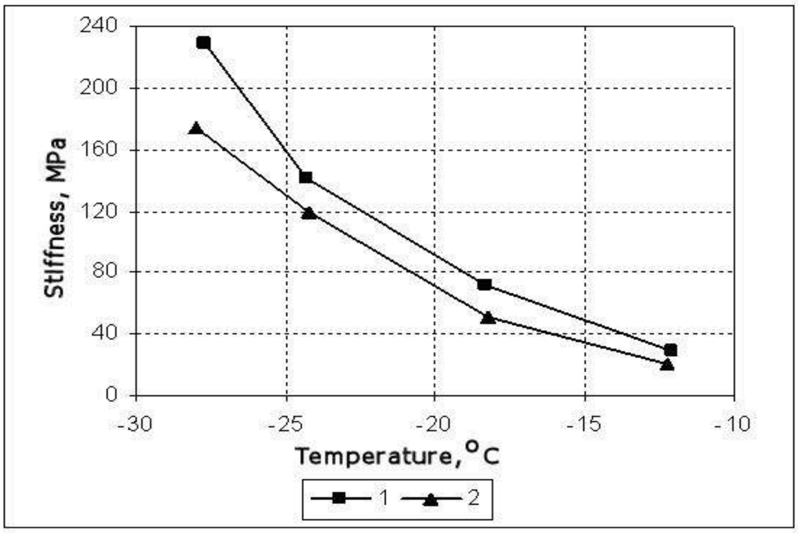

Figure 8. Bitumen stiffness-temperature relationship

The temperature relationships of the index of stress relaxation rate (m) for the bitumens tested are found to be completely different (Figure 9). With lowering the temperature, index m of the Almaty plant bitumen reduces according to the rectilinear relationship from 0.41 at -12°C to 0.36 at -28°C. Index m of the Pavlodar plant bitumen decreases in compliance with the nonlinear law. It is evident that this bitumen has a higher rate of stress relaxation. At a temperature of -12°C it is substantially higher than that of the Pavlodar plant bitumen.

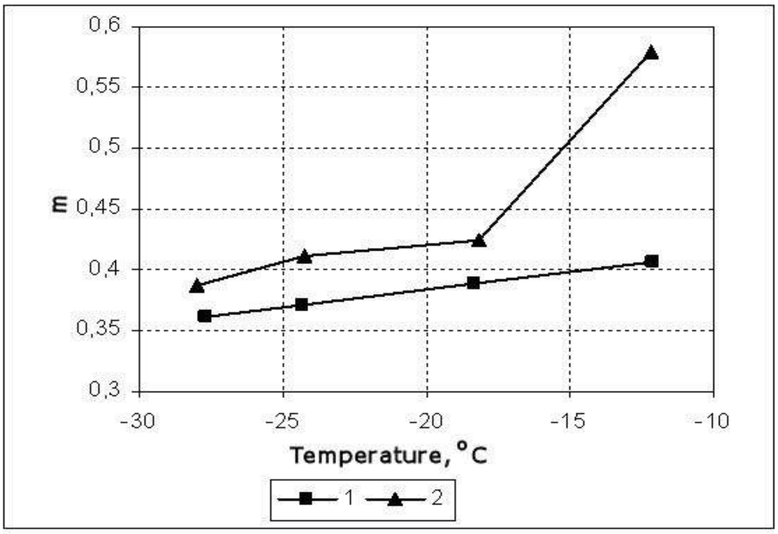

Figure 9. Stress relaxation rate-temperature relationship for bitumens

Thus, based upon the analysis of indices of the mechanical behavior for the bitumens examined, it can be stated that BND 90/130 bitumen of the Pavlodar plant, having better deformation and relaxation capacities and lower stiffness at negative temperatures, possesses the highest crack resistance. This bitumen has relatively high crack resistance, particularly at the lower values of negative temperatures (approximately up to -10...-15°C). The results obtained are in good agreement with composition data for the studied bitumens presented in Table 6.

Table 6. Composition of bitumens studied

Component name	Content in bitumen, %	
	Pavlodar plant	Almaty plant
Parafin-naphthene hydrocarbons (PN)	22.7	19.8
Monocyclic aromatic hydrocarbons (MA)	9.5	8.7
Bicyclic aromatic hydrocarbons	4.7	6.6
Polyciclic aromatic hydrocarbons	20.1	20.9
Petroleum benzene resins	6.6	11.5
Alcohol-benzene resins	20.7	20.4
Asphaltenes	15.7	12.1

As can be seen from the analysis of Table 6, the Pavlodar plant bitumen contains more asphaltenes that essentially provide the thermal resistance and the sum of PN and MA in it is higher (32.2%) than that in the bitumens of the Almaty plant (28.5%).

When comparing the results of evaluating the low-temperature characteristics of these bitumens and the requirements for them based on the performance conditions (Figure 1), one can conclude that only in the south and southwest Kazakhstan regions it is possible to expect the absence of the low-temperature deformations of asphalt pavements. From the test results and physical-mechanical characteristics of other industrial bitumens it follows that in fact there are no bitumens that meet the performance conditions of the most part of the Kazakhstan territory [6]. This substantiates the necessity to apply polymer-modifiers that are widely checked in situ in Kazakhstan with the aim of choosing technically expedient and cost-effective solutions. In recent years a number of polymer additives introduced into bitumen or asphalt mix has been appraised: Kraton, Elvaloy, Sasobit, Butonal, TAFPACK-Super (TPS), TPS-F, etc. It has been established that at their introduction the low-temperature properties of polymer modified bitumen binder do not change (Kraton, Sasobit) or change insignificantly (2°C for Elvaloy per 1% polymer) while the thermal resistance improves substantially: for each one percent of introduced additive the increase is approximately by 6°C for Kraton, by 14°C for Elvaloy, and 9°C for Sasobit. These results are in good agreement with the actual pavement condition.

CONCLUSIONS

1. The normative document base of the former USSR did not take into account the peculiarities of the sharp-continental climate in Kazakhstan in full measure.

2. On the basis of the analysis of climatic conditions and the research results, zoning of the Republic territory has been developed with taking into consideration the climate changes during the last ten-year period.

3. The results of studies of the high-temperature stability of bitumens applied in road building in Kazakhstan have indicated that they meet the requirements of climatic conditions only partially.

4. The analysis of the research results of the low-temperature characteristics of bitumens has made it possible to establish that they satisfy the climatic condition requirements for a relatively small part of the territory.

5. The compliance of bitumen and asphalt concrete performance with climatic conditions can be achieved with the use of polymers. For this purpose the Republic is carrying out studies and monitoring of the built road sections.

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