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The impact of the temperature and humidity state of the road on heat and mass transfer in winter

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Abstract. Sharp diurnal temperature fluctuations in Astana, Kazakhstan, in winter, as well as freezing up to 2 or more meters leading to the destruction of the roadway, especially during the spring thaw, prompted a detailed study of the state of roads. In this work, the temperature and humidity of the highway structure layers were monitored in winter, and the mass transfer of water in the gaseous state due to the negative pressure of cryosuction in the frozen layers was also considered. It was determined that mass transfer of water in the form of steam 1.44 10^{-4} g/h per 1 dm^3 of soil at temperature fluctuations of -5-8 °C. The rate of vapor passage towards the freezing front in the soil was 0.467 m/h. The freezing of the ground base continued for 132 days in the winter period of 2021-2022 in Astana with the formation of 456.72 g of ice due to the migration of water in a gaseous state in every 1 m^3 of soil, which increases the humidity by 40 % or more and significantly reduces the bearing road capacity during the spring thaw. As a solution to the problem of water migration in the form of steam, it is proposed to introduce an additional layer of vapour barrier over the soil base at a depth of -60 cm.
Keywords: highway structure, temperature and humidity monitoring, heat transfer, moisture transfer, soil freezing.

1. Introduction

The temperature and humidity state of the foundation of roads has a huge impact on their strength and deformation characteristics [1, 2]. This is especially true for regions with a continental climate where there are a large number of transitions through zero degrees [3]. At low temperatures, part of the water contained in the road subgrade soil passes from a liquid state to a solid state (ice). Freezing temporarily improves the deformation and strength characteristics of the subgrade soil [4, 5]. Sharp temperature fluctuations during the day in winter in Astana, Kazakhstan, as well as freezing up to 2 or more meters leading to the destruction of the roadway, especially during spring thaw, prompted a detailed study of the state of roads [6].

According to the results of previous studies, the cooling of pavement layers is more intense compared to unpaved roadside soils [7]. Highway construction materials with higher thermal conductivity are a zone of more intense cooling and thus, due to cryosuction forces, attract unfrozen water and, together with it, deicing chemicals used for surface treatment of highways and accumulated during cleaning in lateral reserves [8].

One of the unresolved problems is mass transfer from water in the gaseous state, which, unlike water in the liquid state, does not have surface tension forces, easily passes through the smallest pores, condenses, and sublimes when the vapour is saturated, and forms ice lenses in these places [9]. In order to study the state of roads and assess their bearing capacity under the influence of negative temperatures, a section of the road was studied in the conditions of the city of Astana. To do this, the temperature of the pavement and subgrade was monitored during the period of temperatures below 0 degrees in winter 2021 - 2022, and soil samples were taken for a more detailed laboratory testing. To study frost heaving as well as the transfer of water from warm to cold layers of soil at the base of the highway, a method presented by Sarsembayeva et al. was used to determine the mass-heat transfer [9].

2. Method

1.1 Experimental study of foundation soils

The investigated section of the road is located near the airport of Astana, in the area of the Karkaraly highway, 8 km from the bypass road towards the town of Kosshy. All soils exposed at the site, according to the results of surveys, are water-bearing deposits. The groundwater regime is subject to seasonal fluctuations: the minimum standing is observed in February, the maximum falls on the end of May. The amplitude of groundwater level fluctuations is 1.0-2.0 m. Groundwater is fed mainly due to infiltration of precipitation. The feeding area is the distribution area of the aquifer.

In January 2022, soil samples were taken in the immediate vicinity of the highway in order to study their condition in winter. The density of the loam base soil was 2.0 g/cm^3, the moisture content in natural condition was 20.2%. By laboratory research methods, the soil filtration coefficient for Quaternary loams was determined - 0.01-0.13 m/day. Groundwater in this section of the road is characterized as sodium chloride, very hard, slightly alkaline, brackish. In relation to concrete grade W4 on Portland cement, groundwater is non-aggressive and slightly aggressive, in relation to reinforced concrete structures it is moderately aggressive. The corrosive aggressiveness of groundwater in relation to the lead and aluminum sheaths of the cable is high. Groundwater is corrosive in relation to steel structures (according to Shtabler). The physical and mechanical characteristics of the foundation soils are given in Table 1.

