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# Evaluation of Low Temperature Cracking Indicators of Hot Mix Asphalt Pavement

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**Abstract:** Low temperature cracking is one of the prevalent types of hot mix asphalt pavement defects, and there are many methods of its evaluation. In this paper, the indicators of hot mix asphalt pavement low temperature cracking are evaluated by a combined approach, where hot mix asphalt tensile strength at low temperatures has been determined by testing in conditions of deformation with constant rate, and low temperature stress has been calculated based on integral equation of linear viscoelasticity theory. Conditions of air cooling have been considered through the temperature falling (cooling) rate. It has been ascertained that for the considered hot mix asphalt at cooling rate from 0.4°C/h to 1.6°C/h, Critical stress and Critical temperature do not depend on cooling rate: critical stress $\sigma_{cr}$ = 6.0 to 6.2 MPa, Critical temperature $T_{cr}$ = -19 to -21°C. The indicator, characterizing the low temperature stress increase rate in hot mix asphalt pavement, at Critical time also does not depend on the cooling rate and has constant value equal to 2.7.

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***Key words**: Asphalt mixture; Critical stress; Critical temperature; Critical time; Low temperature cracking.*

## Introduction

Low temperature cracking is one of the main defects of hot mix asphalt pavement, affecting service life of the road [1-3]. Therefore, the development of reliable methods of evaluating low temperature cracking indicators of hot mix asphalt should be considered [4-7]. A number of methods are known at present, including the following: bending beam test, indirect tensile test, and thermal stress restrained specimen test. But these methods do not adequately consider actual conditions for temperature variation during the cold season of the year. Therefore, results of testing by the above methods sometimes do not show data obtained in field conditions. Moreover, results of the work [8] show that, compared with thermal stress restrained specimen test, the bending beam test, indirect tensile test, and contraction coefficient test are not appropriate for the evaluation of an asphalt mixture's low temperature performance. Recently, an evaluation of low-temperature indicators of hot mix asphalts began to apply new methods, such as the dish-shaped compact tension test [9], the acoustic emission techniques [9], and the semi-circular bending test [10-12]. Well-known works include those of research groups under the leadership of H. Bahia at the University of Wisconsin-Madison [13, 14] and under the leadership of M. Marasteanu at the University of Minnesota [15, 16], which are directed to take into account glass transition and physical hardening in determining low-temperature indicators of hot mix asphalts.

In this paper, evaluation of low temperature cracking indicators of hot mix asphalt pavement has been carried out by a combined method, where hot mix asphalt tensile strength at low temperatures were determined in conditions of deformation with constant rate, and low temperature stress was calculated based on integral equation of linear viscoelasticity theory. With such approach, one can consider the properties of hot mix asphalt as well as conditions of temperature falling (cooling) in specific areas.

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## Materials and Methods

### Used Materials

In this paper, bitumen of BND-90/130 grade was used, meeting the requirements of Kazakhstan standard ST RK 1373. Performance grade of the bitumen is PG 64-40 [21]. Basic standard indicators for bitumen are shown in Table 1. Bitumen has been produced by Pavlodar processing plant from crude oil of Western Siberia (Russia) by direct oxidation.

Dense graded hot mix asphalt of type B under Kazakhstan standard ST RK 1225 has been prepared with the use of aggregate of fractions 5-10 mm (20%), 10-15 mm (13%), 15-20 mm (10%) from Novo-Alekseevsk rock pit (Almaty region), sand fraction 0-5 mm (50%) from the plant "Asphaltconcrete-1" (Almaty city), and activated mineral powder (7%) from Kordai rock pit (Zhambyl region).

Bitumen content in hot mix asphalt is 4.8% by weight of dry mineral material. Basic standard indicators for aggregate and hot mix asphalt are shown in Tables 2 and 3 respectively. The asphalt mixture grading curve for its mineral part is shown in Fig. 1.

### Indicators of Bitumen Low Temperature Stability

The indicator of bitumen low temperature stability-creep stiffness (S) and the indicator, characterizing rate of stress relaxation (m-value) of bitumen, have been determined by testing on bending beam rheometer (BBR) (Fig. 2) at temperatures -18, -24, -30 and -36°C under standard ASTM D 6648 after aging of bitumen under standards ASTM D 2872 and ASTM D 6521. The device has been produced by the company ATS (Applied Test Systems Inc., USA).

**Table 1.** Characteristics of Bitumen on Standard ST RK 1373.

| Indicator | Measurement Unit | Test Method | Standard Requirements | Value |
|---|---|---|---|---|
| Penetration, 25°C, 100 g, 5 s | 0.1 mm | ASTM D 5 | 91-130 | 98 |
| Penetration Index PI | - | ST RK 1373 | -1.0 to +1.0 | -0.96 |
| Ductility: | cm | ASTM D 113 | | |
| - 25°C | | | ≥ 65 | 139 |
| - 0°C | | | ≥ 4.0 | 5.5 |
| Softening Point | °C | ASTM D 36 | ≥ 43 | 45.3 |
| Fraas Point | °C | DIN EN 12593 | ≤ -20 | -24.6 |
| Dynamic Viscosity, 60°C | Pa·s | DIN EN 12596 | ≥ 75 | 174.2 |
| Kinematic Viscosity | $mm^2/s$ | ASTM D 445 | ≥ 180 | 409.0 |

