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Temperature and moisture in highways in different climatic regions

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Abstract. The article represents the results of experimental research for temperature and moisture variations in pavements and subgrade of highways located in five different climatic regions, an analysis of cyclic freezing and thawing of a pavement. To measure temperature and moisture in pavements and subgrade the sensors have been used which allow making measurement of these characteristics simultaneously in the points of interest. The peculiarities of variation were analyzed for air temperature, temperature in pavements and subgrade in different regions in warm and cold 24 hours. The differences were established in distribution of temperature and moisture in pavements and subgrade in warm and cold 24 hours. To analyze cyclic freezing and thawing (FT) of a pavement the air temperature values have been used during twenty sequential winter seasons in six geographical points of Kazakhstan. The dependences were established for the number of FT cycles on duration and minimal temperature of the cycles.

1. Introduction

A highway during its service life is subject to the impact of mechanical and climatic factors [1–3]. Out of climatic factors the most dynamic (non-stationary) one is a temperature which is varied both in the annual cycles and in 24-hour ones [4–14]. The temperature impacts greatly on an asphalt concrete and a cement concrete pavements [15–20] and on subgrade [4–9, 20–23].

At designing of pavements [24–28] the deformation and strength characteristics of the asphalt concretes and other materials containing organic binders are determined depending on calculated temperature values. Deformation characteristics of soils (especially of clay soils) depend greatly on moisture. Therefore, deformation properties of soils at designing of pavements are determined depending on a type of soil and moisture.

It is known that at low temperatures part of water contained in soil pores transforms into a solid condition (ice) [7–9, 21–23]. Mechanical properties of frozen soils differ greatly from those of ordinary (non-frozen) ones [29–32]. Unfortunately, frozen condition of soils of subgrade is not taken into account at designing of pavements in Kazakhstan [27, 28], Russia [26] and other countries of former Soviet Union.

The abovementioned shows practical importance of information about temperature and moisture variation in a pavement and subgrade of a highway.

This article is a continuation of the authors' works for the research of temperature and moisture in pavements and subgrade of highways. It contains the results of experimental research for temperature and moisture variation in pavements and subgrade of highways located in five regions of Kazakhstan, and the analysis of cyclic freezing and thawing of a pavement.

As the selected test sections are located in different geographical regions of a large territory of Kazakhstan (the 9th position in the world) their climatic conditions differ greatly. As it is seen from Table 1, the average multiyear air temperature of January in Shymkent is equal to -21.7°C, and in Oskemen it is equal to -49°C; the number of days per year with average daily air temperature higher than 0°C in Petropavlovsk and

Shymkent is equal to 194 and 304 respectively; the largest thickness of snow cover in Petropavlovsk and Turkestan is 124 cm and 34 cm respectively, i.e. the difference can be up to 4 times; frost penetration depth of a highway in Petropavlovsk and Shymkent is 241.1 cm and 69.3 respectively, i.e. the difference is 3.5 times.

Such a big difference in climatic characteristics of the geographical regions where the test sections are located can provide essential variations in temperature and moisture values in pavement and subgrade layers.

Experimental results, included into the article, are of high value at designing of pavements and operation of highways not only in Kazakhstan, but also in many countries of the world, for example in Russia, the USA, China, Canada, Mexico, Brasilia, India, in European countries and other countries, as they have the climatic conditions close to those ones which are considered in the article.

Table 1. Climatic characteristics and geographical coordinates.

Characteristic	City						
	Petro-pavlovsk	Almaty	Nur-Sultan	Turkestan	Oskemen	Atyrau	Shymkent
Average multiyear minimal air temperature in January, ºC	-42.5	-22.1	-39.4	-26.4	-49.0	-35.9	-21.7
Average multiyear maximal air temperature in July, ºC	35.7	37.8	39.2	44.2	43.0	41.0	41.7
Number of days with average daily air temperature ≥ 0 °C	194	254	198	279	211	240	304
The largest thickness of snow cover, cm	124	43	42	34	104	42	62
Average quantity of precipitation per year, mm	345	450	318	448	441	169	493
Average annual wind velocity, m/s	2.4	0.7	2.9	2.0	2.4	2.8	1.8
Frost penetration depth of a highway, cm	241.1	101.2	222.1	91.3	231.8	131.7	69.3
Geographical coordinates:							
- latitude (n.l.):	54°52'00"	43°15'24"	51°10'48"	43°17'50"	49°58'17"	47°07'00"	42°17'57"
- longitude (e.l.):	69°09'00"	76°55'42"	71°26'45"	68°15'06"	82°36'21"	51°52'59"	69°35'59"
Altitude above sea level, m	142	787	358	214	287	-25	513

2. Methods

2.1. Test sections

For the purpose of long-term monitoring realization for temperature and moisture variation in points of pavements and subgrade of highways the test sections have been selected which are located in different climatic regions of Kazakhstan (Fig. 1) and temperature and moisture sensors have been installed. Sensors for the test section of “Nur-Sultan-Burabai” highway (km 76+30) were installed in 2009, and for the test sections of “Almaty-Bishkek” (km 58+895), “Atyrau-Astrakhan” (km 598+50), “Kyzylorda-Shymkent” (km 2097+00) and

"Oskemen-Zyryanovsk" (km 0+75) the sensors were installed in 2013. Geographical coordinates for the cities located close to the selected test sections are given in Table 1.