Table 1 – The physical and mechanical characteristics of foundation soils

Characteristic	Units	Value
Moisture content	%	20.2
Liquid Limit	%	26.5
Plastic Limit	%	15.1
Plasticity Index	%	11.6
Consistency index	-	0.5
Bulk density	g/cm^3	2.0
Particle density	g/cm^3	2.7
Void ratio		0.7
Degree of saturation	-	0.8
Deformation modulus	MPa	6.5
Cohesion	KPa	23.5
Angle of internal friction	degree	22

1.2 Monitoring the temperature of the roadway in winter

The construction of the road is a non-rigid pavement made of an underlying layer of gravel-sand mixture 15 cm thick on the compacted base soil (Figure 1). On top is the bottom layer of the base of the crushed stone-sand mixture with a thickness of 15 cm, then the top layer of the base of the hot highly porous asphalt mixture with a thickness of 12 cm. Above is a 10 cm hot mix asphalt pavement layer. And a 5 cm hot mix asphalt pavement surface layer.

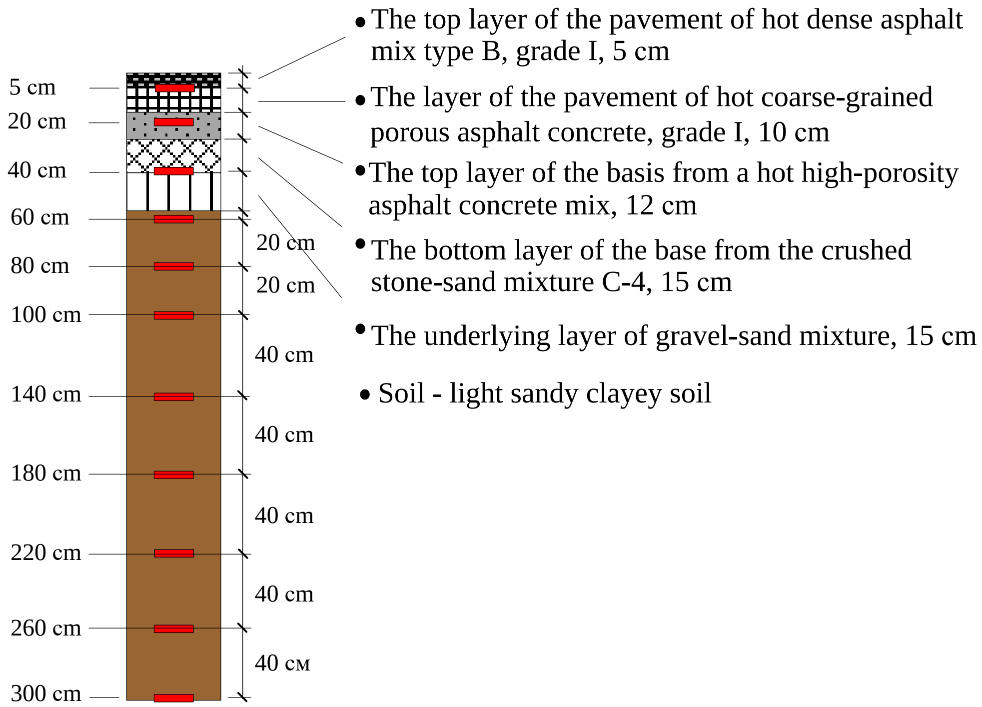


Figure 1 – The structure of the highway base

The temperature was recorded by automatic measurement by sensors embedded in metal capsules installed at a depth of 0.05; 0.2; 0.4; 0.6; 0.8; 1.0; 1.4; 1.8; 2.2; 2.6 and 3.0 m from the asphalt concrete surface. The air temperature was also measured, taken here as the temperature of the earth's surface 0 cm. Sampling frequency was 1 time per hour.

1.3 Calculation of the moisture transfer from the base layers upwards the freezing front

Figure 2 schematically shows the direction of water vapour migration to layers with higher thermal conductivity and, accordingly, lower temperatures in winter. Water mass transfer in a gaseous state from lower and warmer layers of the highway base towards the upper colder layers was calculated according to the method described in detail by [9].

