Cyclic freezing and thawing of a pavement structure

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Abstract. This paper examines the cyclic freezing and thawing of a pavement structure on a section of the Almaty-Bishkek highway in southeastern Kazakhstan. Temperature measurements were made using a continuous monitoring system with sensors. The characteristics (amount, duration and minimum temperatures) of the freeze-thaw cycles on the asphalt concrete pavement surface and at different depths were determined. Their dependences on depth were constructed and analyzed.

Keywords: pavement, monitoring system with sensors, freeze-thaw cycles, duration, minimum temperature.

1. Introduction

In road science and practice the main types of road pavement failure are considered to be rutting, fatigue and low-temperature cracks [1, 2]. The current US regulatory document contains methods for taking these mechanical failures into account at the design stage of road pavement structures [3]. In accordance with the requirements of standards [4, 5] in Kazakhstan flexible road pavement structures are designed taking into account the fatigue failure of monolithic (asphalt concrete) layers. Since the deformation and strength properties of asphalt concretes, soils and other road materials depend on loading parameters [6-8], temperature [9, 10] and moisture [11], it is necessary to have as detailed information as possible about the modes of movement of transport facility [12, 13], changes in temperature and moisture.

Field experimental studies have shown that freeze-thaw cycle (FTC) processes in road pavement layers should be given special attention in the southeastern region of Kazakhstan [14-16]. In particular the study [16] showed that during the last cold period (winter of 2024-2025) the amount of FTCs of the asphalt concrete pavement surface in Almaty was 76. FTCs significantly accelerate the degradation of wet road materials (especially asphalt concrete pavement surface) due to the "wedge effect", which gradually reduces the adhesion between bitumen and aggregate materials and accelerates the peeling of aggregate materials.

This paper examines the characteristics of FTCs on a section of the Almaty-Bishkek highway located in the southeastern region of Kazakhstan.

2. Experimental

2.1. Experimental section

For the purpose of a long-term monitoring of temperature and moisture in layers of a highway

pavement and its subgrade, an experimental section was selected not far from Almaty (at 58 km + 895 m) on the "Almaty-Bishkek" highway, where a set of sensors for temperature and moisture were installed.

The pavement structure includes six layers. The properties of the pavement layers and subgrade soil are presented in Table 1.

Table 1. Pavement layers and subgrade soil properties in the test section [17]

No.	Materials of pavement layers and subgrade soil	Thickness h, cm
1	Fine-grained dense asphalt concrete	5
2	Coarse-grained porous asphalt concrete	10
3	Fine-grained dense asphalt concrete	6.5
4	Coarse-grained porous asphalt concrete	15
5	Fine sand and gravel mix	25
6	Coarse sand and gravel mix	35
Subgrade soil	Heavy sandy clay loam	140

2.2. Temperature and moisture monitoring system

A highway monitoring system for long-term temperature and moisture measurements was installed (Fig. 1), consisting of above-ground and underground parts. The above-ground unit includes solar panels, power storage and a data control/transfer module. The underground part contains temperature (thermal resistance) and moisture (dielectric permittivity) sensors placed at different depths in the pavement and subgrade layers (3-300 cm) (Fig. 2). Data are recorded hourly and stored automatically [18].



a) b)

Fig. 1. Temperature and moisture monitoring system: a) above-ground module; b) sensors. The photographs presented in this paper were taken by the author Aizhan Muta during field studies carried out on December 8, 2025 on the experimental section located near Almaty (58 km + 895 m on the Almaty–Bishkek highway)

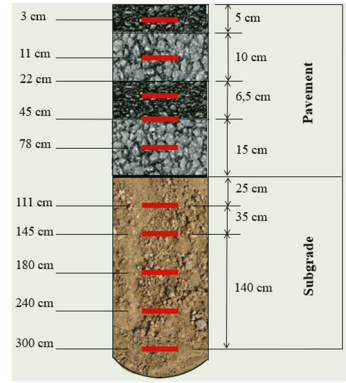


Fig. 2. Sensor layout in the pavement structure and subgrade on the experimental section of the Almaty-Bishkek highway

3. Results and discussion

3.1. Freeze-thaw cycles

As illustrative examples Figs. 3 and 4 show graphs of changes in air temperature and at a depth of 11 cm (in the middle of the second asphalt concrete layer of the pavement) during the cold period (autumn, winter and spring seasons) of 2021 and 2022.

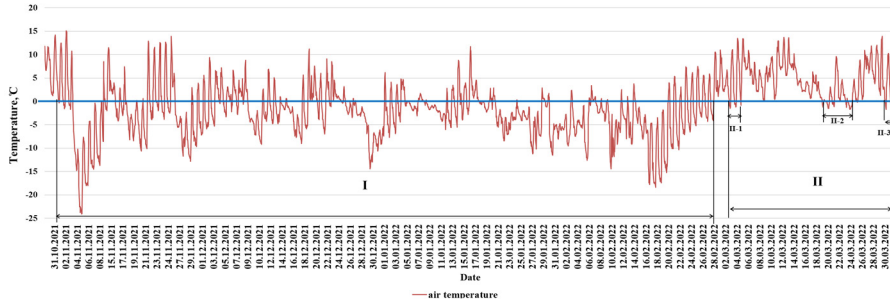


Fig. 3. Graph of air temperature changes indicating freeze-thaw cycles

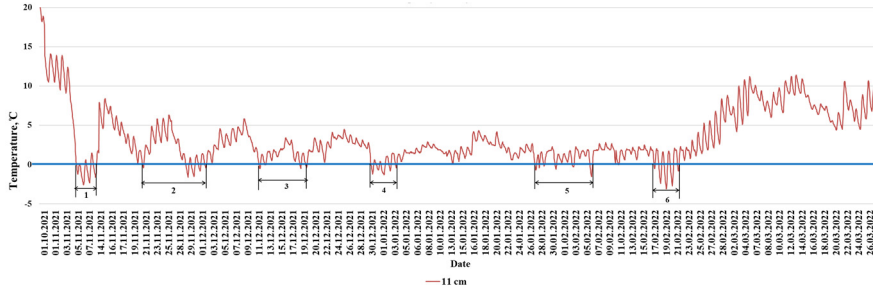


Fig. 4. Graph of air temperature changes indicating freeze-thaw cycles at a depth of 11 cm