**Table 2.** Characteristics of Aggregate on Standard ST RK 1284.

| Indicator | Measurement Unit | Test Method | Standard Requirements | Value | |
|---|---|---|---|---|---|
| | | | | Fraction 5-10 mm | Fraction 10-20 mm |
| Average Density | $g/cm^3$ | ASTM C 127 | - | 2.55 | 2.62 |
| Elongated Particle Content | % | BS 812.105.2 | ≤ 25 | 13 | 9 |
| Clay Particle Content | % | ST RK 1213 | ≤ 1.0 | 0.3 | 0.2 |
| Bitumen Adhesion | - | ST RK 1218 | - | satisf. | satisf. |
| Water Absorption | % | ASTM C 127 | - | 1.93 | 0.90 |

**Table 3.** Characteristics of Hot Mix Asphalt on Standard ST RK 1225.

| Indicator | Measurement Unit | Test Method | Standard Requirements | Value |
|---|---|---|---|---|
| Average Density | $g/cm^3$ | ST RK 1218 | - | 2.39 |
| Water Saturation | % | ST RK 1218 | 1.5-4.0 | 2.3 |
| Voids in Mineral Aggregate | % | BS EN 12697 | ≤ 19 | 14 |
| Air Void Content in Hot Mix Asphalt | % | BS EN 12697 | 2.5-5.0 | 3.8 |
| Compression Strength: | MPa | ST RK 1218 | | |
| - 0°C | | | ≤ 13.0 | 7.3 |
| - 20°C | | | ≥ 2.5 | 3.4 |
| - 50°C | | | ≥ 1.3 | 7.3 |
| Water Stability | - | ST RK 1218 | ≥ 0.85 | 0.92 |
| Shear Stability | MPa | ST RK 1218 | ≥ 0.38 | 0.40 |
| Crack Stability | MPa | ST RK 1218 | 4.0-6.5 | 4.1 |

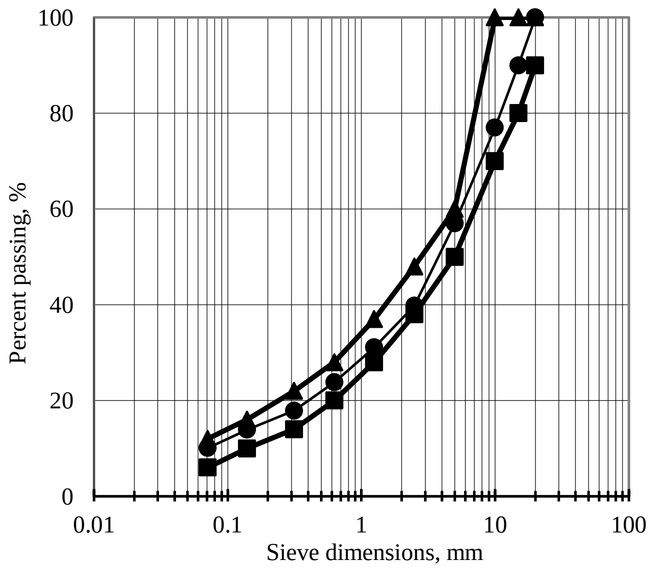


**Fig. 1.** Asphalt Mixture Grading Curve.


**Fig. 2.** Bending Beam Rheometer.

A sample of bitumen in the form of beam with dimensions 125x12.5x6.35 mm was tested by applying a load of 100 g (980 mN) to the center of the sample. Deflection of the center of the beam has been measured at 8, 15, 30, 60, 120 and 240 s. Stiffness was calculated by Eq. (1):

**Fig. 3.** Testing System TRAVIS.

$$S(t) = \frac{PL^3}{4\,b\,h^3\,\delta(t)} \tag{1}$$

where S(t) = stiffness at load time duration t;
P = applied load;
L = length of beam span;
b, h = width and height of beam;
δ(t) = deflection of center of beam span at time t.

### Hot Mix Asphalt Tensile Strength

Hot mix asphalt tensile strength has been determined by testing of samples in the form of beam with dimensions 40x40x160 mm in special testing system TRAVIS, produced by the company InfraTest (Germany) (Fig. 3). Tests were performed in accordance with the requirements of standard EN 12697-46 at temperatures 20, 10, 0, -10, -20 and -30°C. During testing, the sample of hot mix asphalt was deformed with constant rate of 1 mm/min. The testing system records stress (strength) and deformation at the moment of sample failure.

### Air Temperature Variation in Winter Season

The results of analysis of air temperature variation in the winter season in cold regions of Kazakhstan for the years 2006-2011 show that sharp decreases in temperature often occur there. Air temperature can fall up to -40°C and lower. The character of temperature variation and its lower value in different years can vary. As an example, Fig. 4 shows two diagrams for air temperature variation using data from the meteorological station of Astana city: the first one shows air temperature variation in January 2006, and the second one shows the same month of 2009. It seems that January of 2006 has been considerably colder than January of 2009. Thus, air temperature of January in 2009 fell up to -26°C and ranged from -22°C to -26°C for the whole month. In January of 2006, the