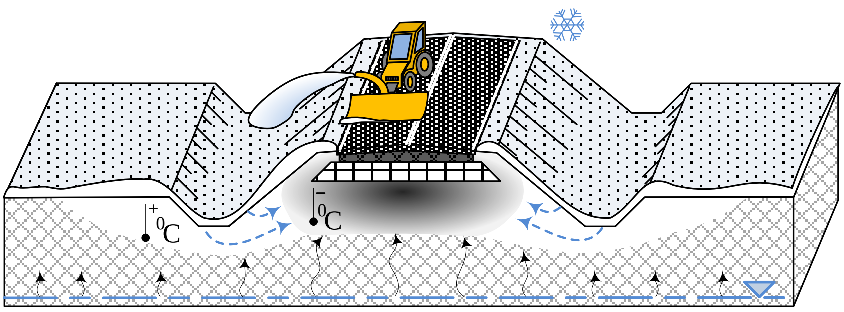


Figure 2 – Moisture migration in the highway base

The vapour speed is calculated as a heat transfer over cumulative void channel dimensions, vapour flow density corresponding to the temperature and time:

$$v_{vapour} = \frac{Q}{C \cdot \rho_{vapour} \cdot A_{air} \cdot \Delta T \cdot t} \tag{1}$$

where, v_{vapour} – average speed of vapour, cm/h; Q – heat transfer in a gaseous state, ΔT – measured temperature difference, °C; C – specific heat of vapour passing through the cumulative air voids cross section, J/kg·°C; ρ_{vapour} – vapour density corresponding to the temperature, g/cm³;

$A_{air\ voids}$ - cumulative cross section of the air voids' $A_{air\ voids} = \frac{\pi \cdot d_a^2}{4}$, cm², corresponding to the porosity coefficient and moisture content; t – time, h.

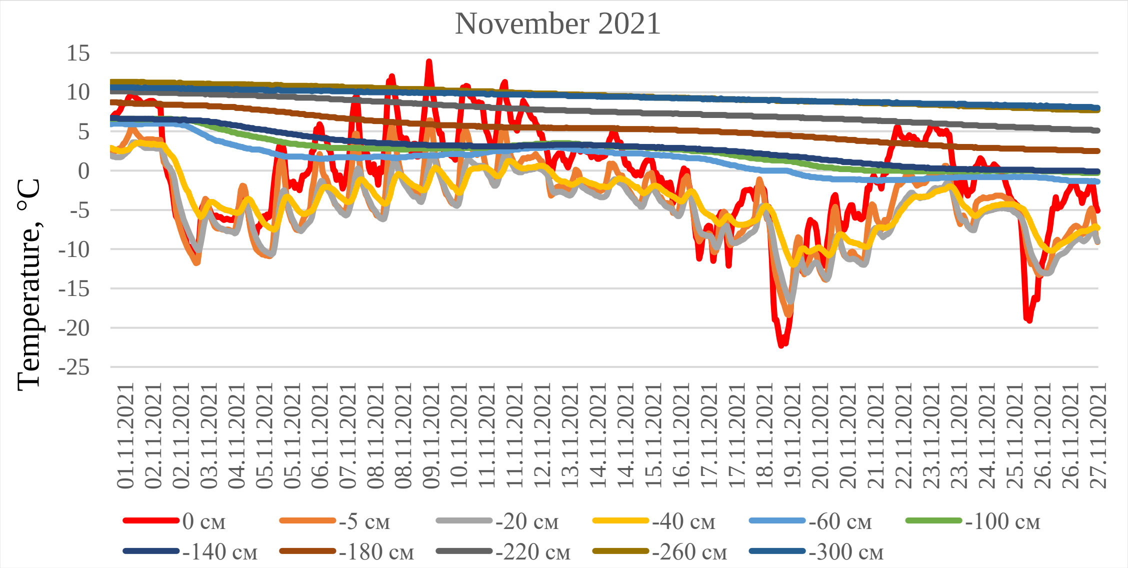
The mass of ice built from the vapour passing over time period t with speed v over the cumulative air channel cross section A_{air} is calculated:

$$m_{ice} = \rho_{vapour} \cdot V_{air\ voids} = \rho_{vapour} \cdot v \cdot t \cdot A_{air} \quad (2)$$