Materials and thickness of pavements layers and soils with their characteristics are represented in Tables 2 and 3 respectively.

Figure 1. Locations of the test sections of the highways.

Table 2. Pavement structures on the test sections.

Layer number	Pavement material and thickness, cm				
	Almaty-Bishkek	Atyrau-Astrakhan	Kyzylorda-Shymkent	Nur-Sultan-Burabai	Oskemen-Zyryanovsk
1	Fine-grained dense asphalt concrete, 5	Fine-grained dense asphalt concrete, 8	Stone mastic asphalt concrete, 5	Stone mastic asphalt concrete, 6	Fine-grained dense asphalt concrete, 3
2	Coarse-grained porous asphalt concrete, 10	Fine-grained dense asphalt concrete, 6	Coarse-grained porous asphalt concrete, 10	Coarse-grained porous asphalt concrete, 9	Coarse-grained cold asphalt concrete, 10
3	Fine-grained dense asphalt concrete, 7	Coarse-grained porous asphalt concrete, 11	Coarse-grained high porous asphalt concrete, 13	Stone treated with bitumen, 12	Sand and gravel mix, 10
4	Coarse-grained cold asphalt concrete, 15	Stone treated with bitumen, 5	Sand and gravel mix, 42	Stone and sand mix treated with Portland cement (7%), 18	–
5	Fine sand and gravel mix, 25	Gravel and sand mix, 60	Dusty sand, 20	Stone and sand mix, 15	–
6	Coarse sand and gravel mix, 35	–	–	Sand, 20	–
Total thick-ness of pavement, cm	97	90	90	80	23

Table 3. Type and characteristics of soils on the test sections.

Test section	Type of soil	Liquidity limit W_L, %	Plasticity limit W_{PL}, %	Plasticity number I_P
Almaty-Bishkek	Heavy sandy clay loam	26.6	13.4	13.2
Atyrau-Astrakhan	Heavy silt clay loam	25.3	12.4	12.9
Kyzylorda-Shymkent	Silt sand	22.0	-	Not plastic
Nur-Sultan-Burabai	Heavy sandy clay loam	34.8	18.7	16.1
Oskemen-Zyryanovsk	Heavy sandy clay loam	26.8	13.5	13.3

2.2. Temperature and moisture sensors

Company “Interpribor” (Chelyabinsk, Russia) produced temperature and moisture sensors on the order of Kazakhstan Highway Research Institute (KazdorNII). Each sensor, produced in the form of a metal capsule, contains an element for measurement of temperature based on the effect of thermal resistance and an element for measurement of moisture through diamagnetic permeability (Fig. 2). Such design concept allows performing simultaneously the measurement of temperature and moisture in points of a pavement and a subgrade.

Temperature elements of sensors were calibrated by the producer and moisture elements were calibrated in the laboratory of KazdorNII. The calibration of the sensors was performed with the use of soils, selected from the location of their installation.

Installation of the sensors into the pavement and the subgrade layers of the highways was performed by the specialists of KazdorNII. Measurement ends of the sensors were put on the surface of the highways and collected in measurement chambers of land system of the set (Fig. 3).

Figure 2. General view of one set of the temperature and moisture sensors.

Figure 3. View of surface part of the temperature and moisture automatic measurement system on the highway “Almaty-Bishkek”.

The depths for temperature and moisture sensors locations on test sections are given in Table 4. As an example, the scheme of sensors locations in pavement and subgrade of “Almaty-Bishkek” highway is shown in Fig. 4.

Table 4. The depths for temperature and moisture sensors locations on the test sections.

Sensor number	Depth for sensor location, cm				
	Almaty-Bishkek	Atyrau-Astrakhan	Kyzylorda-Shymkent	Nur-Sultan-Burabai	Oskemen-Zyryanovsk
1	2	2	2	6	2
2	5	10	10	15	12
3	15	20	15	45	23
4	21	30	30	80	35
5	38	90	70	115	70
6	65	115	90	150	105
7	100	140	120	185	140
8	135	165	150	220	175
9	170	190	180	-	210
10	205	215	210	-	245
11	240	240	240	-	280

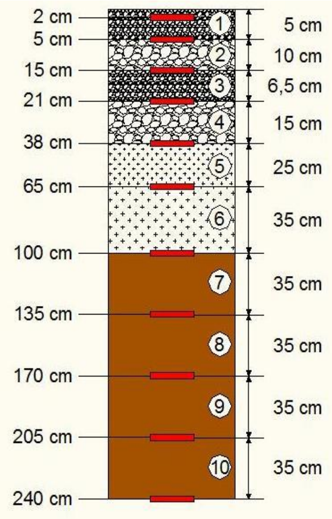

Figure 4. Pavement structure and scheme of sensors location on the highway "Almaty-Bishkek" – a sensor of temperature and moisture.

Complete procedure for installation of the sensors was performed in the following consecutive sequence:

1. A well was developed with diameter of 16 cm and depth 280 cm from the pavement surface by a machine drilling.
2. Soil was carefully removed from the well, then it was stored in separate portions in a row, and measures were taken for observance of its initial moisture content without change.
3. The sensor, installation of which was provided in the depth of 280 cm, was laid on the bottom of the well.
4. A portion of soil was excavated from the subgrade in the depth of 280 cm and filled above the sensor.
5. The soil was compacted physically up to the designed level.

