

Article

Freezing and Thawing Processes of Highways in Kazakhstan

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Abstract: This paper presents the results of an experimental study of freezing and thawing patterns of highways in Kazakhstan. Special sensors measure temperature and moisture change every hour in automatic mode. The purpose of this work is to develop a methodology for determining the depth of freezing of subgrade soils of roads of Kazakhstan, and the task is to establish the pattern of cold temperature change (temperature “0 °C”) through certain points (sensors) at any time. In the upper part of the pavement (up to 30–40 cm), the temperature changes in annual and daily cycles. As the depth increases, the daily temperature fluctuations disappear, leaving only the annual fluctuation. At a depth of 180 cm and below, temperature fluctuations occur only in the annual cycle. The freezing rate varied from 14 cm/day to 0.33 cm/day. The maximum freezing depth was 227 cm. The descending branch of thawing occurs almost uniformly, with an average rate of 6.25 cm/day to a depth of 220 cm; the average rate of the ascending branch of thawing is 0.9 cm/day. Asphalt-concrete layers of the pavement and the upper part of the subgrade were in a frozen state for 151 and 166 days, respectively. In the subgrade at the beginning and end of the cold period, there are abrupt changes in moisture, which are explained by phase transitions of the second order: the transition from the liquid state to the solid (ice) at the beginning of the cold period and the transition of moisture from the solid state to liquid at the end of the cold period.



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Keywords: road; pavement; subgrade; freezing; thawing; temperature; moisture; measuring station

1. Introduction

Severe winter conditions such as long-lasting freezing weather with heavy snowfall in the northern regions of Kazakhstan make the operation of roads extremely difficult. The possibility for frost heaving of road pavement increases, and during spring thawing, the subgrade soil loses its initial bearing capacity due to excessive moisture, which can lead to road pavement failures under large axial loads. Thus, during the winter freezing and spring thawing, a special water-thermal regime is formed in road structures, requiring the development of urgent engineering measures to ensure the reliability and long-term service life of highways.

It is known that the high initial moisture of the soil increases its thermal conductivity, which also complicates the regime of its freezing [1]. There are great variety of empirical models developed by researchers to determine soil thermal conductivity; however, there is no single standard empirical model that can be applied to all soil types [2–5]. When water freezes, the heat of ice formation is released, resulting in the fact that the rate and depth of freezing of wetter soil will be less than soil with lower moisture. The depth of soil freezing is also affected by the sum of negative air temperatures, and the duration and intensity of the negative air temperature. Frozen soil is accepted as an indicator of climate change [6–8]. The depth of freezing of the subgrade soil also depends on the height of the snow cover and the groundwater level. Thus, it can be said that the depth of soil freezing or “the temperature characteristics of active layers in frozen soil” are strongly dependent on the type of soil used, relative density in situ (degree of compaction on site), the presence

of clay and its plasticity index, climatic, hydrological, and other natural conditions, which vary widely [6,9–11]. That is why the depth of freezing varies from year to year, as does the climate on the Earth [12,13].

The work [14] also mentions that the temperature field formed on the road surface is determined by climatic factors such as solar radiation, air temperature, wind, etc. An accurate forecast for the temperature field of the road surface is crucial to the design of the road surface, the winter maintenance of roads, and the formation of a microclimate of the surface environment.

The influence of precipitation should be considered from different sides, including evaporation (phase transition), convection, and water flow [15]. Water infiltration has a direct effect on the thermal properties of road materials, especially for the porous surface layer of the pavement. This problem becomes severe in winter when freezing or thawing of the road structure occurs.

All over the world, researchers are dealing with the problems of the influence of environmental factors on the road condition, among which temperature and moisture rank highly. The authors emphasize the need to create databases to monitor these indicators, recorded in real-time. Information from such monitoring systems allows us to analyze and simulate road properties [16–18]. When obtaining the necessary parameters in different years, the researchers use various measuring means [16,19–23]. At the same time, basically all researchers use sensors based on the principle of thermal resistance to measure temperature, and sensors based on diamagnetic permeability are used to measure moisture.

In other works [24,25], the authors investigated the peculiarities of the temperature and moisture distribution at the points of the pavement and the subgrade and their variations over time during different periods of the year, including the winter season.

The purpose of this paper is to develop a methodology for determining the depth of freezing of subgrade soils in Kazakhstan.

This paper is a continuation of our earlier works on the study of temperature and moisture in the structural elements of highways [26–29] and presents the results of an investigation of freezing and thawing on sections of highways located mainly in the northern region of Kazakhstan with a long cold period.

2. Research Background and Method

In the Republic of Kazakhstan, for an experimental study of the water and heat regime of highways during 2020–2021, 28 measuring stations equipped with temperature and moisture sensors were installed all over the country (Figure 1). Temperature and moisture sensors were installed along vertical wells at different depths (Figure 2a). The pavement structure with the locations of the sensors on the road section near Kostanai is shown in Figure 2b. Sensors measured temperature and moisture data every hour in an automatic regime. Additionally, an air-temperature-measuring sensor was installed on the mast of the GPGS transmitter at a height of 2 m from the ground surface (Figure 2). All measured data were transmitted via GPGS to a special website, from which they were downloaded to the database of the Kazakhstan Highway Research Institute (KazdorNII). Temperature and moisture sensors were supplied by Real Style Co. (Kostanay, Kazakhstan). The measuring stations were assembled at the KazdorNII, together with Real Style Co.