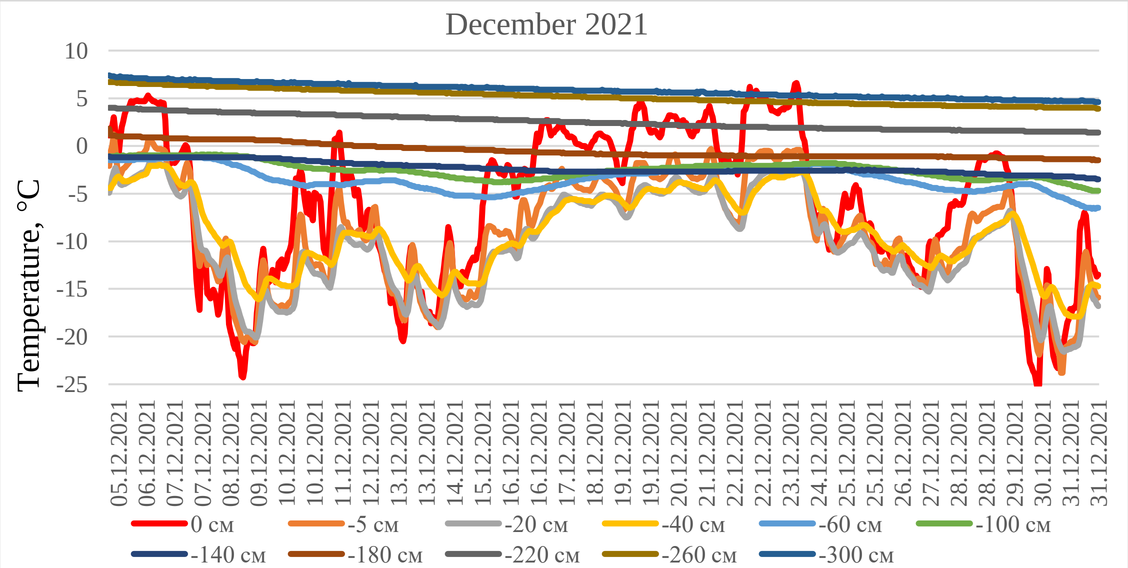
where, m_{ice} - mass of built ice in grams; ρ_{vapour} - is taken as an average density value of the vapour densities at the start and end time point, g/cm³.

3. Results and Discussion

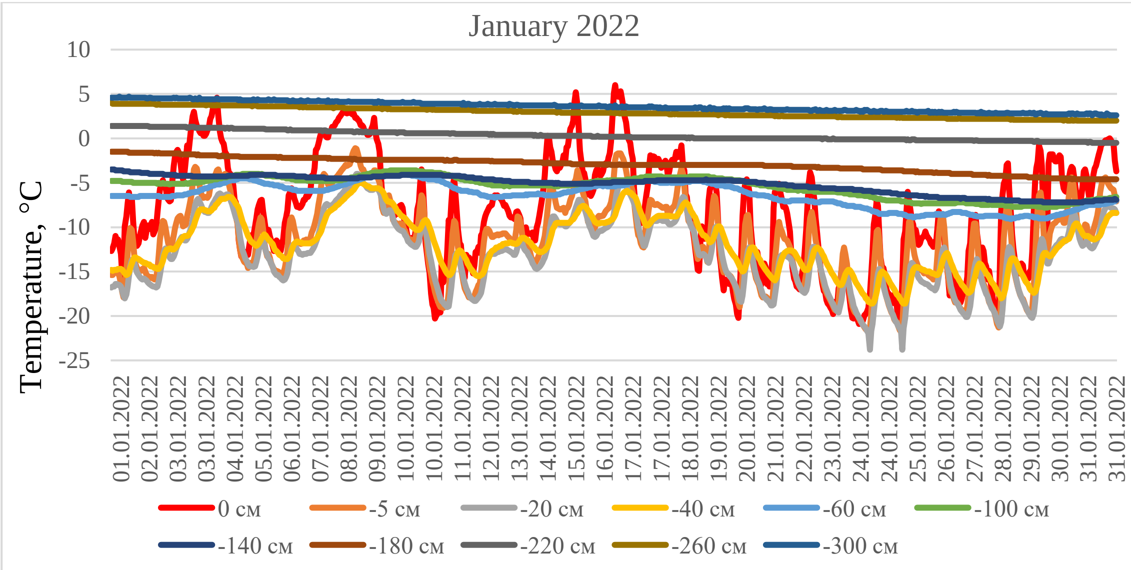
The results of temperature monitoring (Figure 3) showed large amplitude jumps during the day in the upper layers of asphalt concrete. During November, eight 0°C crossings were recorded. In contrast to the asphalt concrete layers, which have sharp temperature fluctuations during the day, the temperature of the base soil slowly and steadily dropped over the course of a month. Soil freezing began on November 19, and then there were no strong jumps in the direction of thawing.