All other sensors were installed by similar way. Portions of soil, excavated from the well, were filled in reversed order and compacted up to the designed level.

3. Results and Discussion

3.1. Air temperature

Comparison of air temperature variations in the cities of Oskemen (eastern region of the country) and Shymkent (southern region of the country) shows that they differ considerably between each other (Fig. 5). The temperature is considerably higher (higher than +40 °C) in the south of the country in a summer season than in the east of it. And the minimal temperature is considerably lower (it reaches -40 °C) in the east of the country in a winter season than in the south of it.

Fig. 6 and 7 represent the graphs for an air temperature variation for warm and cold 24 hours on the test sections of highways located in different regions of Kazakhstan. The graphs have been constructed according to the temperature values measured by the sensors. As it is seen from Fig. 6, the air temperature of warm 24 hours is varied quasi-harmonically practically in all considered regions. Meanwhile, as a rule, the highest temperatures occur between 3 p.m. and 6 p.m., and the least ones occur between 3 a.m. and 6 a.m. As one should expect, the highest temperature value equal to 37.5 °C has been obtained on "Kyzylorda-Shymkent" highway (in the south of the country), and the least temperature value equal to 15.5 °C has been measured on "Nur-Sultan-Burabai" highway (in the north of a country). Daily amplitude of the temperature for warm 24 hours of northern part of the country was 16.8 °C, and in the southern part of the country it was equal to 15 °C.

Behavior of air temperature variation for cold 24 hours in the regions is greatly different from that one of warm 24 hours (Fig. 7). Practically for all the considered highways (except for "Almaty-Bishkek" highway) the air temperature for the considered 24 hours has been little varied: daily temperature variation was 2.5 °C, 2.0 °C and 3.8 °C for the highways "Nur-Sultan-Burabai", Kyzylorda-Shymkent" and "Oskemen-Zyryanovsk" respectively. And for "Almaty-Bishkek" highway the temperature increase for 6 °C from -5.5 °C to 0.5 °C occurred from 11 a.m. to 4 p.m. and further the temperature was varied within the limits of -3.5 °C and 1.0 °C.

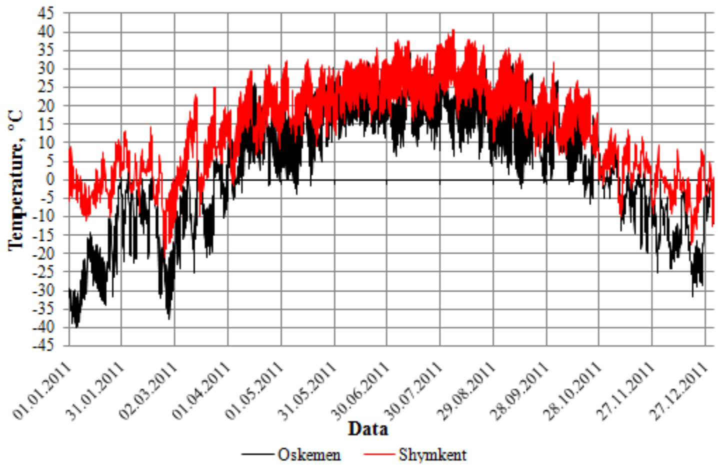

Figure 5. Graphs of an air temperature variation in the cities of Oskemen and Shymkent in 2011.

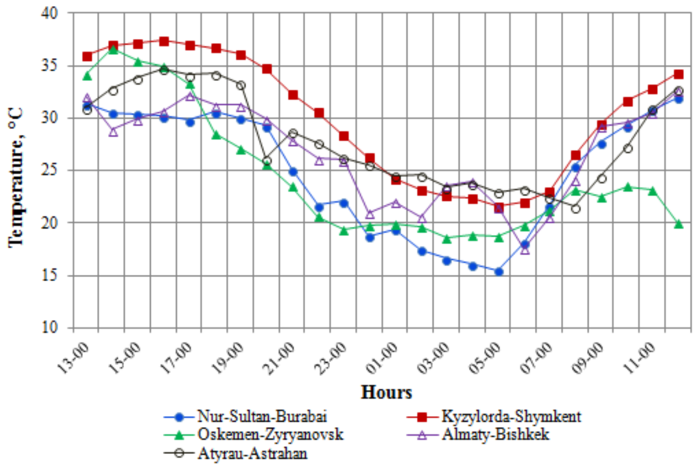

Figure 6. Air temperature variation for warm 24 hours.

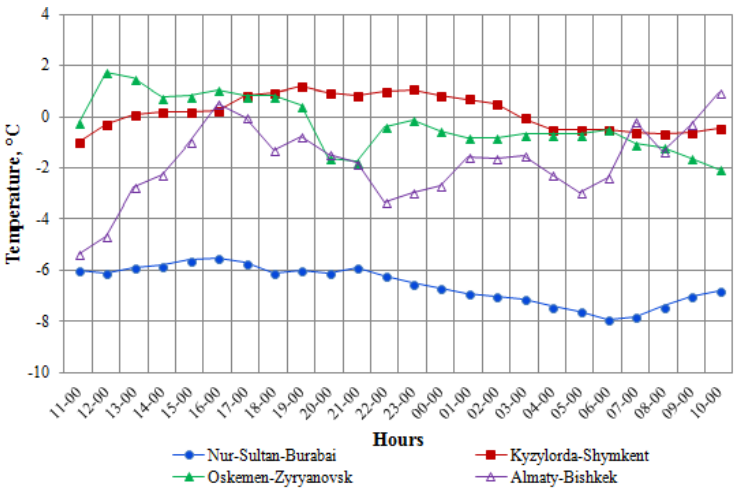

Figure 7. Air temperature variation for cold 24 hours.