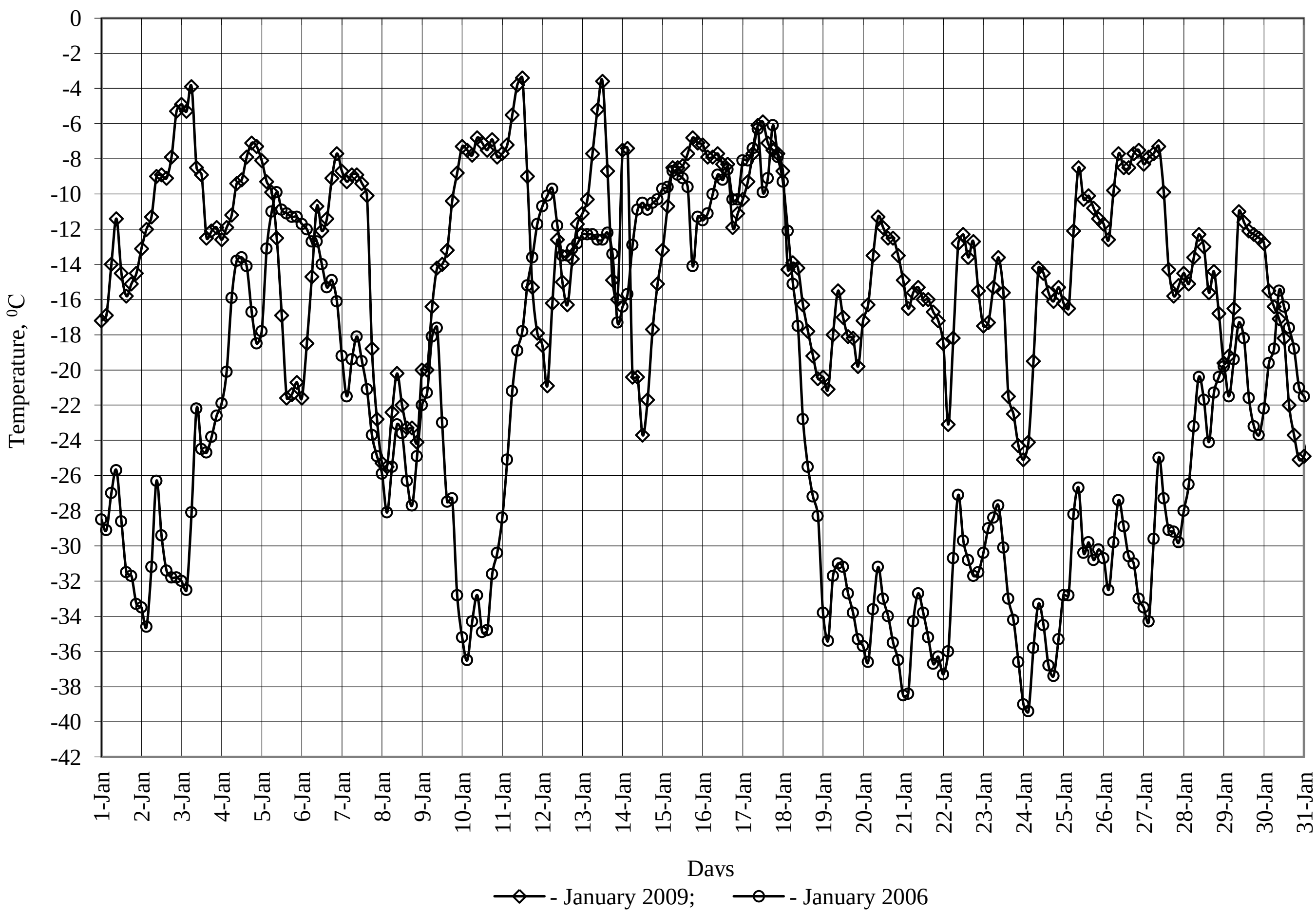


**Fig. 4.** Air Temperature Variation in Astana.

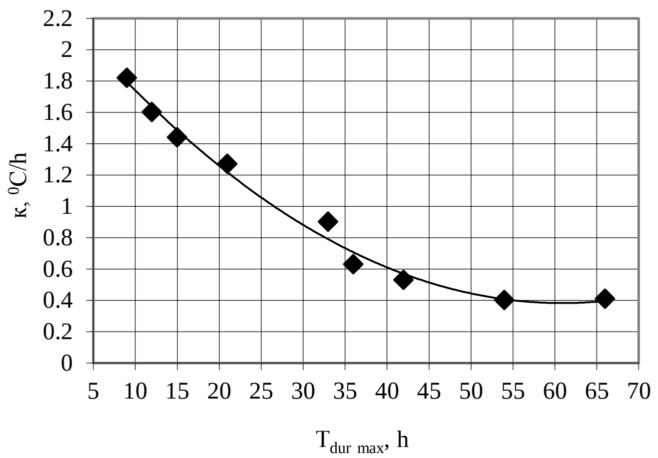


**Fig. 5.** Air Cooling Rate Versus Maximum Duration of Cooling.

lowest air temperature fell approximately to -40°C, and for nearly half of the month, the temperature had value less than -26°C.

As a result of statistical processing for specific indicators of air temperature in Astana, it was ascertained that:

- in 80 cases out of 100, sharp decreasing of air temperature starts from 0 to -16°C;
- maximum rate of air temperature falling is 1.9°C/h;
- in 33% of temperature falling, the cooling rate is within 0.5-0.7°C/h;
- maximum duration of single air temperature falling reaches 66 hours.

A reliable correlation between the air temperature falling (cooling) rate and maximum duration with single (unit) temperature falling occurs as follows:

$$\kappa = 2.3263 - 0.0639 \cdot T_{\text{dur max}} + 0.00053 \cdot T^2_{\text{dur max}} \tag{2}$$

where $\kappa$ = air cooling rate, °C/h;
$T_{\text{dur max}}$ - maximum duration of cooling, h.
A diagram for the above dependency is shown in Fig. 5, which shows that air temperature falling with duration more than 42 hours is realized with the cooling rate approximately 0.4-0.5 °C/h. And, in the case of air temperature falling with duration less than 42 hours, the maximum value of cooling rate depends linearly on air temperature falling duration.