In this article, the northern region of Kazakhstan (Kostanay, Pavlodar) with the longest cold climate was chosen for the experimental study of freezing and thawing processes.

Graphs showing changes in temperature and moisture are built on the basis of data received directly from the measuring stations. Graphs of the depth of freezing and thawing are built, also using the temperature values obtained from the measuring stations. At the same time, it was assumed that the pavement materials and subgrade soils begin to freeze even at a temperature of 0 °C.

Figure 2 shows the external view of the transmitting antenna and the schematic view of the pavement structure with sensors' location depths.



Figure 1. Map of locations of measuring stations on the territory of Kazakhstan.

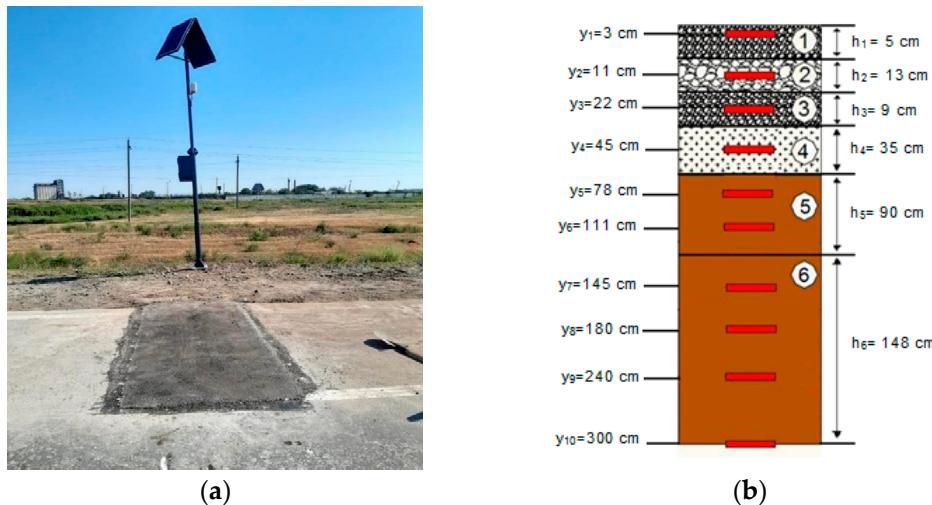


Figure 2. (a) External view of the measuring stations across Kazakhstan; (b) schematic view of the pavement structure with sensors' location depths; 1–3—asphalt concretes; 4—mixture of crushed stone, gravel and sand; 5—sand; 6—black soil.

The road structure consists of three layers of asphalt concrete, a layer of a mixture of crushed stone, gravel and sand, sand soil, and black soil. Names of materials for structural layers and their thickness are given in Table 1. The values of optimal moisture content (W_{opt} , %), maximum density (ρ_{max} , g/cm³), and plasticity number (I_p , %) of soils are as follows: sandy loam—1.88; 16.2; 11.4, respectively; black soil—1.81; 16.3; 15.8, respectively.

Table 1. Materials for structural layers and soils.

Name of Materials for Structural Layers and Soils	Layers Thickness, cm
Fine-grained (20 mm) dense asphalt concrete	$h_1 = 5$
Coarse-grained (40 mm) porous asphalt concrete	$h_2 = 13$
Coarse-grained (40 mm) high porous asphalt concrete	$h_3 = 9$
Mixture of crushed stone, gravel, and sand (80 mm)	$h_4 = 35$
Sandy loam	$h_5 = 90$
Black soil	$h_6 = 148$

3. Results and Discussion

3.1. Air, Pavement, and Subgrade Temperature

For a visual analysis, Figures 3–5 show graphs of changes in air temperature at the points of the pavement and subgrade over time. It can be seen that in the upper part of the asphalt concrete pavement (3 cm) on 20 September 2021, the temperature drops to 0°C , and in the spring of 10 April 2022, it changes from negative to positive values. Thus, it can be said that in the region under consideration, the upper part of the asphalt concrete pavement has negative temperatures for almost half of the year.