3.2. Temperature in pavement and subgrade

Daily temperature variations in points of the pavement (in the depths of 10 cm, 30 cm and 80 cm) for cold and warm 24 hours are shown in Fig. 8-11. It is clearly seen that for warm 24 hours (Fig. 8) a temperature variation in the depth of 10 cm (on the bottom part of asphalt concrete layers) has a clear harmonicity. A temperature in this depth is higher than an air temperature. And for cold 24 hours (Fig. 10) the harmonicity for the temperature variation is interrupted. An amplitude for daily temperature variation is decreased with the depth increase (faster in winter): the temperature is not practically varied for warm (Fig. 9) and cold (Fig. 11) 24 hours in the depths of 80 cm and 30 cm respectively.

Fig. 12 and 13 represent the graphs for a temperature distribution in the depth of pavement and subgrade on test sections for warm and cold 24 hours. The graphs show that the temperature is decreased in the depth in summer season and it is increased in the depth in winter season. The temperatures in the depth of 100 cm of “Nur-Sultan-Burabai” and “Kyzylorda-Shymkent” highways were: 21 ºC and 37 ºC respectively for summer 24 hours; -4.0 ºC and 4.2 ºC respectively for winter 24 hours. It is clearly seen (Fig. 18) that for the considered 24 hours (14 January 2015) the freezing depth for “Atyrau-Astrakhan”, “Almaty-Bishkek”, “Oskemen-Zyryanovsk” and “Nur-Sultan” highways was 101 cm, 112 cm, 140 cm and 174 cm respectively.

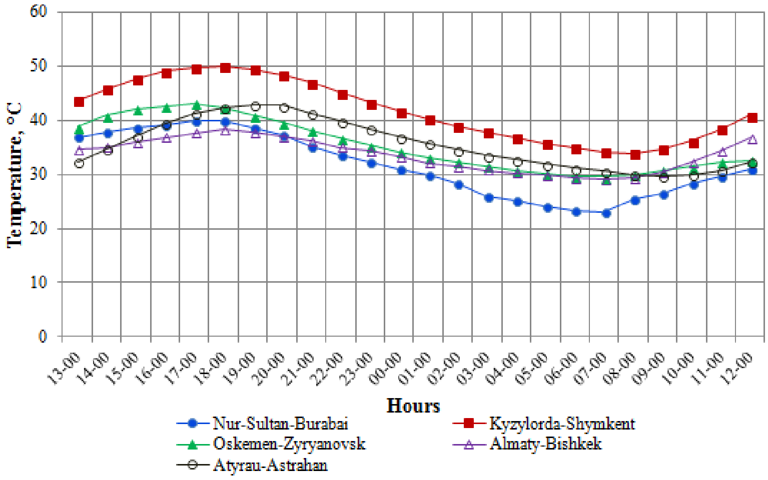

Figure 8. Temperature variation for warm 24 hours in the depth of 10 cm.

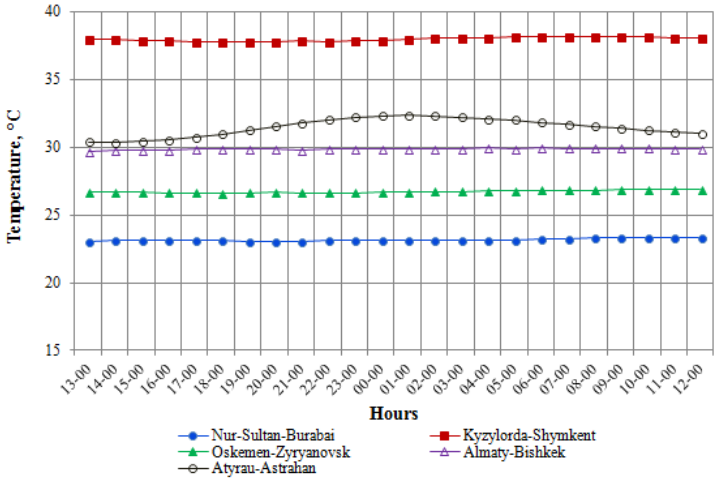

Figure 9. Temperature variation for warm 24 hours in the depth of 80 cm.

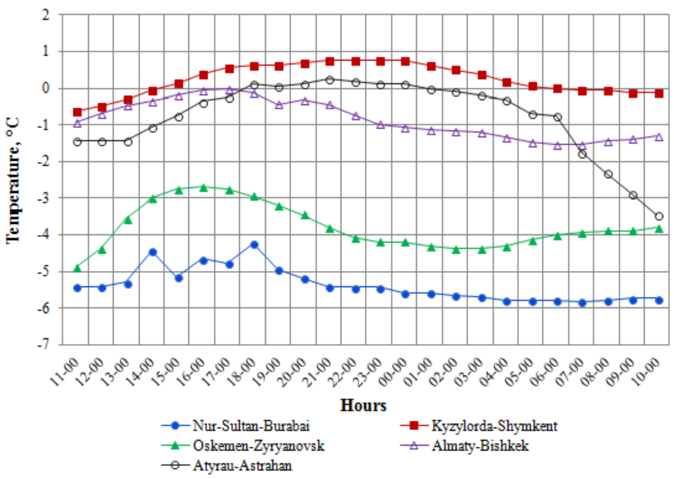

Figure 10. Temperature variation for cold 24 hours in the depth of 10 cm.