## Calculation of Temperature Stress in Hot Mix Asphalt Pavement

### Temperature Stress

Road specialists believe that low temperature cracking in hot mix asphalt pavement occurs due to the impossibility of free deformation of pavement (compression) in horizontal direction with temperature falling. Its neighboring sections prevent any section of continuous hot mix asphalt pavement from deforming freely. The value of non-realized temperature deformation in hot mix asphalt pavement at time t can be determined under Eq. (3):

$$\varepsilon_T(t) = \alpha\,[T(t) - T_0] \tag{3}$$

where α = linear temperature contraction coefficient of hot mix asphalt, 1/°C;
$T_0$ = initial temperature, °C;
T(t) = temperature at time t.

The present paper considers hot mix asphalt pavement as an infinite bar, lying on continuous homogeneous base, between which there is no friction. The temperature of hot mix asphalt pavement will be characterized by its value on the surface of pavement, i.e. air temperature.

Temperature variation during time is set by Eq. (4):

$$T(t) = T_0 - \frac{1}{3600} \cdot k \cdot t \tag{4}$$

where k = air cooling rate, °C/h;
t = time, s.

Hot mix asphalt is a typical viscoelastic material, mechanical properties of which depend on load duration and temperature [1, 2]. Therefore, temperature stress in hot mix asphalt pavement can be determined by the following integral equation of linear viscoelasticity theory [17]:

$$\sigma_T(t) = \int_0^t E(t-\tau)\,d\varepsilon_T(\tau) \tag{5}$$

where E(t) = hot mix asphalt relaxation function;
t = time, in which stress $\sigma_T(t)$ has been calculated;
$\tau$ = parameter of integration;
$\varepsilon_T(\tau)$ = non-realized temperature contraction in hot mix asphalt pavement.

### Relaxation Function of Hot Mix Asphalt

Hot mix asphalt relaxation function has been described by correlation model of Witczak [18]:

$$\begin{aligned} log|E^*(f)| &= -1{,}249937 + 0{,}029232 \cdot P_{200} - 0{,}001767 \cdot (P_{200})^2 \\ &- 0{,}002841 \cdot P_4 - 0{,}058097 \cdot V_a - 0{,}802208 \cdot \left(\frac{V_{beff}}{V_{beff}+V_a}\right) \\ &+ \frac{3{,}871977 - 0{,}0021 \cdot P_4 + 0{,}003958 \cdot P_{38} - 0{,}00017 \cdot (P_{38})^2 + 0{,}00547 \cdot P_{34}}{1 + exp[-0{,}603313 - 0{,}313351 \cdot log(f) - 0{,}393532 \cdot log(\eta)]} \end{aligned} \tag{6}$$

where $|E^*(f)|$ = absolute value of complex modulus for hot mix asphalt at frequency f, $10^5$ psi;
η = bitumen viscosity, $10^6$ poise;
$f$ = loading frequency, Hz;
$V_a$ = air void content, %;
$V_{beff}$ = effective content of bitumen, %;
$P_{34}$, $P_{38}$, $P_4$ = cumulative remainders on the sieves with size 19 mm, 9.5 mm, 4.75 mm respectively, %;
$P_{200}$ = full passing through sieve with size 0.075 mm, %.

In the represented model, temperature dependence of bitumen viscosity is described by Eq. (7):

$$\log\log(\eta) = A + VTS \cdot \log(T_R) \tag{7}$$

where $\eta$ = bitumen viscosity, cP;
$T_R$ = temperature, $^oR$ (degree in Rankine temperature scale);
*VTS* = temperature susceptibility of bitumen viscosity;
*A* = regression intercept.

By determination of dynamic viscosity of bitumen by mean of vacuum viscometer at temperatures 40, 50, 60, 70, 80, and 90$^o$C under the standard of Kazakhstan ST RK 1211, it was found: $A$ = 10.990, $VTS$ = 3.689.

From the hot asphalt mixture grading curve, it was found that: $P_{34}$ = 0%, $P_{38}$ = 18%, $P_4$ = 39% and $P_{200}$ = 11.25%.

Volume indicators of hot mix asphalt have been determined under methods [19]: $V_a$ = 3.79% and $V_{beff}$ = 9.87%.

Transition from complex modulus of hot mix asphalt at loading frequency $f$ (Hz) to relaxation modulus at duration of loading $t(s)$ has been realized by method of Van der Poel [20], in accordance with which relation between f and t is as follows

$$f = \frac{1}{2\pi t} \tag{8}$$

Transition from temperature under Celsius scale ($^o$C) to the temperature under Rankine scale ($^o$R) is shown in Eq. (9).

$$T_R = \frac{9}{5}T_C + 491.67 \tag{9}$$

## Results and Discussion

### Evaluation of Bitumen Low Temperature Stability

The indicators of low temperature stability of the considered bitumen stiffness S and m-value at load duration of 60 s, determined on the bending beam rheometer (BBR) at temperatures -28, -34, -40 and -46$^o$C, are shown in Figs. 6 and 7. Superpave specifications require bitumen stiffness not to exceed 300 MPa at load duration of 60 s at estimated minimum temperature, and m-value should be not less than 0.3 [21]. We note that m-value decreases as temperature decreases, but with all temperatures, it exceeds the lower limit value 0.3. Bitumen stiffness S exceeds upper limit value 300 MPa only at the temperature -46$^o$C, and at other considered temperatures it has value lower than limit value. It should be noted that impact of temperature on bitumen stiffness is essential. Thus, temperature falling from -40$^o$C to -46$^o$C for 6$^o$C caused a 2.13 times increase of bitumen stiffness.

Therefore, based on the above results for evaluation of low temperature stability of the considered bitumen under Superpave specifications, it can be observed that hot mix asphalt pavement with the use of this bitumen is resistant to low temperature cracking in the regions with minimum winter temperature up to -40$^o$C.

