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REGULATION OF THE WATER-HEAT REGIME OF THE SUBGRADE OF CEMENT-CONCRETE ROAD

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ABSTRACT: Cement concrete pavements are widely used due to their numerous advantageous characteristics, making them a preferred choice for modern highway infrastructure. The popularity of these pavements stems from their exceptional durability, enabling them to withstand the constant stresses imposed by heavy vehicular traffic. However, the issue of preserving concrete pavements during their operation in various sharply continental climatic conditions remains open and requires further research and solutions. This study presents the investigation of the influence of the thermal conductivity of road materials. The pavements are considered an independent research object under the influence of operational environmental factors. According to the results of the study, the correlation between the moisture content of the soil and its thermal conductivity was presented, indicating that with increasing moisture content, the thermal conductivity rises. However, this process is suspended with an increasing moisture content of 14% and above. Thus, the calculation of temperatures of pavement layers and subgrade soils can be based on the scheme of stationary heat exchange. Accounting for thermal conductivity enables informed decisions regarding the optimization of a road design for specific climatic and traffic conditions, ultimately creating safer and more durable roads.

Keywords: Road Pavement, Thermal Conductivity, Heat Regime, Soil

1. INTRODUCTION

The technical level of modern highways is largely determined by the perfection of their high-quality pavements. Nowadays cement concrete pavements are widely used in many countries due to their durability [1].

Experience with cement concrete shows that the surface of concrete road pavement is not sufficiently protected from the effects of weather-climatic factors [2-3]. Such a process leads initially to intensive corrosion micro-destruction of the surface layer of coatings (its wear, display of peeling, formation of microcracks) with the subsequent development of macro-destruction of concrete structure in the volume of the structural layer of concrete surface.

Due to the tendency of an increasing number of paved roads in the territory of Kazakhstan, the operation of these roads requires high attention to maintenance and road safety [4]. Adverse conditions for motor vehicle traffic, often occurring in winter, when traffic on roads is complicated by the appearance of various types of snow and ice formations, have a particular impact [5].

Applying chemical reagents for roads with asphalt concrete pavement is not possible for cement concrete roads because the pavement is subject to moisture absorption [6-7]. Thus, chemical solutions, easily penetrating the body of cement concrete, contribute to damage to the pavement [8]. This process in climatic zones with sharply continental climates intensifies the likelihood of delamination of the cement stone with subsequent concrete milling (flaking) and loss of strength due to the low resistance of this material [9]. On the surface of cement concrete pavements can also form various types of cracks, which are caused by pores of cement concrete moisture.

This process is especially dangerous in the early spring when the daily air temperature is not stable, and as a result, peeling or small cracks may form on the surface of the pavement [10]. Four main destructive factors affect the surface of cement concrete pavement: the dynamic loads of vehicles, causing wear of the pavement; solar radiation, maximum heating of the pavement in summer and causing temperature warping of concrete slabs; unstable temperatures and various cooling gradients, causing temperature stress and critical deformation, resulting in microcracks; precipitation, as well as moisture transfer in the concrete pavement [11-12].

As noted in the studies of the greatest operating load, causing gradual changes leading to the destruction of the structure of concrete road pavement is experienced by the surface layer of concrete. The question of analyzing the operating conditions of the thin surface layer of the coating:

its temperature regime and the temperature-stress state directly related to it is currently open.

In this regard, the presented study will determine the physical-mechanical and thermophysical characteristics of the materials of each layer of the pavement of the road, and in its different states depending on the humidity and air temperature and the determination of the correlation between the moisture content of the soil and its thermal conductivity.

2. RESEARCH SIGNIFICANCE

The study presents laboratory studies on the thermophysical characteristics of pavement materials. Important parameters such as the thermal conductivity of road materials, soil moisture, and density have been determined. The results have shown the possibility of simplifying the methods of calculation of water-heat regimes by replacing non-stationary processes with stationary ones. The presented results are important for one of the stages of estimation of cement concrete pavement destruction under the influence of a water-thermal regime. On the base of these results significantly streamlines pavement design and maintenance, enhancing the durability and resilience of cement concrete road infrastructure.