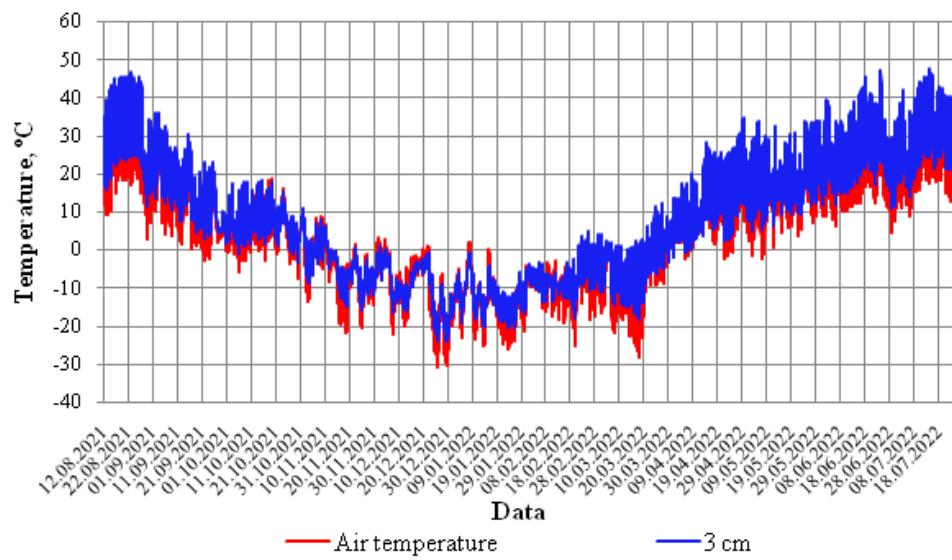


Figure 3. Graphs of air temperature and temperature changes in the upper part of the asphalt concrete pavement (3 cm).

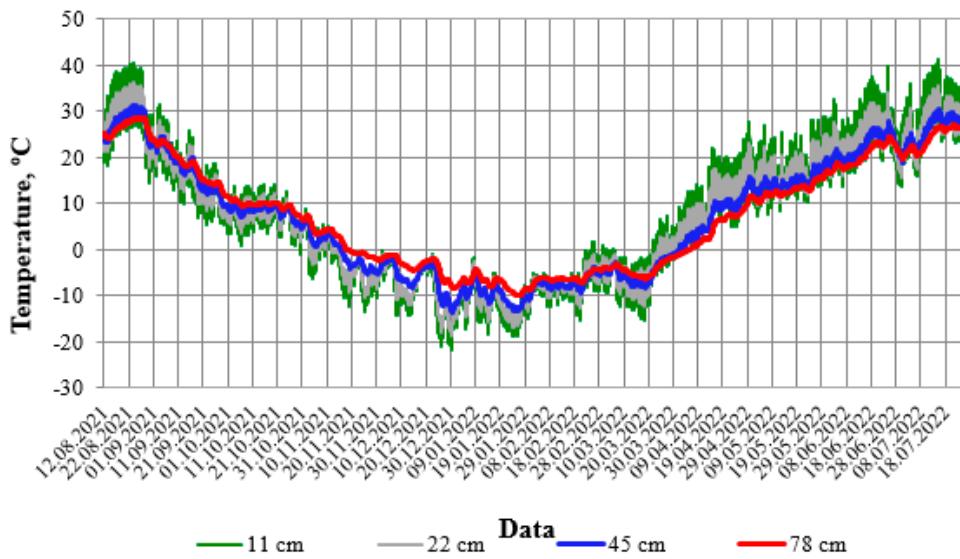


Figure 4. Graphs of temperature changes in the pavement and in the upper part of the subgrade.

From these figures, it can be established that in the upper part of the pavement (up to 30–40 cm), the temperature changes in annual and daily cycles; with increasing depth, daily temperature fluctuations disappear, and only the annual fluctuation remains; it can be assumed that at a depth of 180 cm and below, temperature fluctuations occur only in the annual cycle.

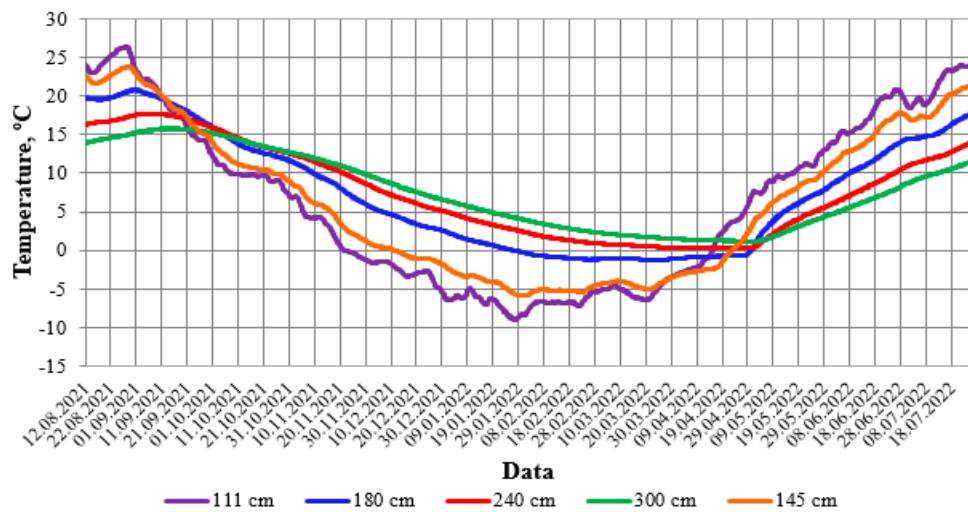


Figure 5. Graphs of temperature changes in the lower part of the subgrade.

In the annual cycle, the temperature of the surface of the asphalt concrete pavement varies within a very wide range: from +42 °C in summer (in August and September) to –32 °C (in December and January).