### Temperature Stress

Temperature stress has been calculated at four values of cooling rate (temperature falling): 0.4, 0.8, 1.2 and 1.6$^o$C/h. The obtained results have been shown in Fig. 8. It is obvious that temperature stress with temperature variation under linear dependence at all considered values for temperature falling increases under nonlinear law. Fig. 9 shows diagrams of variations for temperature stress rate. As

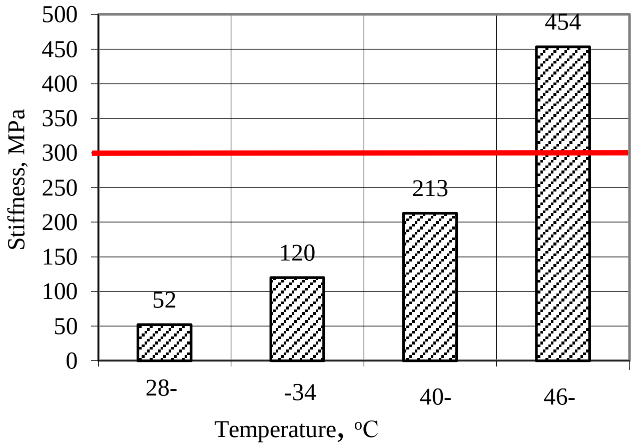


**Fig. 6.** Bitumen Stiffness at Low Temperatures

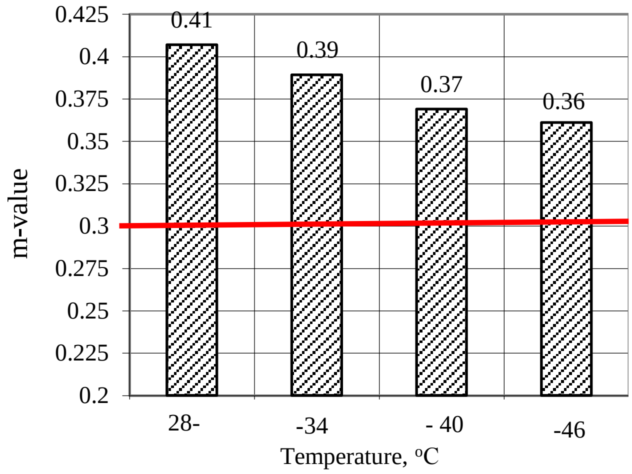


**Fig. 7.** m-value for Bitumen at Low Temperatures.

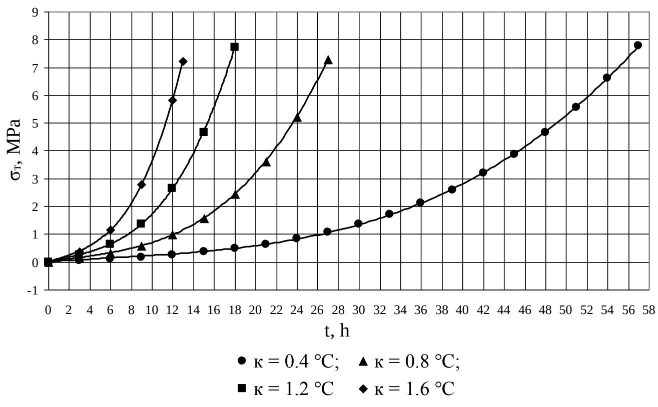


**Fig. 8.** Low Temperature Stress in Hot Mix Asphalt Pavement.

expected, the rate of temperature falling greatly affects the rate of temperature stress increase. Thus, at temperature falling rate k =0.4$^o$C/h, the rate for temperature stress increase $\dot{\sigma}_T$ = 0.4 MPa/h has been reached only after 57 hours, and at k =1.6$^o$C/h already in 14 hours since cooling commencement $\dot{\sigma}_T$ exceeds 1.7 MPa/h.