3. MATERIALS AND METHODS

3.1 Theoretical Foundations of Heat and Heat Transfer

To determine the effect of the thermophysical properties of cement concrete pavement on air temperature was considered the heat exchange process in the pavement layers and their dependence on the environment and the thermal conductivity of materials. In operation, concrete road pavement is actively influenced by three groups of environmental factors [13]. The first factors include total solar radiation; atmospheric precipitation; air humidity; air temperature; air temperature change rate; and air speed over the pavement. The second group of environmental factors includes transport (mechanical) impacts: static vertical forces and horizontal tangential forces arising from the acceleration (deceleration) of vehicles. The third group of energy factors of the external environment is the impacts due to the subgrade's temperature and humidity conditions and groundwater level [14-15]. For sharp climatic conditions, the impact of environmental factors on the surface layers of concrete pavements is the leading factor.

The heat coming from solar radiation Q is not completely absorbed by asphalt concrete pavement, part of it is reflected from the surface. The reflected heat coefficient Q2 depends on the reflection coefficient (Fig. 1). For asphalt concrete reflection coefficient R=0.1, respectively, the absorption coefficient A=0.9, then the amount of heat absorbed will be: Q1 = 0.9-Q [16]. The heat transfer from the heated surface of the cement concrete is mainly by convection heat transfer. Heat transfer by convection is carried out by the movement in space of unevenly heated volumes of gas.

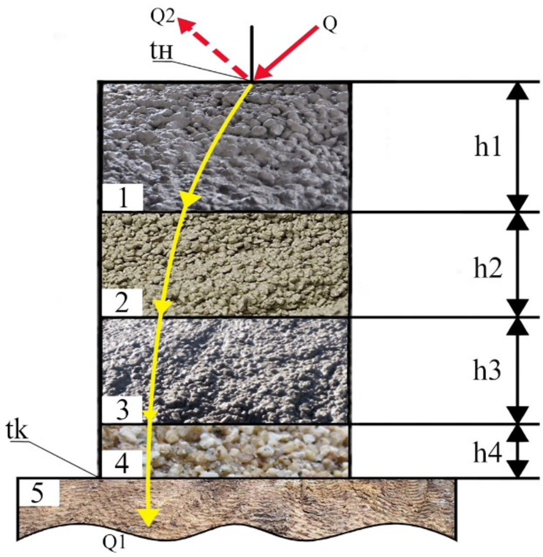

Fig.1 Distribution diagram of the amount of heat

Heat transfer from the heated surface of cement concrete is mainly by convection. Heat transfer by convection is realized by the movement of unevenly heated volumes of gas in space. Convective heat transfer between a solid surface and a gas is called heat transfer. According to the Newton-Richman law, the heat flux Q from a solid surface to a gas is proportional to the heat exchange surface F and the temperature difference between the surface temperature t_s (W) and the air (gas) temperature t_g which is determined by the Eq. (1):

$$Q = \alpha \cdot F(t_s - t_g) \tag{1}$$

Air (gas) motion can be laminar or turbulent. In laminar mode, gas particles move in layers without mixing. Turbulent mode is characterized by continuous mixing of all air layers. The transition of the laminar regime into a turbulent regime is determined by the critical value of a dimensionless complex called the Reynolds number by the Eq. (2):

$$Re_{cr} = \frac{\omega \cdot l}{\vartheta} \tag{2}$$

where ω is air velocity, m/s; ϑ is kinematic viscosity coefficient, cm^2/s; l is the characteristic size of the streamlined surface.

The intensity of heat transfer depends on the vehicle traffic mode, which creates turbulent air movement over the pavement. In a turbulent boundary layer, heat transfer in the direction of the pavement is due to turbulent air mixing. However, directly near the surface of the coating, in the laminar sublayer heat will be transferred by conduction. In a laminar boundary layer, heat is transferred toward the coating only by conduction.

The main heat source (positive or negative in wintertime) in the equation describing the heat transfer process in the pavement layers is the temperature of the air and the thickness of each layer of the pavement. In addition, the heat transfer coefficient of the materials of each pavement layer and their importance is also of key importance in the calculation. Since the solid surface has a layer of fixed air, the heat exchange process in the pavement layers, considering the change in air temperature and humidity, can be described by Fourier's law, if the OZ axis (considering a system in which there are molecules whose concentration n(z) depends on the coordinate z and visually placing a square of area S, orthogonal to the axis z, at the point with coordinate z, then in the system there is a process of equalization of concentration n of particles, accompanied by their transfer in the direction of decreasing n) is directed perpendicular to the pavement surface [1].

$$q = -\lambda \cdot (\frac{\partial t}{\partial z})_{z=0} \tag{3}$$

where $\boldsymbol{q = \alpha \cdot (t_s - t_g)}$, $\boldsymbol{\alpha}$ is the heat transfer coefficient from solar radiation to pavement materials, W.