3.2. Freezing and Thawing

Freezing depth is an important characteristic of asphalt concrete roads operating in cold climate regions. It corresponds to points in the pavement and subgrade (subgrade) at which the temperature is approximately 0 °C. Thus, within the freezing depth, a part of the road is in a frozen state, and outside it, the temperature has a positive value.

It is useful to have more detailed information about the processes of freezing and thawing of pavement and soil base layers, since the strength and deformation characteristics of pavement materials and soil, as a rule, change significantly due to temperature variation and the amount of phase state of moisture contained in them.

It turned out that during the considered cold period on the selected section of the road, the freezing process follows a complex pattern (Figure 6). Around 27 October 2021, the freezing of the surface of the asphalt concrete pavement occurred, and on November 16 it reached a freezing depth of 44 cm, i.e., the freezing rate was 2.32 cm/day. Then, the freezing rate increased sharply to 14.75 cm/day, with which freezing reached a depth of 103 cm in 4 days; then, over the next 12 days, the freezing rate gradually decreased to a depth of 137 cm. The average rate in this period of time was 2.83 cm/day. Then, for a long time (95 days), from a depth of 137 cm to a depth of 219 cm, freezing proceeded at an even lower average rate of 0.86 cm; at the most recent characteristic freezing interval, the rate had a minimum value of 0.33 cm/day, and a maximum freezing depth of 227 cm was reached.

The thawing process follows a simpler regularity: both “bottom-up” and “top-down” thaws take place, which begin at approximately the same time points (27–30 March 2022); the descending branch of thawing occurs almost uniformly, at an average rate of 6.25 cm/day from the surface of the asphalt concrete pavement to a depth of 220 cm; the average rate of the ascending branch of thawing is 0.9 cm/day.

The temperature distributions over the depth of the pavement and the subgrade at different characteristic times are shown in Figure 7. These time points are not chosen randomly; they are the times at which some characteristic physical processes take place, which are associated with the freezing and thawing of the pavement and the subgrade: 27 October 2021—the beginning of freezing of the asphalt concrete pavement; 16 November 2021—the beginning of freezing of subgrade; 30 November 2021—the beginning of freezing of the subgrade at a constant rate (at a depth of 130 cm); 27 March 2022—the beginning of thawing of the asphalt concrete pavement; 30 March 2022—maximum freezing depth (227 cm); 1 April 2022—the beginning of thawing of subgrade (at a depth of 62 cm).

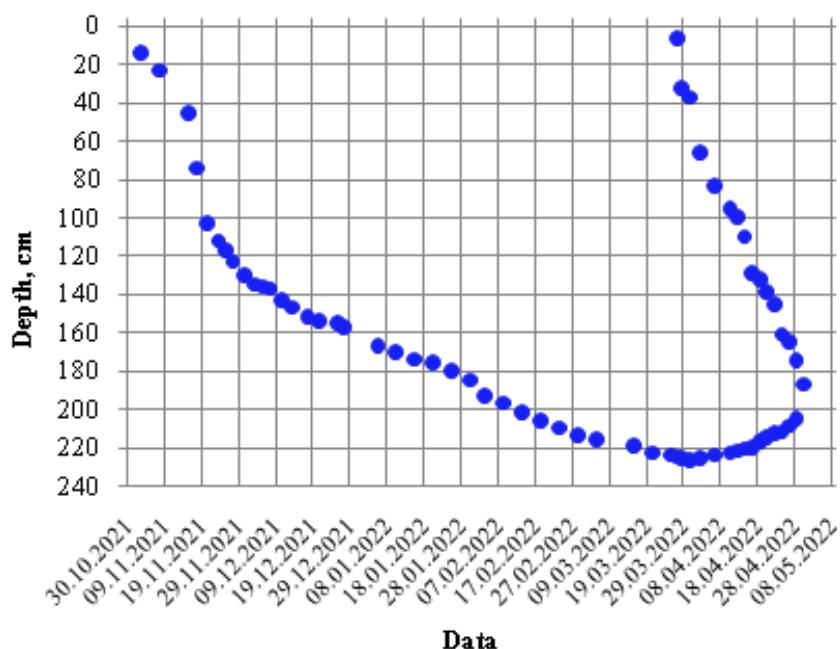


Figure 6. Freeze and thaw curves for pavement and subgrade.