### Results of Determination of Hot Mix Asphalt Tensile

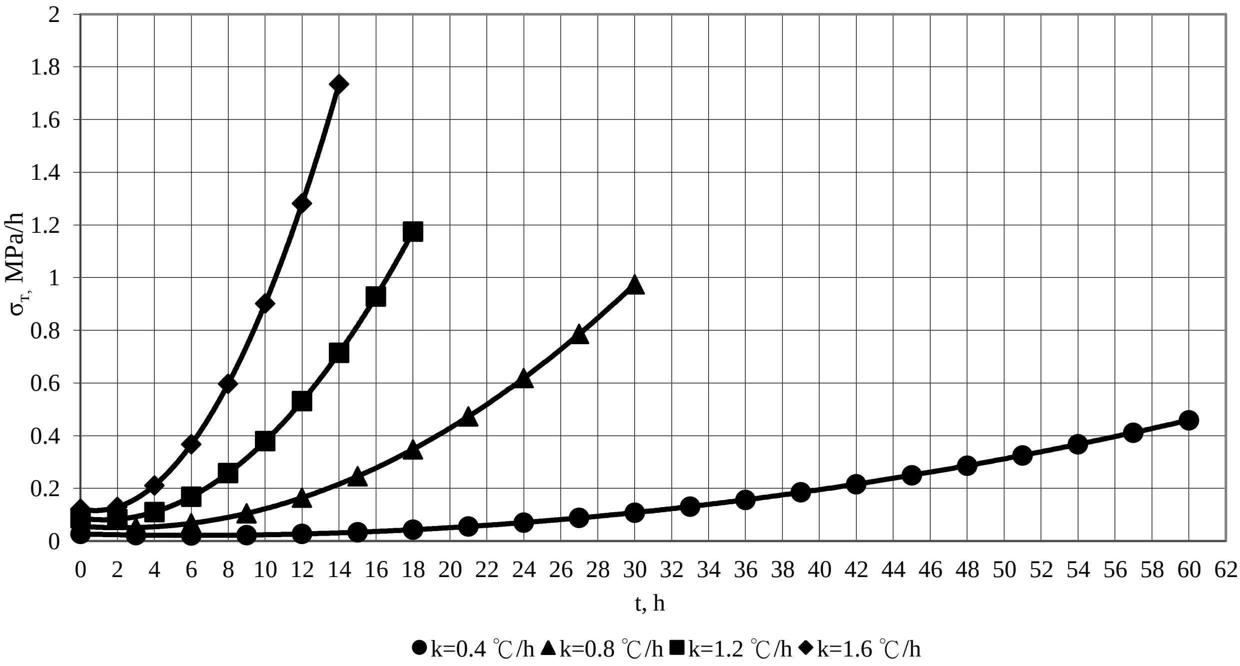


**Fig. 9.** Low Temperature Stress Rate in Hot Mix Asphalt Pavement.

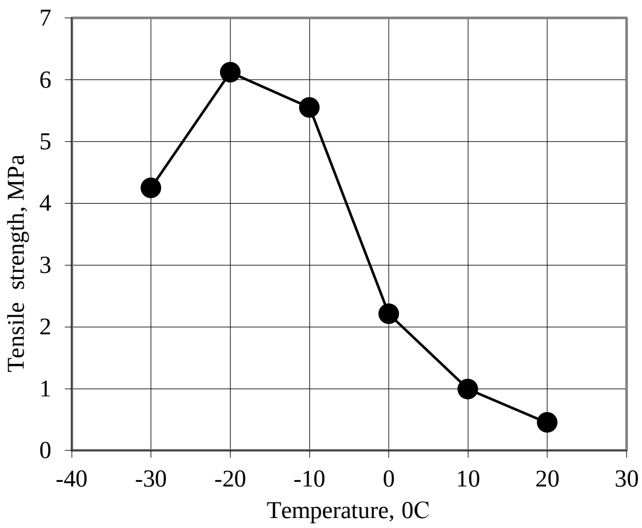


**Fig. 10.** Tensile Strength of Hot Mix Asphalt Versus Temperature.

## Strength

Fig. 10 shows dependence of hot mix asphalt tensile strength on temperature. Dependence has a complex character. With temperature ranging from +20°C to -10°C, hot mix asphalt tensile strength increases with the increased rate. At temperature ranging from -10°C to -20°C, the tensile strength also increases, but with a lower rate than in the first range.

Maximum strength occurs at temperature -20°C and is equal to 6.2 MPa. With further temperature falling to -30°C, the strength falls quickly and corresponds to 4.3 MPa. The most dramatic falling of strength has been obtained at temperature ranging from -10°C to 0°C. Thus, in the beginning of this range, the strength had value equal to 5.6 MPa, and in the end - only 2.3 MPa. In other words, in the stated range, the temperature increase for 10°C caused the 2.43 times decrease of hot mix asphalt.

## Critical Time, Critical Temperature, and Critical Stress

Fig. 11 represents diagrams showing temperature stress increase in hot mix asphalt pavement with temperatures falling at various cooling rates. These diagrams show dependence of hot mix asphalt tensile strength on temperature, represented before in Fig. 10. Such a combination of diagrams allows finding important indicators for appearance of cracks on hot mix asphalt pavement. Thus, dropping a vertical line from cross point of diagrams, on the horizontal axis one can find Critical temperature $t_{cr}$, when low temperature cracking occurs on pavement. Drawing a horizontal line from cross point of diagrams, one can determine Critical stress $\sigma_{cr}$ on the vertical axis, when low temperature cracks occur. Knowing values of Critical stress, from the diagram of Fig. 8, one can determine values for Critical time $t_{cr}$ at various rates of cooling. Critical time shows the length of time since the commencement of cooling that low temperature cracking occurs on pavement.

Obtained by the above methods, the values of Critical time, Critical temperature, and Critical stress are presented in Table 4. These tables show that Critical time considerably depends on the rate of temperature falling. At low rates of cooling, the occurrence of low temperature cracks on pavement is expected after a long time, and at high rates of cooling, the cracks can occur in relatively short time. Thus, at k = 0.4°C/h, $t_{cr} \approx 53$ hours, and at k = 1.6°C/h, $t_{cr}$= 12 hours.

It has been found that Critical temperature and Critical stress in accepted conditions of cooling and accepted hot mix asphalt do not depend on cooling rate: $\sigma_{cr}$ = 6.0 to 6.2 MPa, $T_{cr}$ = -19 to -21°C. In other words, regardless of cooling rate and cooling duration, the first low temperature cracks on hot mix asphalt pavement can occur