$$\boldsymbol{\alpha = -\frac{\lambda}{t_s - t_g} \cdot (\frac{\partial t}{\partial z})_{z=0}} \tag{4}$$

where $\boldsymbol{\lambda}$ is the heat conductivity coefficient of materials of each layer of pavement, W/(m·grad); $\boldsymbol{t_s}$ is a natural environment, transferred to the upper (first) layer, pavements ^{o}C; $\boldsymbol{t_g}$ is the temperature of the next layer, the second layer of pavement, ^{o}C. The heat flux density during the transition from one layer to the next depends on the heat flux per unit of time over the isothermal surface of the pavement through the structural layers.

$$\boldsymbol{q = \frac{d^2 Q_\tau}{dFd\tau} = -\lambda \frac{\partial t}{\partial n} = -\lambda \mathrm{gradt}} \tag{5}$$

From Eq. (1), the heat transfer coefficient is determined by:

$$\boldsymbol{\lambda = -\frac{d^2 Q_\tau}{\frac{\partial t}{\partial n} dFd\tau}} \tag{6}$$

3.2 The Object Characterization

The considered section "Almaty - Kapshagai" of the highway "Almaty - Ust-Kamenogorsk" 14-118 km is a part of the international transport corridor (Fig.2). The highway "Almaty - Ust-Kamenogorsk" is important in providing local, inter-oblast, and international road transportation of goods and passengers. Geographically, the survey area is located within the Iliysk neotectonic depression, bounded by the Zailiyskiy Alatau ridge of the North Tien Shan from the south and the North Tien Shan ridge from the north. Zailiyskiy Alatau ridge of the North Tien Shan, and the Dzungarian Alatau ridge of the Dzungar-Balkhash fold from the north. Dzungarian Alatau of the Dzungarian-Balkhash folding system of the Caledonian complex, passing in the northwest to the vast sandy deserts of Taukum and Saryesik-Atyrau.

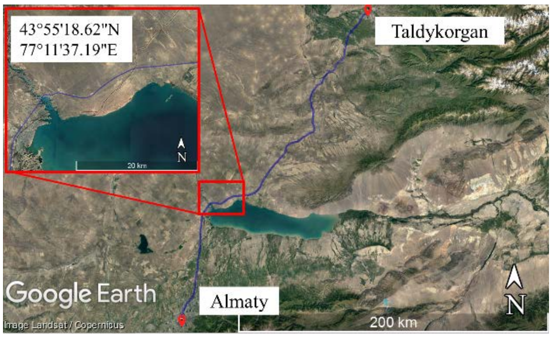

Fig.2 Map of road construction [17]

The road section belongs to the I technical category with a length of 32 km which provides for a minimum of 2 lanes with a width of 3.75 m in each direction. The 1st category road is intended for mass traffic and is made of high-quality concrete pavement (capacity from 7000 cars per day, speed from 120 to 150 km/h).

The geological structure of the engineering-geological survey area includes rocks of Cenozoic and Paleozoic ages, representing two structural stages [18]. The upper stage is composed of sandy-clay deposits of Middle Quaternary-modern and Upper Quaternary-modern (QII-IV-QIII-IV) and Quaternary (Q) ages.

On the sections:

- 46-47 km of the highway from the surface are spread Middle Quaternary - co-modern sediments of alluvial-proluvial genesis (apQII-IV), represented mainly by yellowish-brown loams, light dusty semi-hard and hard, the exposed thickness of the sediments reaches 1 meter;
- 47-69 km Upper Quaternary - modern sediments of eluvial-deluvial genesis (edQIII-IV) are developed, represented

mainly by yellowish-brown fine sands, the uncovered thickness of sediments reaches 12 meters;
- 69-77 km, undissected Quaternary deposits of eluvial-diluvial genesis (edQ) are developed from the surface, represented mainly by yellowish-brown sandy loam of hard to plastic consistency with thickness up to 3.5 m and gravelly sands with thickness up to 1.2 m.

According to hydrogeological zoning of the territory of Kazakhstan in a survey of the site km 45-77 of the road, water-bearing complexes of Cenozoic sediments are spread, which is confirmed by conducting the present study of the water-bearing complexes of Cenozoic sediments.