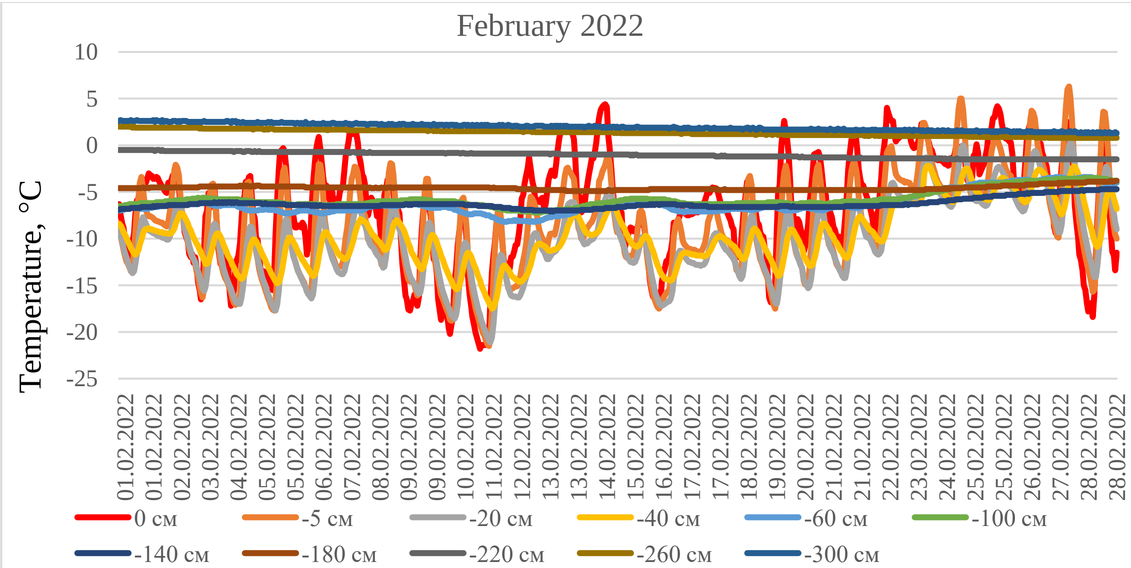
a) Temperature distribution for November 2021



b) Temperature distribution for December 2021



c) Temperature distribution for January 2022



d) Temperature distribution for February 2022

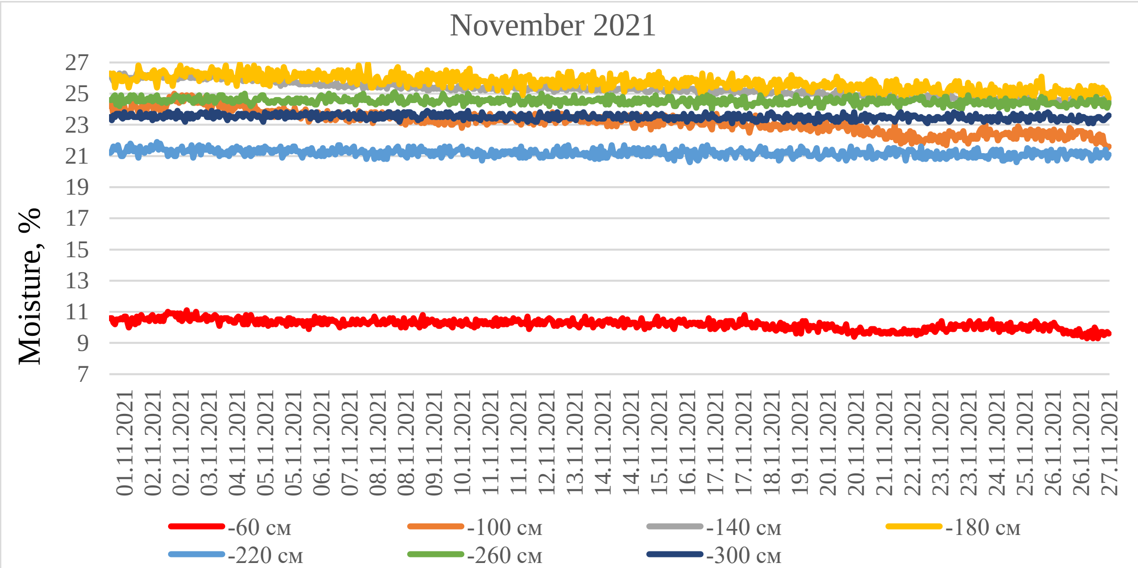
Figure 3 – Temperature distribution over time

In December, 8 transitions through 0°C were recorded, but the underlying layers of the gravel sand mixture remained frozen, apparently by compensating for the heat transfer of the underlying cooler layers. The relative stabilization of the foundation soils reached at a depth of -1.2 m at negative temperatures in the range of -5 -2°C. The freezing depth continues to steadily increase from 1.60 m to 2.0 m during the month. At the end of January, the freezing depth reaches 2.20 m and at the end of February 2.50 m.