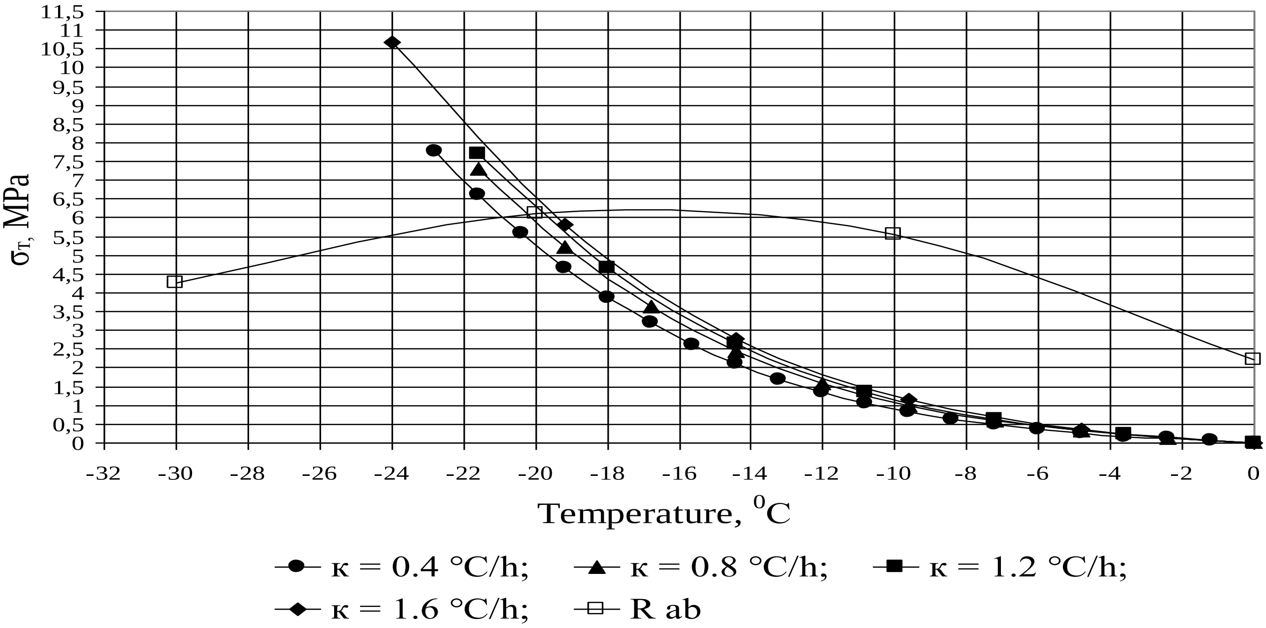


**Fig. 11.** Combined Diagrams of Low Temperature Stress in Hot Mix Asphalt Pavement and Tensile Strength of Hot Mix Asphalt Versus Temperature.

**Table 4.** Critical Time, Critical Temperature and Critical Stress.

| Temperature Falling Rate $\kappa$, $^{o}$C | Critical Time $t_{cr}$, h | Critical Temperature $T_{cr}$, $^{o}$C | Critical Stress $\sigma_{cr}$ , MPa |
|---|---|---|---|
| 0.4 | 52.6 | -19.4 | 6.2 |
| 0.8 | 25.3 | -19.9 | 6.1 |
| 1.2 | 16.5 | -20.5 | 6.1 |
| 1.6 | 12.0 | -21.2 | 6.0 |

at a temperature of approximately -20$^{o}$C.

## Analysis of Specific Indicators for Hot Mix Asphalt Pavement

It is known that with the development of evaluation method for low temperature stability of bitumen binders the principle of temperature-time superposition has been used. It has been accepted that for many types of bitumen binders at negative temperatures, the effect of temperature increasing for 10$^{o}$C is equal to the effect of loading time increasing in 120 times. In other words, by increasing temperature for testing for 10$^{o}$C, it is possible to reduce load duration from 2 hours to 60 seconds. A correlation dependence between bitumen stiffness modulus at a load duration of 2 hours and intensity of low temperature cracks occurrence on hot mix asphalt pavement has been ascertained [22].

Table 4 shows that in the considered cases, Critical time is considerably more than 2 hours, i.e. time of occurrence of cracks is considerably more than 2 hours and depends on the temperature falling rate. Therefore, we will further analyze some characteristic indicators of hot mix asphalt at duration of temperature falling for 2 hours and at Critical time. Values of temperature stress and rate of temperature stress at the determined time are shown in the Tables 5 and 6. It seems that except for temperature stress at Critical time, all

**Table 5.** Temperature Stress in Specific Time.

| Temperature Falling Rate $\kappa$, $^{o}$C | Temperature Stress $\sigma_T$, MPa | |
|---|---|---|
| | at Duration of Temperature Falling for 2 Hours | at the Moment of Appearance of Crack |
| 0.4 | 0.05 | 6.2 |
| 0.8 | 0.11 | 6.1 |
| 1.2 | 0.17 | 6.1 |
| 1.6 | 0.24 | 6.0 |

**Table 6.** Temperature Stress Rate in Specific Time.

| Temperature Falling Rate $\kappa$, $^{o}$C | Temperature Stress Increase Rate $\dot{\sigma}_T$ (MPa/h) | |
|---|---|---|
| | at Duration of Temperature Falling for 2 Hours | at the Moment of Appearance of Crack |
| 0.4 | 0.02 | 0.35 |
| 0.8 | 0.05 | 0.69 |
| 1.2 | 0.08 | 0.99 |
| 1.6 | 0.13 | 1.28 |

the considered indicators increase with the increase of temperature falling rate. The increase of temperature falling rate from 0.4 $^{o}$C/h to 1.6 $^{o}$C/h causes the increase of temperature stress at duration for 2 hours in 4.7 times.

Superpave specifications as an indicator, characterizing the rate of stress relaxation in bitumen binders, have chosen the so-called m-value at load duration 2 hours [21]. This indicator has been determined by Eq. (10):

$$\mathrm{m-value} = \mathrm{m(t)} = \frac{\mathrm{d}\log \mathrm{S(t)}}{\mathrm{d}\log \mathrm{t}} \tag{10}$$

where log S(t) = logarithm of bitumen stiffness S(t);
log t = logarithm of time t.