3.2. Characteristics of FTCs

It can be seen that the characteristics of FTCs (start, end, duration and minimum temperature) are stochastic. These characteristics also depend on depth. The analysis revealed that the durations of individual FTCs on the asphalt concrete pavement surface (according to the air temperature graph) and at certain depths (3 cm and 22 cm) vary widely. For example, the maximum duration of freeze-thaw cycles on the asphalt concrete pavement surface and at a depth of 22 cm reaches 218.2 and 731 hours, respectively. And at a depth of 11 cm this value is 22.2 hours.

The highest minimum temperature at all the depths considered and on the asphalt concrete pavement surface is practically the same and ranges from –0.1°C to –0.3°C; the absolute values of the lowest and average minimum temperatures increase with depth (Table 2).

Table 2. Characteristics of FTCs at different depths

Depth, cm	Amount of FTCs	Duration of FTCs, hour			Minimum temperature of FTCs, °C		
		Minimum	Maximum	Average	Lowest	Highest	Average
0	70	2.0	218.2	110.1	–2.4	–0.1	–1.3
3	83	4.0	104.4	54.2	–2.9	–0.2	–1.6
11	26	5.0	22.2	13.6	–12.5	–0.1	–6.3
22	9	4.0	731.0	367.5	–24.1	–0.3	–12.2

The results show that the amount of freeze-thaw cycles decreases with increasing depth and this dependence can be approximated by an exponential function ($R^2 = 0.83$) (Fig. 5); the

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dependences of the absolute values of the lowest and average minimum temperatures on depth are also described with high accuracy ($R^2 = 0.92$ and $R^2 = 0.94$, respectively) by an exponential function (Fig. 6): the absolute value of the lowest minimum temperature decreases with depth and the absolute value of the average minimum temperature increases with depth [16].

Reducing the amount and the absolute value of the minimum temperature of FTCs with depth has a positive effect as it makes it possible to use relatively cheap frost-resistant materials in the lower layers of the pavement. When designing a pavement according to the mathematical model in Fig. 5 it is possible to determine the annual amount of FTCs for which it is necessary to choose a frost-resistant material.

There is a correlation between the amount and the absolute value of the lowest minimum temperature of FTCs (Fig. 7).

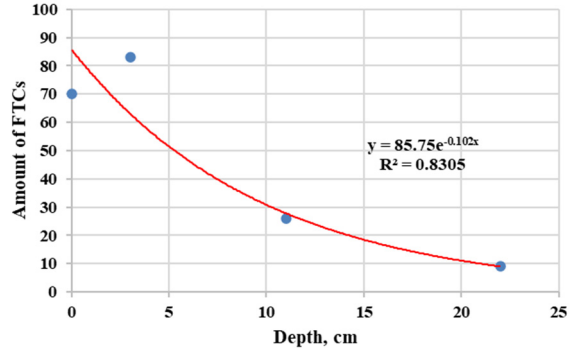


Fig. 5. Change in the amount of FTCs by depth

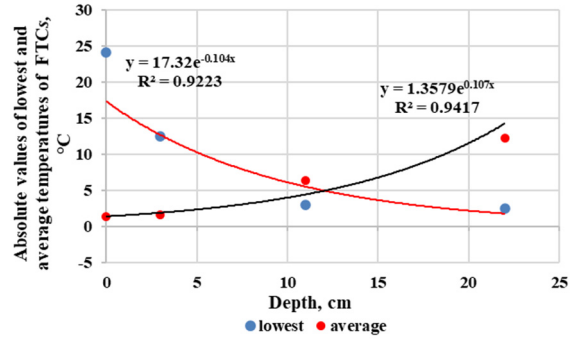


Fig. 6. Dependence of the absolute value of the lowest minimum temperature of FTCs on depth

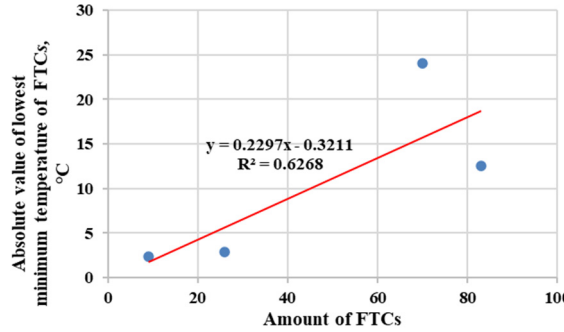


Fig. 7. Relationship between the amount of FTCs and the absolute value of the lowest minimum temperature

4. Conclusions

1) In order to accumulate data it is necessary to continue measuring temperature.

2) Since the characteristics of FTCs have a stochastic (random) nature after accumulating the required sample sizes it is recommended to apply the methods of the probability theory and the mathematical statistics for processing and further analysis.

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflict of interest

The authors declare that they have no conflict of interest.

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