3.3 Construction Solution for Road Pavement

The pavement design is adopted with the following characteristics: a type of pavement – capital; design service life of the pavement - 25 years; static load on the surface of the pavement from the wheel of the design vehicle - Qk=65 kN (according to SN RK 3.03-19-2006); pressure in tires – 0.6 MPa; traffic intensity, units/day, in the first year of pavement service - 22957 auto/day; annual growth rate of traffic intensity - q=1.04; road-climatic zone - IV; working layer moistening scheme - 1; strength coefficient - 1.00; reliability level - 0.95. The pavement structure of the road consists of cement concrete pavement, crushed stone sandy gravel mixture with the addition of cement 7%, crushed stone sandy gravel mixture, sandy gravel mixture, and a subbase layer which is presented in Fig. 3.

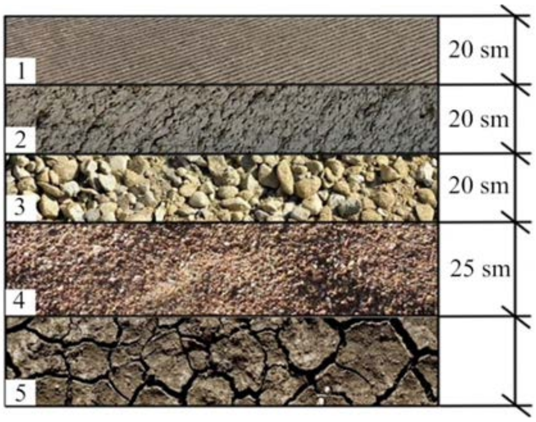

Fig.3 Sampling process for pavement materials

The design provides:
- pavement layer - the top layer of the two-layer pavement is made of frost-resistant, durable, and polish-resistant crushed stone. A concrete strength class is established at the age of 28 days of hardening in normal conditions according to GOST 10180 and GOST 18105, and when using slow hardening cement at 90 days in wet conditions [19-20].
- the top layer of the base - in crushed stone mixtures for wedging crushed stone of narrow fractions and category of wear resistance characterized by the coefficient of micro - Deval, introduced in ST RK 1284-2004 "Crushed stone and gravel from dense rocks" for construction works “Technical conditions” [21].
- the bottom layer of the base - based on GOST 25607-2009 [22]. Technical conditions considering climatic peculiarities of the Republic of Kazakhstan [23].
- road pavement- used from gravel-sand and boulder-gravel-sand rocks according to GOST 31426 and used for the device of the lower layers of bases for road surfaces, drainage layers, road embankments, temporary highways, backfilling of excavations, trenches, cushions for monolithic foundations, backfilling of bases for various sites, for planning and landscaping, for reclamation and in other types of construction, in accordance with the requirements of national building codes and regulations for the relevant types of work [24-25].

3.4 Conducting the Experiment

For the laboratory analysis of the thermal properties of the pavement and pavement materials in the field, samples were taken from the materials of each layer during their dissection (Fig.4).

Fig.4 Sampling process for pavement materials

When sampling with a cutter, the samples are wet. Therefore, the prepared samples were pre-dried at t=+40-50ºC. Samples prepared with the seam slicer are obtained dry and their humidity corresponds to the natural humidity (Fig.5). The thermal conductivity of medium-grained asphalt concrete was also considered for correlation purposes.

Fig.5 Samples of pavement materials for the thermo-technical test

The studies were performed on the laboratory equipment LKT-1 (Fig.6). The LCT series contains integrated laboratory complexes, expansion module kits, and stand-alone specialized measurement systems.

Fig. 6 General view of equipment LKT-1

Tested samples were made square-shaped, 3.2 x 3.2 cm in size and 1.1-1.4 cm thick. After thermophysical tests by the hydrostatic weighing method, the density of the samples was determined. Given that the same materials in road structures in different regions of Kazakhstan, depending on climatic conditions, have different humidity and given that at different humidity the same material has different thermal conductivity. The thermal conductivity of each test sample at different humidity was determined. The resistance of the heat-generating elements of the furnace is 10 Ohm, the maximum supply voltage is 20 V, and the maximum power is 40 W.

The sample under study was placed on the plate, the ballast calorimeter was placed on top, which is pressed by the rod with the help of two springs. The springs are attached to two pins and can be removed if necessary. The free (exposed) surface of the sample was covered with thermo-isolating skin.