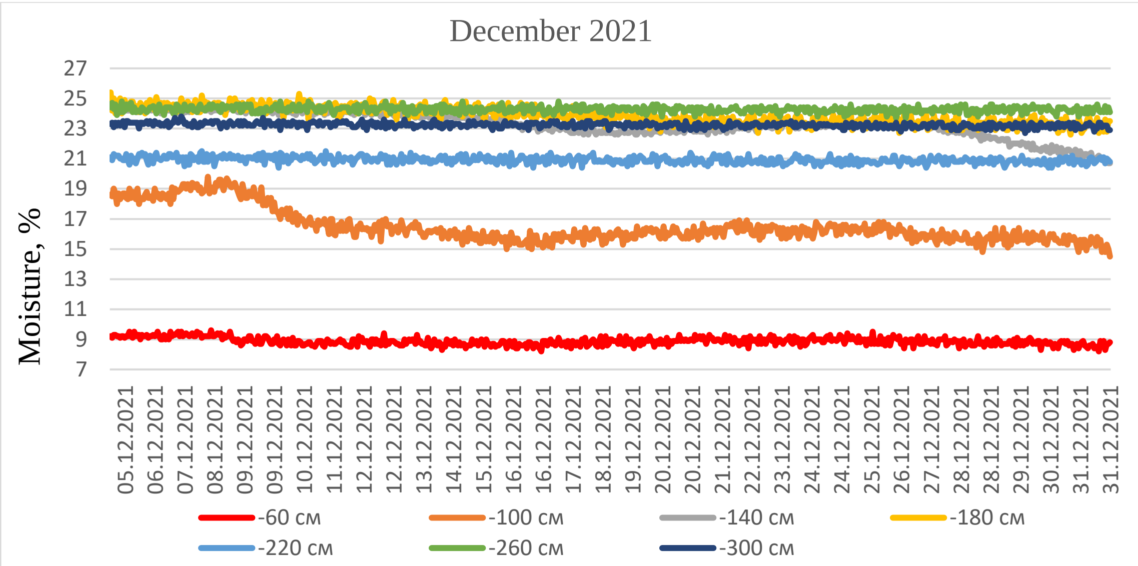
Table 2 – Brief information on the surface temperature of highway surface in Astana during the winter months

Month	November	December	January	February
Transitions over 0 °C	8	8	8	14
Average temperature, °C	-0.74	-6.04	-8.12	-6.46
Minimum temperature, °C	-22.0	-24.3	-20.9	-21.8