Having made similar mathematical calculations under Eq. (11):

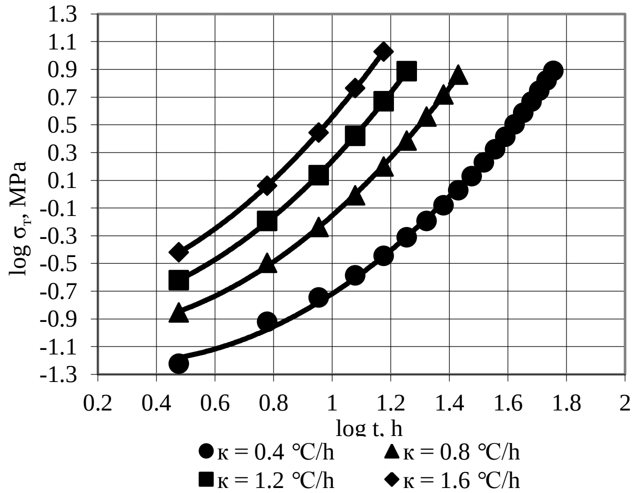


**Fig. 12**. log $\sigma_T(t)$ versus log t.

**Table 7.** Stress Relaxation Indicator at Specific Times.

| Velocity of Temperature Falling κ, $^o$C | $m_{ac}$-value | |
|---|---|---|
| | with Duration of Temperature Falling for 2 Hours | at the Moment of Appearance of Crack |
| 0.4 | 0.05 | 2.74 |
| 0.8 | 0.39 | 2.74 |
| 1.2 | 0.65 | 2.73 |
| 1.6 | 0.83 | 2.68 |

**Table 8.** Modulus of Elasticity for Hot Mix Asphalt in Specific Instant Time.

| Temperature Falling Rate κ, $^o$C | Elasticity Modulus of Hot Mix Asphalt, MPa | |
|---|---|---|
| | at Duration of Temperature Falling for 2 Hours | at the Moment of Appearance of Crack |
| 0.4 | 14 020 | 8 727 |
| 0.8 | 14 580 | 10 340 |
| 1.2 | 15 260 | 11 670 |
| 1.6 | 16 060 | 12 970 |

$$m_{ac} - \text{value} = m_{ac}\ (t) = \frac{d \log \sigma_T(t)}{\sigma \log t} \tag{11}$$

the indicator $m_{ac}(t)$ has been obtained, which characterizes the rate of temperature stress relaxation in hot mix asphalt pavement.

Relationships $\log\sigma_T(t)$ - logt, obtained from diagrams in Fig. 8 at all values of cooling temperature stress rate are represented in Fig. 12. As it has been mentioned above, at all values of cooling rate, temperature stress increases with the time increase. Moreover, at similar times, the temperature is higher when the cooling rate is higher too.

Table 7 shows values of $m_{ac}$-value of hot mix asphalt at characteristic time and at the accepted cooling rates. It is obvious that values of $m_{ac}$-value of hot mix asphalt at duration of two hours depend greatly on the cooling rate. Thus, with the increase of cooling rate from 0.4$^o$C/h to 1.6$^o$C/h $m_{ac}$-value increases approximately 17 times. On the contrary, the m-value of hot mix asphalt at Critical time is practically independent of the cooling rate: it has the similar value, equal to 2.7, at all Critical times.

Table 8 represents the value of elasticity modulus of hot mix asphalt, corresponding to the considered characteristic instant time, from where it is obvious that elasticity modulus of hot mix asphalt depends on the cooling rate.

Therefore, the analysis of characteristic indicators for hot mix asphalt has shown that indicators such as temperature stress, temperature stress increase rate, m-value of hot mix asphalt at duration of 2 hours and Critical time depend on the cooling rate. And indicators such as Critical temperature, Critical stress, and $m_{ac}$-value of hot mix asphalt at Critical time proved to be practically independent of the cooling rate. Critical temperature has a value equal to -20$^o$C, Critical stress equals to 6.0 to 6.2 MPa, and average value of $m_{ac}$-value equals 2.7.

Having in mind the results obtained it is required to further study the above indicators considering other types of bitumen, types of hot mix asphalt, and conditions of temperature falling.

## Conclusions

In this work, the indicators of low temperature cracking on hot mix asphalt pavement have been evaluated. Peculiarities of air temperature variation have been analyzed in the winter season in Astana city. Conditions of cooling have been considered through the temperature falling rate. The obtained results allow the following conclusions:

1. Air cooling has been observed in the northern part of Kazakhstan with the rate up to 1.9$^o$C/h and duration of 12 hours. With the cooling rate in 0.4 - 0.5$^o$C/h, the maximum duration reaches 66 hours. Reliable correlation has been ascertained between air cooling rate and maximum duration of cooling.
2. Combined experimental-analytic method allows considering properties of hot mix asphalt, including viscoelastic ones, as well as conditions of temperature falling.
3. It has been found that for dense graded hot mix asphalt of type B for bitumen grade BND-90/130 at the cooling rates from 0.4$^o$C/h to 1.6$^o$C/h, Critical stress and Critical temperature do not depend on cooling rate: Critical stress $\sigma_{cr}$ = 6.0 to 6.2 MPa, Critical temperature $T_{cr}$ = -19 to -21$^o$C.
4. The indicator m-value has been introduced by analogy with superpave method for characterizing temperature stress relaxation rate in hot mix asphalt pavement. It has been ascertained that the m-value at Critical time does not depend on cooling rate and has practically constant value, equal to 2.7.

## Recommendation

The results obtained in this work show the necessity of further research of indicators for low temperature cracking of hot mix asphalt pavement under the employed method, considering other bitumen, types of hot mix asphalt, and conditions of temperature falling.

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