Thermal insulation to prevent loss of heat to the environment. Through the connector, the module is connected to the measuring system IST-2M (Fig.7). The toggle switch "VENT" turns on the fan. Sockets "H1" and "H2" are included in parallel to the heater and are used to measure the voltage on the heater when it is necessary to accurately determine the heater power.

Fig.7 Measuring system IST-2M

To establish the dependence of calorimeter temperature on time, the calorimeter temperature was measured at 60-second intervals for 15-20 min (15-20 measurements), also controlling the temperature of the plate. The rate of heating of the calorimeter was used to determine the thermal conductivity of the sample.

$$\lambda = C - \frac{\frac{dT}{dh} \cdot h}{S\,(T_0 - T)} \tag{7}$$

where T_o is the furnace temperature, °C; T is the calorimeter temperature, °C; h is the thickness of the studied sample, m; S is the contact area of the calorimeter cylinder with the sample, S=18 cm^2; C is the heat capacity of the aluminum calorimeter cylinder, C=125 J/K.

The thermal conductivity of the subgrade was calculated similarly by Eq. (1).

4 RESULTS

The thermal conductivity coefficients of the pavement materials were found to be essential inputs for accurate water-heat regime calculations, allowing for more efficient planning and resource allocation in road construction projects. Managing soil moisture and density in line with these findings can extend the lifespan of cement concrete pavements, reducing maintenance costs and environmental impact. Additionally, controlling density ensures the stability and load-bearing capacity of the subgrade, further reducing the risk of pavement failure.

The thermal conductivity coefficients of the pavement materials are shown in Table 1 and Fig. 8.

Table 1 Heat transfer coefficients of pavement materials

№ layer	Materials of pavement layers	Furnace temperature, T_o, + ^{0}C	Calorimeter temperature with interval 60 s., T, +°C	Thermal conductivity coefficient, W/(m·grad)
1	Medium-grained asphalt concrete	50	32.9; 33.6; 34.1; 34.8; 35.3; 35.0; 35.9; 37.0; 38.1; 39.4; 40.9; 42.9; 43.5; 44.7; 45.9	1.36
2	Cement concrete on strong crushed stone	50	33.3; 33.6; 34.0; 34.5; 35.0; 35.6; 37.4; 38.2; 39.0; 39.9; 40.9; 41.8; 43.1; 44.2; 45.4	1.21
3	Skinny concrete	50	32.1; 32.5; 32.9; 33.5; 34.4; 35.0; 35.7; 36.4; 37.2; 38.0; 38.9; 39.7; 40.7; 41.8; 42.9	0.78

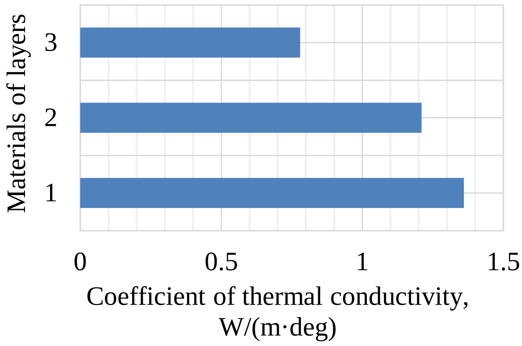

Fig.8 Thermal conductivity diagram of pavement materials

Table 2 and the curve in Fig. 9 show that as the moisture content increases, the thermal conductivity of the ground increases.

Regarding Table 2 humidity is low the heat conductivity is much lower, for example with 4 % moisture content of loamy soil density is 1.36 t/m^3, heat conductivity is 1.46 W/m·deg., and with 12 % moisture content density is 1.64 t/m^3, heat conductivity 2.71 W/m·deg.

Further, as the level of humidity of 12% and lower the density decreases, and consequently the thermal conductivity as well. Such phenomena essentially influence the strength of the subgrade of road pavement and subgrade. This is emphasizing the critical importance of maintaining suitable moisture levels for long-lasting and safe infrastructure.