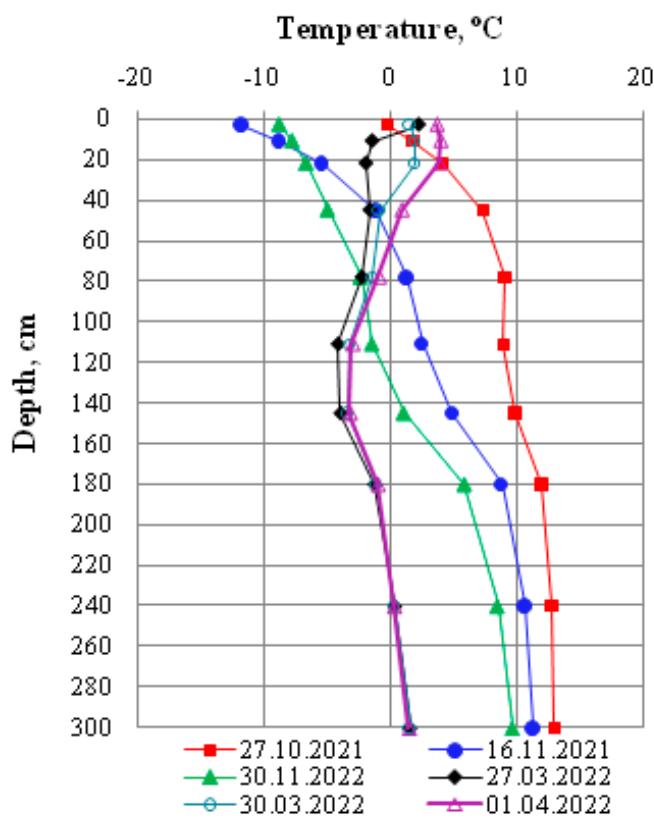


Figure 7. Temperature distribution curves in pavement and subgrade at different characteristic times.

This figure clearly shows that with the onset of the cold period, the temperature distribution curves shift towards lower temperatures. Within 20 days (from 27 October 2021 to 16 November 2021), the surface temperature of subgrade soil (at a depth of 62 cm) drops from 8.5 °C to 0 °C. Despite the short period of time (only 5 days from 27 March 2022 to 1 April 2022), the temperature in the lower asphalt concrete layers (depth 20–30 cm) during the thawing period changes significantly (from −3 °C to +4 °C).

Moreover, according to the aforementioned method, the patterns of the freezing–thawing process at measuring stations located near the settlements of Oskemen, Balkhash, Kossy, Kazaly, Almaty, Ucharal, and Zaisan were studied. These stations represent different climatic conditions in the regions of the Republic of Kazakhstan. For example, the village of Kossy is located near the city of Astana, which belongs to central Kazakhstan.

The southeast of the country is represented by stations Balkhash, Almaty, Oskemen, Ucharal, and Zaisan, which belong to the east of the country. Moreover, the south and southwest of the Republic is represented by one station, located in the city of Kazaly. Additionally, the city of Kostanay, as already mentioned above, is located in the north of the Republic.

Table 2 summarizes all the data characterizing the geographical coordinates of the location of the stations, the date of the beginning of freezing, and the end of thawing of the soil in each measuring station, and the maximum depth of freezing in each of them.

Table 2. Maximum freezing depths of roads in Kazakhstan.

Station Name	Freezing Start	End of Thawing	Maximum Freezing Depth, cm
Oskemen	03.11.21	29.04.22	218
Kostanai	02.11.21	30.04.22	227
Balkhash	12.11.21	10.03.22	178
Kossy	05.11.21	30.04.22	219
Kazaly	01.12.21	30.04.22	131
Almaty	20.11.21	03.03.22	61
Ucharal	10.12.21	05.03.22	112
Zaisan	02.11.21	10.04.22	225

Figure 8 shows combined graphs of freezing–thawing processes at eight measuring stations. This form of presentation of the results of the study allows us to compare the results of individual parameters. For example, although the Oskemen, Ucharal, and Zaisan measuring stations are located in the same geographical region, they differ significantly in the depth of freezing and in the duration of freezing. The duration of freezing of the road sections located near Oskemen, Zaisan, and Ucharal is 165, 128, and 42 days, respectively. The depths of freezing reach 218 cm, 112 cm, and 225 cm. Thus, an example of strong influence of terrain, proximity to a large reservoir, and constant winds on freezing patterns is proved. In the first case, the mountainous terrain around the city of Oskemen affects the process of freezing in that area. Moreover, in the case of Zaisan, the influence of the proximity of a large reservoir is obvious. Different patterns of freezing in the Ucharal region can be explained by the presence of a wind of a constant direction.

Almost identical freezing depths in winter 2021–2022 are recorded in Oskemen, Kostanai, and Kossy (218 cm, 227 cm, 219 cm). Additionally, the duration of freezing is almost the same for all of them. The most difficult thing is to explain the features of the freezing–thawing process in the city of Kazaly. Here, almost for a month, the beginning of freezing is late and, as a result, the freezing depth only reaches 131 cm. As expected, the station near Almaty turned out to be the warmest among the measuring stations under consideration. Here, the freezing depth reaches only 61 cm, with a freezing duration of 104 days.

Thus, the geographic coordinates of the area or so-called climate zone do not always determine the magnitude of the freezing depth. To accomplish this, it is also necessary to take into account the duration of stay in the frozen state of the structural layers of the road pavement and the soil base layer, which is determined by the climatic features of the area.

The topic of studying the processes of freezing and thawing in roads in the Republic of Kazakhstan is poorly developed, and not a lot is known about it. The practical value of this work lies in its uniqueness, since this topic in such a detailed format (with maximum coverage of all regional features) is being studied experimentally for the first time in Kazakhstan.