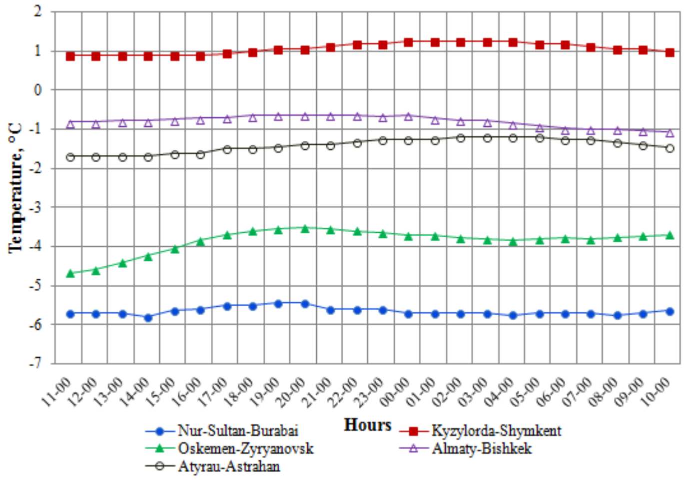

Figure 11. Temperature variation for cold 24 hours in the depth of 30 cm.

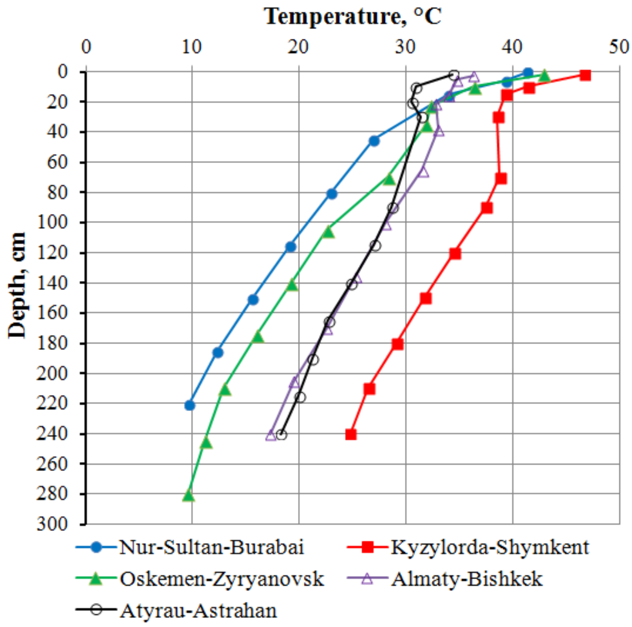

Figure 12. Temperature distribution in the depth of pavement and subgrade for warm 24 hours.

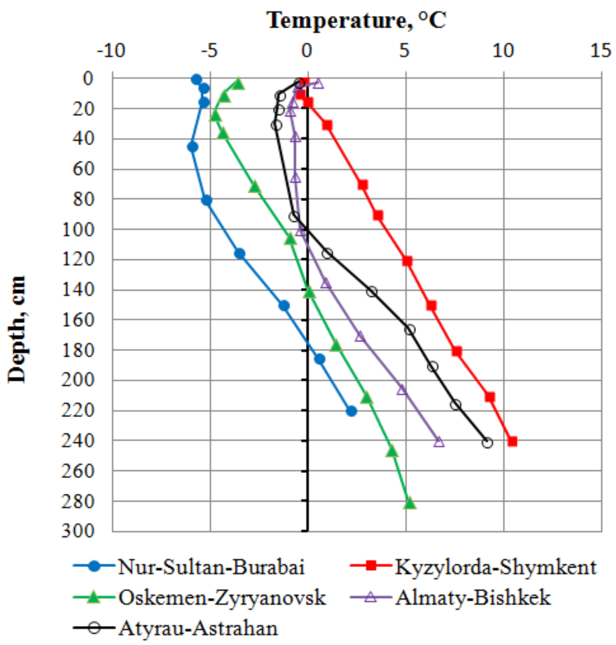

Figure 13. Temperature distribution in the depth of pavement and subgrade for cold 24 hours.

3.3. Moisture in pavement and subgrade

Moisture distribution in the depth of pavements and subgrade on test sections for warm and cold 24 hours is represented in Fig. 14 and 15. These graphs show that moisture distribution in the depth of pavements and subgrade (up to 240–280 cm) is of complex nature for all the considered test sections. Moisture values in pavement layers and points of subgrade of “Almaty-Bishkek”, “Atyrau-Astrakhan” and “Kyzylorda-Shymkent” highways are between the limits of 2 % and 10 % for warm and cold 24 hours. An exception is only the “Oskemen-Zyryanovsk” highway. Moisture in this highway is varied between wider limits: 2 % and 17.5 %.

Part of moisture transforms into solid state (ice) at negative temperatures in winter season. This phenomenon reduces the content of liquid moisture in points of a pavement and subgrade which is clearly seen in Fig. 16 and 17.