Table 2 Test results of soils of different moisture content

Loamy soil					
W, %	p, t/m^3	λ, W/(m·grad)	W, %	p, t/m^3	λ, W/(m·grad)
1	2	3	1	2	3
4	1.3	1.58	10	1.8	2.55
	1.4	1.64		1.6	2.47
	1.5	1.43		1.4	2.33
	1.2	1.22		1.7	2.03
	1.4	1.42		1.6	2.17
average	1.36	1.46	average	1.62	2.31
6	1.5	2.06	12	1.6	3.11
	1.6	2.13		1.6	3.12
	1.4	1.81		1.8	3.07
	1.4	1.75		1.5	2.75
	1,3	1.58		1.7	2.65
average	1.44	1.67	average	1.64	2.94
8	1.5	2.11	14	1.6	3.74
	1.6	2.22		1.5	3.16
	1.7	1.46		1.5	2.75
	1.3	1.77		1.6	2.58
	1.8	3.09		1.4	2.21
average	1.58	2.13	average	1.52	2.71

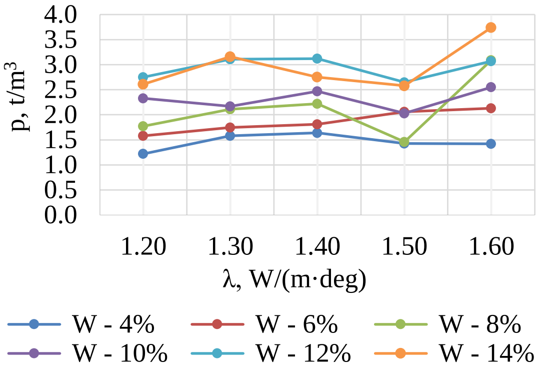

Fig.9 Results of thermal conductivity and density for soils of different moisture content

One of the principles of simplifying water-thermal regime calculation methods is replacing non-stationary processes with stationary ones. The possibility of applying such a calculation principle in several cases can be justified as follows. It is convenient to characterize the relationship between water and thermal regime by the criterion of A. V. Lykov [13].

$$L_u = \frac{\alpha_l}{\alpha} \tag{8}$$

The criterion L_u characterizes the relationship between heat and mass transfer, the intensity of change in the moisture exchange potential field relative to the change in the temperature field. The coefficients α_l, α determine the speed of temperature and humidity equalization in the layer. The greater α_l or α , the faster all points of the body will reach the same humidity or temperature.

On this basis, was considered the process of increasing or decreasing the thermal conductivity coefficient of materials of each pavement layer in laboratory conditions. The humidity of the tested sample of materials of pavement layers varied from 4 to 14 % (Table 2).

At the same time, the heating temperature of the calorimeter remained the same. In Fig. 10, the correlation relationship between soil moisture content and its thermal conductivity is shown, with increasing moisture content value, the thermal conductivity rises. However, this process is suspended with increasing humidity from 14 % and above. For soils and materials, the L_u criterion of A. V. Lykov decreases with decreasing humidity [13].

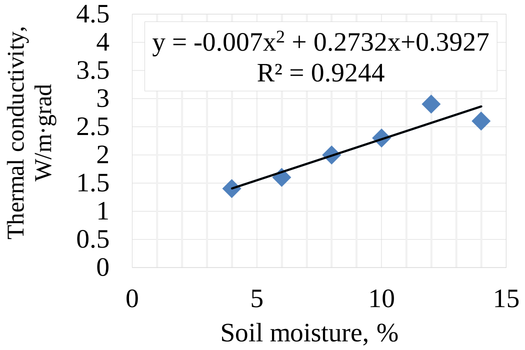

Fig.10 Correlation between the moisture content of soil and its thermal conductivity

For each material, it is possible to establish the criterion moisture content according to the dependence $L_u = \int W_{op}$ below which the assumption of stationarity within the ΔT thermal regime is acceptable. For some varieties of clay soils in a wide range of moisture fluctuations the criterion L_u is less than one.

5 CONCLUSION

Regulation of the water-heat regime of the subgrade of a road is essential for maintaining the structural integrity and longevity of the pavement. The subgrade is the natural soil or compacted material underneath the road surface, and its properties significantly influence the overall performance of the road. Proper regulation of the water-heat regime involves managing both moisture and temperature levels to prevent detrimental effects such as settlement, frost heave, and rutting. Cement concrete pavement is a hygroscopic material and is easily exposed to moisture absorption. This process in climatic zones with sharply continental climates aggravates the probability of cement stone delamination with subsequent concrete sloughing (flaking) and loss of durability due to the low resistance of this material.

The cause is the penetration of moisture into the pores of cement concrete. This process is especially dangerous in the early spring period, when the daily air temperature is not stable, and may result in flaking of the pavement surface or small cracks.

The obtained results of the study showed that if $\mathbf{L_u}$<1, then the calculation of temperatures of the layers of roadway and subgrade soils can be made on the basis of the scheme of stationary heat exchange.

6 ACKNOWLEDGMENTS

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