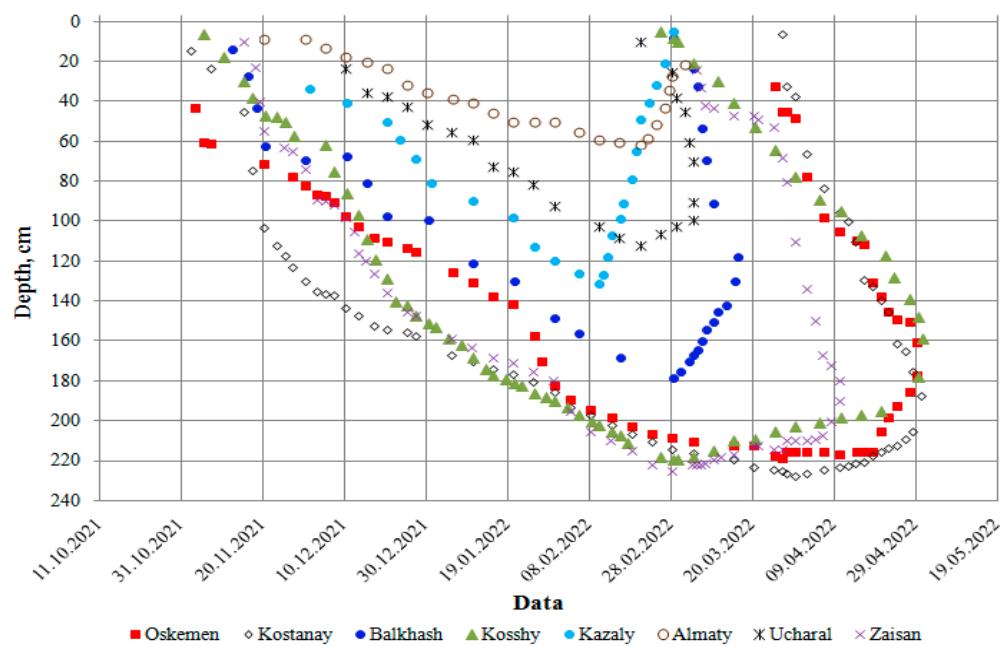


Figure 8. Combined freezing and thawing patterns of roads in Kazakhstan.

3.3. Moisture

Figures 9 and 10 show graphs of changes in moisture in the lower part of the pavement and in the subgrade. As can be seen, in the considered almost annual period, the absolute value of moisture in the considered part of the road is in the range from 8% to 35%. At the same time, the following phenomena take place: at the beginning of the cold period, the moisture at the points decreases abruptly, and at the beginning of the warm period, it increases abruptly; moisture values during the entire cold period are lower (from 2–3% to 8–9%) than in the warm periods of the year.

On the combined graphs of changes in moisture and temperature (Figures 11 and 12), it can be established that the above abrupt changes in moisture at the points of the pavement and the subgrade occur at times when the temperature has a value of approximately 0 °C.

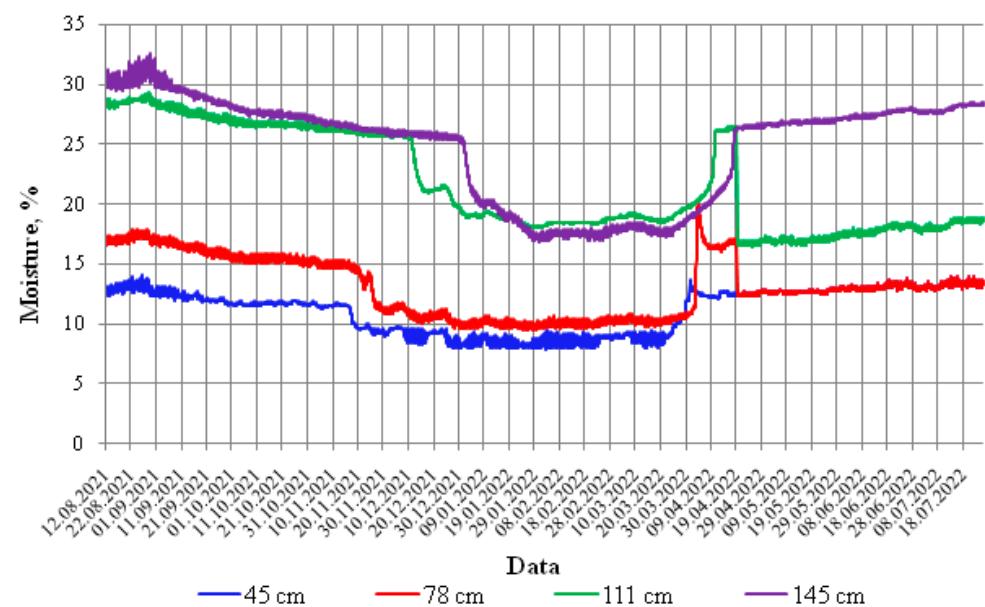


Figure 9. Graphs of changes in moisture in the lower part of the pavement and in the subgrade.