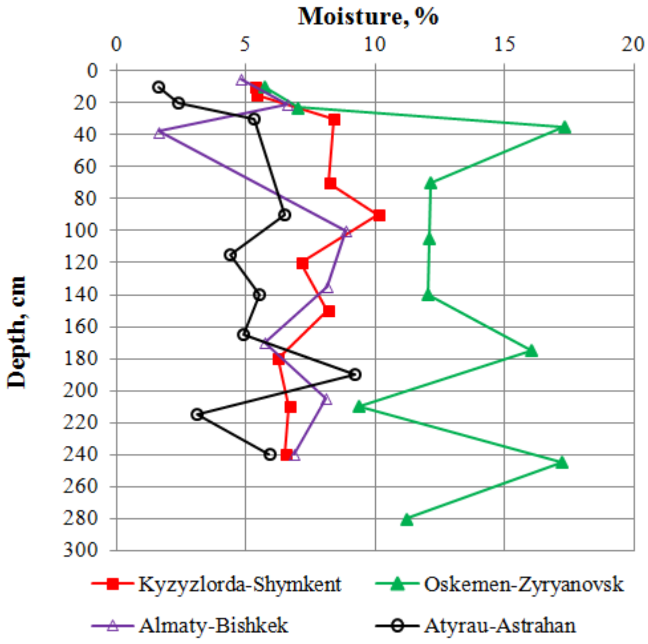

Figure 14. Moisture distribution in the depth of pavement and subgrade for warm 24 hours.

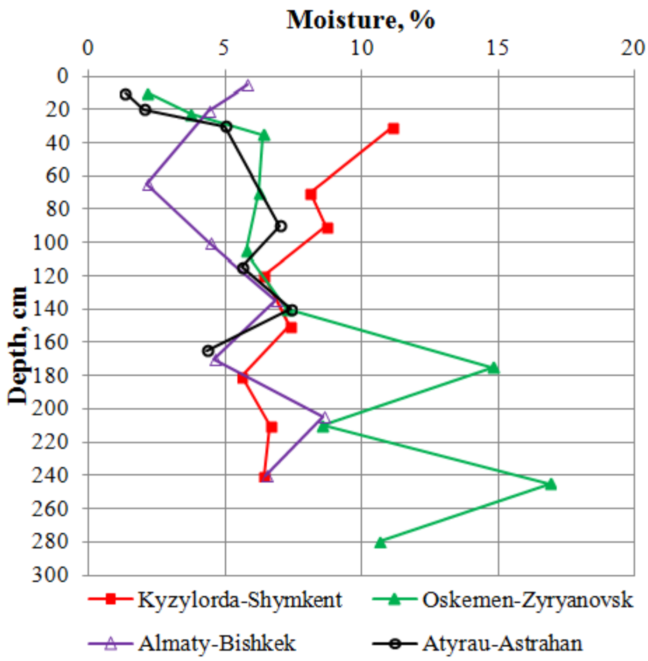

Figure 15. Moisture distribution in the depth of pavement and subgrade for cold 24 hours.

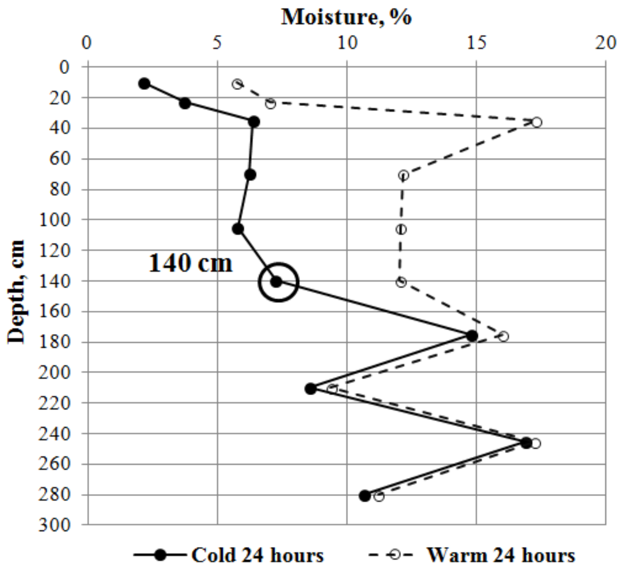

Figure 16. Temperature distribution in the depth of pavement and subgrade for warm and cold 24 hours on "Oskemen-Zyryanovsk" highway: ◯ is a frost bound.

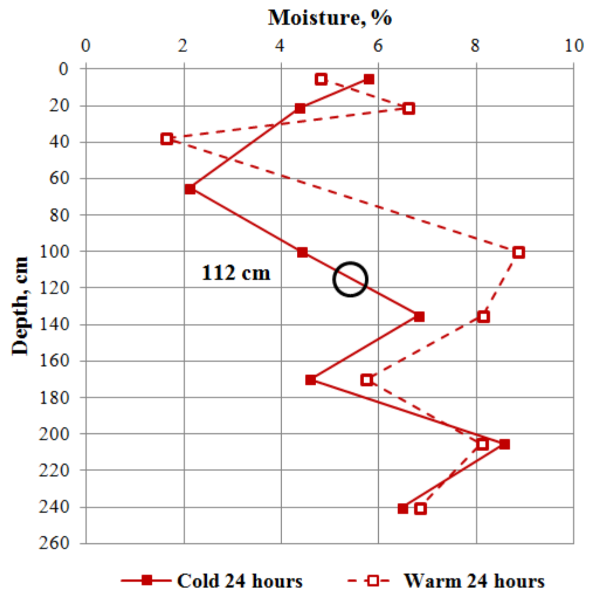

Figure 17. Temperature distribution in the depth of pavement and subgrade for warm and cold 24 hours on "Almaty-Bishkek" highway: ◯ is a frost bound.