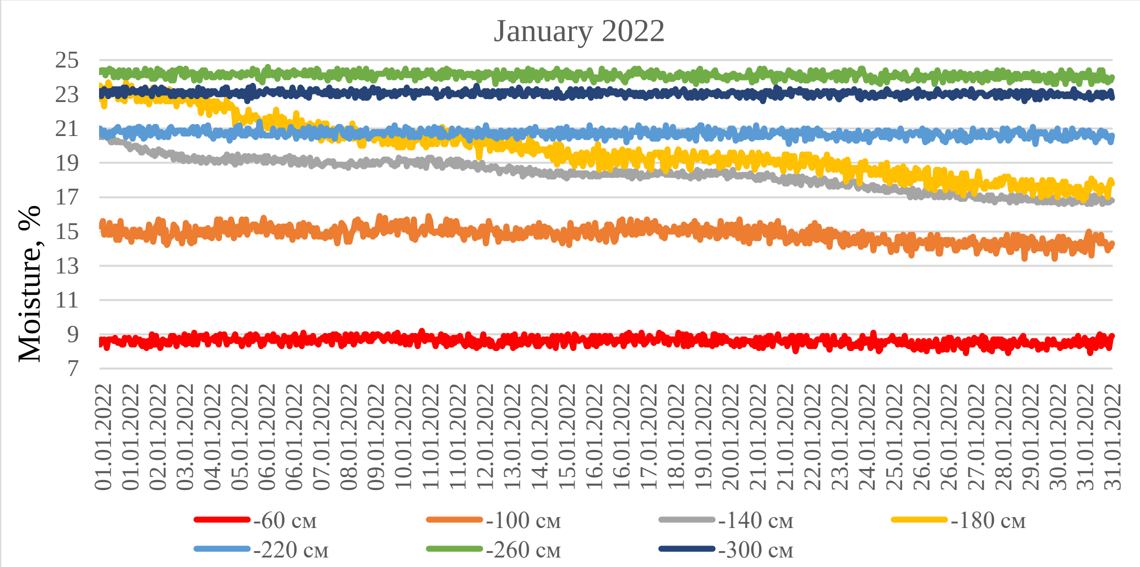
Figure 4 shows the change in the moisture content of the pore space in the soil base during the winter months. The difference from 21 to 11 % between the layers of 60 cm and 100 cm in November (Figure 3a) indicates a freezing front between these layers and an urgent solidification of moisture in the frozen part. A decrease in saturated vapor pressure in the pore space in the frozen part causes the migration of moisture in the gaseous state towards the freezing front. The lack of pore pressure (negative pressure) is compensated by vapour migration from the warm part from below. In December, from 8 to 12, a freezing front occurs at a depth of 100 cm and is accompanied by a drop in humidity in the pore space from 19 to 15%. And in January, freezing occurs at a depth of 140 cm and 180 cm, as evidenced by a drop in humidity from 21 and 23%, respectively, to 17% in a frozen state. During February, there is a decrease in humidity at a depth of 2.20 m, which means freezing of this layer.



a) November 2021 humidity measurements



b) December 2021 humidity measurements



a) January 2022 humidity measurements

d) February 2022 humidity measurements

Figure 4 – Moisture distribution over time

When calculating the amount of moisture migrating in 1 hour in 1 dm^3 of soil according to the method described by [9], we found that the water flow rate depended on the packing density of solid soil particles and the temperature distribution over the soil layers. The water mass transfer in a form of vapour $1.44 \cdot 10^{-4}$ g/h per 1 dm^3 of soil at with temperature fluctuations -5-8 °C. The rate of passage of vapour towards the freezing front in the soil was 0.467 m/h.

Thus, 0.144 g of ice is formed per hour in 1 cubic meter at a temperature of -5-8 °C at a depth of -60-160 cm from the road surface, while in a day this amount is 3.46 g of ice formed by transferring moisture from warmer soil layers. Now, given that the freezing of the soil base lasted 132 days in 2021-2022 winter period in Astana city, we can assume that during this time, only due to the migration of water in the gaseous state under the influence of cryosuction negative pressure in 1 cubic meter of the road base, 456.72 g of ice formed, which will increase the soil moisture to 40 % and more, which will significantly reduce the bearing capacity of the road during spring melt time.

Thus, the effect of water transport in frozen ground is greatly underestimated and it is necessary to install an additional layer of vapor barrier in order to prevent the accumulation of ice lenses under the pavement structure.

4. Conclusions

Based on the results of the study, the following outcomes were highlighted:

1. In the upper layers of asphalt concrete, from 8 to 14 transitions through 0 C per month were registered, while the temperature of the crushed sand-stone mixture at -37 cm depth remained in a stable frozen condition.

2. The freezing of the layers is accompanied by a sharp drop in the humidity of the pore space from 21-23 to 11-14 %, when part of the water in the gaseous state sublimates and forms a negative cryosuction pressure in these layers.

3. Base soil located at a depth of -60 cm consisting of light sandy sandy clayey soil is a frost susceptible and is in a stably frozen state at a temperature of -5-8 °C.

4. The water mass transfer in a form of vapour $1.44 \cdot 10^{-4}$ g/h per 1 dm^3 of soil at with temperature fluctuations -5-8 °C. The rate of passage of vapour towards the freezing front in the soil was 0.467 m/h.

5. The freezing of the ground base continued for 132 days in the winter period of 2021-2022 in Astana with the formation of 456.72 g of ice due to the migration of water in a gaseous state in every 1 m^3 of soil, which increases the humidity by 40 % or more and significantly reduces the bearing road capacity during the spring thaw.

6. As a solution to the problem of water migration in the form of vapour, it is proposed to lay an additional layer of vapor barrier over the soil base at a depth of -60 cm.

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