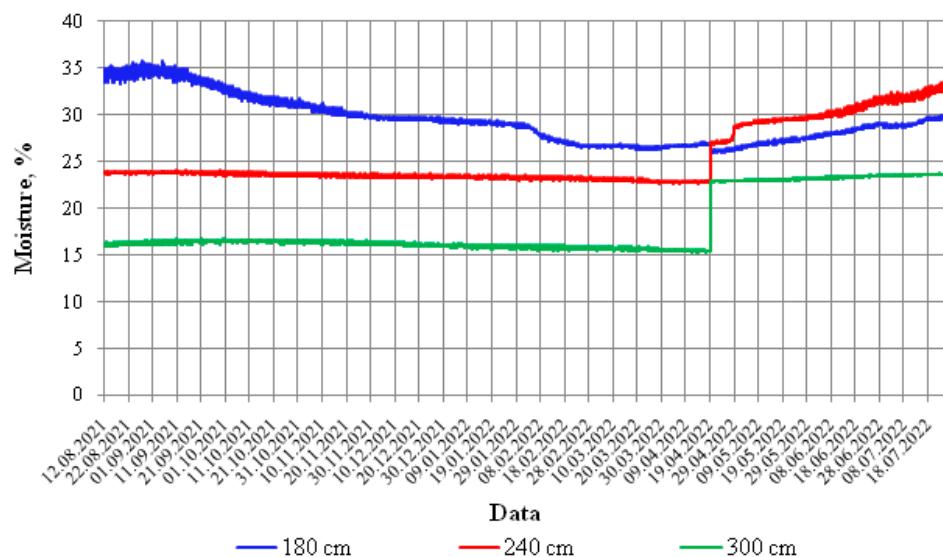


Figure 10. Graph of moisture change in the lower part of the subgrade.

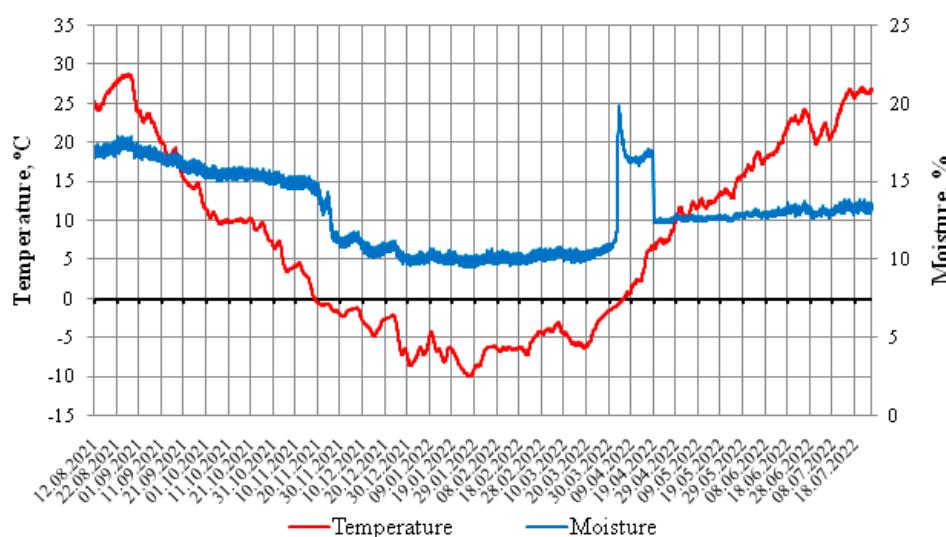


Figure 11. Combined graphs of moisture and temperature changes at a depth of 70 cm in the subgrade.

Thus, abrupt changes in moisture at the beginning and end of the cold period are explained by phase transitions of the second kind: the transition of the liquid state to the solid state (ice) at the beginning of the cold period and the transition of moisture from the solid state to the liquid state at the end of the cold period.

An important indicator that strongly affects the mechanical behavior of the pavement and the subgrade, and therefore the strength and durability of the road, is the moisture content of the subgrade soil (subgrade) within the “working layer” (up to a depth of 145 cm). Figure 13 clearly shows that the moisture content of the subgrade is not evenly distributed over the depth; in autumn, on the surface of the subgrade soil, the humidity is 14%. It increases unevenly to a depth of 180 cm, where it reaches its maximum value (30–31%), then to a depth of 300 cm, it decreases evenly to a value equal to 16–17%. The nature of the distribution of moisture in depth in the spring period is qualitatively the same as in the autumn distribution, but there are significant quantitative differences: in the spring period on the surface of the subgrade, the moisture is 10–12%. At depths of 78, 111, 145, and 180 cm, it has a value equal to 11%, 19%, 18%, and 26%, respectively.