3.4. Cyclic freezing and thawing

To analyze cyclic freezing and thawing (CFT) of a highway pavement the air temperature values have been used during twenty consecutive winter seasons (from the 1st of January 1992 to the 31st of December 2011) at six geographical points (in the cities of Nur-Sultan, Almaty, Shymkent, Oskemen, Petropavlovsk and Zhanybek village) located in various regions of Kazakhstan. Geographical coordinates and climatic characteristics of these communities are given in Table 1. The temperature values have been measured in the specialized meteorological stations of RSE "KAZHYDROMET" [33].

Fig. 18 and 19 represent the histograms showing visually a dependence between the number of cycles for freezing and thawing (FT) and cycle duration. It is found out that the number of FT cycles is sharply decreased with the cycle duration increase. For example, 88–97 % of all FT cycles have a duration up to 100 hours. Meanwhile, the duration for 72–80 % of all FT cycles is up to 200 hours. It should be also mentioned that the duration of FT cycles is considerably lower in warm regions than in the cold ones. For example, the largest duration of cycles in Almaty and Shymkent reaches up to 700 hours, in Oskemen it reaches up to 2600 hours, and in Petropavlovsk it reaches up to 3400 hours.

As it is shown in Fig. 20 and 21, there is a reliable correlation relationship between the number of FT cycles and cycle duration. This correlation relationship for all the considered communities is approximated with a high accuracy by the following power function:

$$N_{cycles} = a \cdot t_{cycle}^{-b}, \quad (1)$$

where N_{cycles} is the number of FT cycles;

t_{cycle} is a cycle duration, hour:

a, b are coefficients.

Coefficient *b* shows for how many orders the number of FT cycles is decreased at the cycle duration increase for one order.

It is found out that there is also a dependence between the number of FT cycles and minimal temperature of the cycle (Fig. 22): the number of FT cycles is decreased with the minimal temperature decrease; as one should expect, an absolute value of a minimal temperature in southern region is less (in Almaty and Shymkent it is above -27 ºC), and in the northern and eastern regions it is more (in Petropavlovsk it is below -42 ºC, in Oskemen it is below -45 ºC); 80–89 % of all FT cycles have a minimal temperature within the limits of -0.1 ºC and -9 ºC.

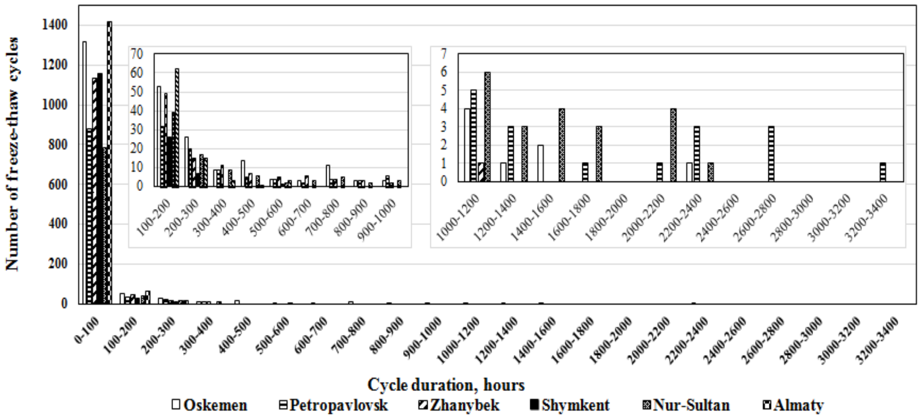

Figure 18. Dependence of the number of freeze-thaw cycles on cycle duration (cycle duration up to 3400 hours).

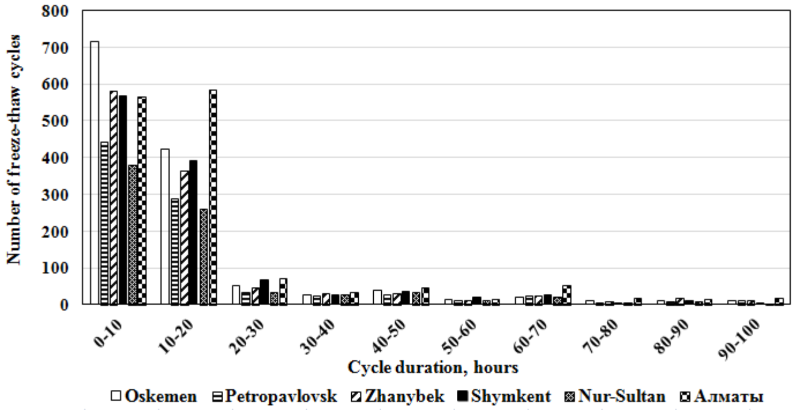

Figure 19. Dependence of the number of freeze-thaw cycles on cycle duration (cycle duration up to 100 hours).

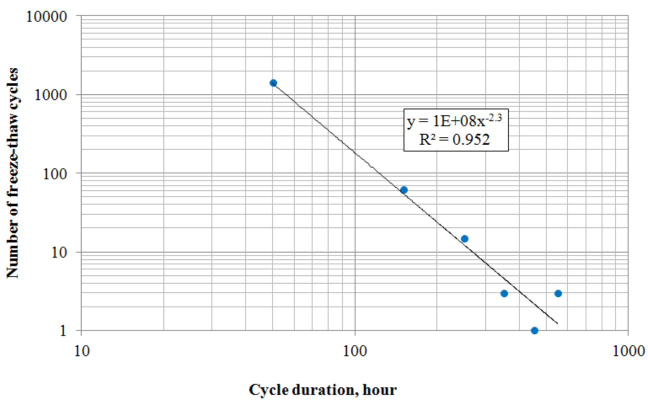

Figure 20. Dependence of the number of freeze-thaw cycles on cycle duration for Almaty.

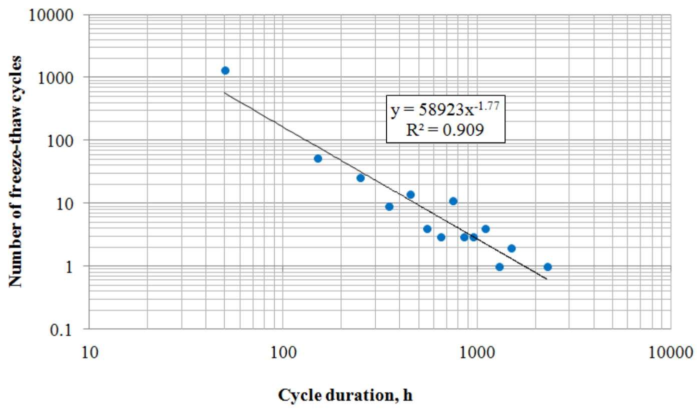

Figure 21. Dependence of the number of freeze-thaw cycles on cycle duration for Oskemen.

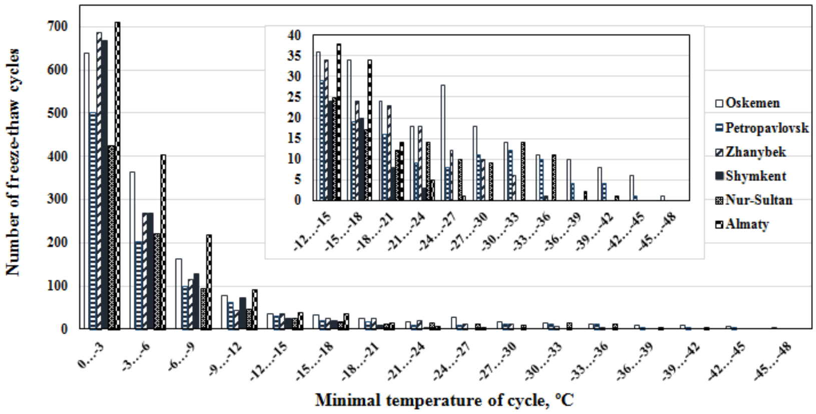

Figure 22. Dependence of the number of freeze-thaw cycles on minimal temperature of cycle.

4. Conclusion

The results of the experimental research for temperature and moisture variation in pavements and subgrade of the highways located in different regions of Kazakhstan and the analysis of cyclic freezing and thawing of a pavement, which are of high value at designing of pavements and operation of highways in many countries of the world, allowed drawing the following conclusions:

1. An air temperature of the upper part of a pavement is considerably varied. In the south the air temperature is considerably higher (above +40°C) than it is in the north and in the east; in winter season a minimal air temperature in the north and in the east is considerably lower (it reaches -40 °C) than in the south.

The air temperature of upper part of a pavement is varied quasi-harmonically in warm 24 hours in all regions. The highest temperatures occur between 3 o'clock and 6 o'clock in the afternoon, and the lowest ones occur between 3 o'clock and 6 o'clock in the morning.

The behavior of the air temperature is considerably different in upper part of a pavement in cold 24 hours than that of warm 24 hours: its quasi-harmonic behavior is interrupted.

The temperature of the upper part of an asphalt concrete pavement in warm 24 hours is higher than the air temperature.

The temperature of a pavement and subgrade is decreased in the depth in summer season, and it is increased in the depth in winter season.

Amplitude of daily temperature variation in the pavement and subgrade is decreased with the depth increase: the temperature is not practically varied in a daily cycle in warm and cold 24 hours in the depths of 80 cm and 30 cm respectively.

2. Moisture distribution in the depth of a pavement and subgrade has complicated behavior. The minimal moisture value is 2 %. The maximal moisture value reaches 10 % in the south, in the north and in the west, and it reaches 17.5 % in the east.

3. The number of cycles is sharply reduced with increase of FT cycles duration. 88–97 % of all FT cycles have duration up to 100 hours and 72–80 % of all FT cycles have duration up to 200 hours.

The duration of FT cycles is considerably lower in warm regions than that of cold regions: the highest duration of cycles reaches 700 hours in warm regions and it is up to 3400 hours in cold regions.

The number of FT cycles is decreased with the minimal temperature in cycles decrease. An absolute value of a minimal temperature in cycles is higher in warm regions and it is lower in cold regions. 80–89 % of all FT cycles have a minimal temperature within the limits of -0.1 °C and -9 °C.

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