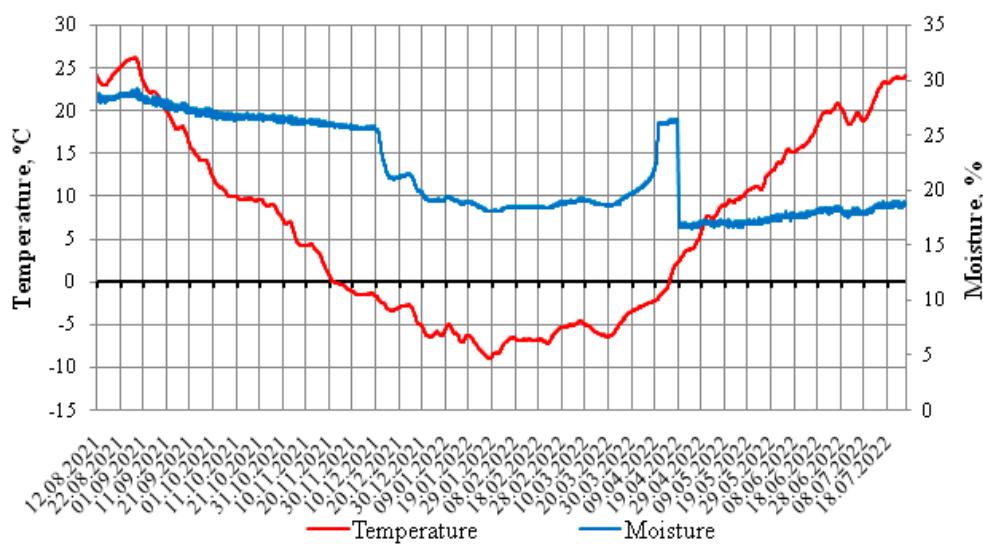


Figure 12. Combined graphs of moisture and temperature changes at a depth of 111 cm in the subgrade.

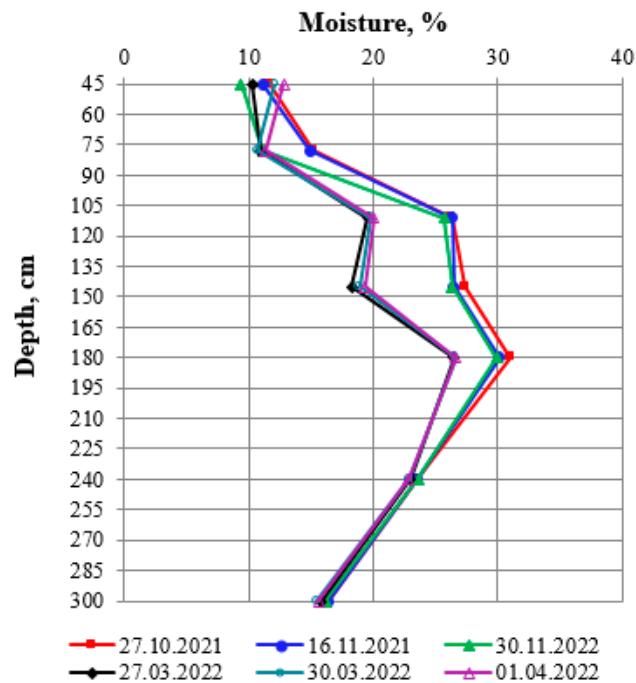


Figure 13. Moisture distribution curves in pavement and subgrade at different characteristic times.

It is important to note that due to phase transitions in the soil part of the “working layer”, the moisture changes from 5% (on the surface of the subgrade soil) to 9% (at a depth of 145 cm).

4. Conclusions

The following conclusions can be drawn from the analysis of the results obtained:

- (1) The measuring stations used in the work make it possible to carry out long-term continuous monitoring of temperature and moisture in pavement and subgrade of highways. The results obtained are very important for road science and practice.
- (2) In the upper part of the pavement (up to 30–40 cm), the temperature changes in annual and daily cycles. As the depth increases, the daily temperature fluctuations disappear, leaving only the annual fluctuation. At a depth of 180 cm and below, temperature fluctuations occur only in the annual cycle.

- (3) During the cold period under consideration, on the selected section of the highway, the freezing process proceeded according to a complex pattern. The freezing rate varied from 14 cm/day to 0.33 cm/day. The maximum freezing depth was 227 cm. The thawing process has a simpler pattern. In this case, both “bottom-up” and “top-down” thawing take place. They begin at approximately the same time points. The descending branch of thawing occurs almost uniformly, with an average rate of 6.25 cm/day to a depth of 220 cm; the average rate of the ascending branch of thawing is 0.9 cm/day. Asphalt-concrete layers of the pavement and the upper part of the subgrade were in a frozen state for 151 and 166 days, respectively.
- (4) In the subgrade at the beginning and end of the cold period (when the temperature has a value of approximately 0 °C), there are abrupt changes in moisture, which are explained by phase transitions of the second order: the transition from the liquid state to the solid (ice) at the beginning of the cold period and the transition of moisture from the solid state to liquid at the end of the cold period.
- (5) In autumn, on the surface of the subgrade, the moisture is 14%. It increases unevenly to a depth of 180 cm, at which it reaches its maximum value (30–31%), then to a depth of 300 cm, and it decreases evenly to a value equal to 16–17%. In spring, on the surface of the subgrade, the moisture content is 10–12%. At depths of 78.111, 145, and 180 cm, it has a value equal to 11%, 19%, 18%, and 26%, respectively. In winter, due to the phase transitions in the subgrade, the moisture changes from 5% (on the surface of the subgrade) to 9% (at a depth of 145 cm).

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