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ENERGY-SAVING THERMAL STABILIZATION SYSTEM AND ASSESSMENT OF TEMPERATURE LOADINGS OF A BRIDGE DECK PAVEMENT

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Resume

To improve the general traffic safety in conditions of winter ice at traffic interchanges and to extend the overall service life of the roadway, it is proposed to use energy-saving thermal stabilization of a bridge deck pavement by transferring the low-temperature geothermal energy by heat pumps. The practical and computational parts of the pilot plant work are demonstrated and discussed. In order to analyze the need to use additional thermal joints, computer simulation was performed in the LIRA-CAD-2018 software package with subsequent extrapolation to a real bridge span.

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1 Introduction

Currently, there are several ways to solve the problem of comfortable travel through traffic interchanges in winter:

1. Traditional mechanical cleaning method combined with the use of chemical reagents [1]. However, in order to ensure the traction between the wheel and the road surface, snowplows must work constantly during the snowfalls, which creates additional difficulties for the movement of vehicles and, on the other hand, traffic makes it difficult for specialized equipment for cleaning the roadway. The use of chemical reagents negatively affects tires and metal parts of cars. At the same time, such cleaning often forms snow dumps on the side of the track, hindering the movement of vehicles [2].
2. Installation of liquid's sprayers of emulsified chemical reagents in the base of the bridge deck pavement. This is a technologically complex module-system, which is responsible for the treatment of the roadway with chemical reagents in automatic mode. At the same time, the scattering density is calculated based on empirical estimates that are not always optimal [3].

Despite the fact that the quality of the de-ice chemical products used is constantly being improved, the composition of the reagents is being updated, the direction of their action remains unchanged - a decrease of the melting point temperature of ice and snow [4].

Obviously, both approaches are not without drawbacks, the main of which are the following:

- limited duration of the chemical reagent exposure;
- the coefficient of the car tires' adhesion with a road surface drops by 30 percent in comparison with a wet surface [5];
- the chemical reagents used are biotoxicants and allergens [6-7];
- oily brine sprayed by moving vehicles, which is formed after melting the ice and snow, reduces visibility and contributes to an increase in road accidents [8].

To eliminate these drawbacks, the authors propose a fundamentally different approach to solving the problem for de-icing of traffic interchanges and roads at subzero temperatures - low-temperature geothermal thermal stabilization of bridge deck pavement with the heat pumps' use.

The process of thermal stabilization maintains the temperature of the roadway surface part in

a fairly narrow interval, optimal both for stabilizing the rheological characteristics of asphalt concrete and for safe ice-free exploitation. At the same time, the main bearing structure of the bridge crossing perceives the thermal loads that differ from the heated surface pavement coating. Therefore, it is necessary to additionally analyze the unevenness of the resulting thermal loads (and, accordingly, possible deformations) and assess the need for additional thermal joints.

This work is devoted to the study of the thermal stabilization technology applicability as part of the implementation of the Russian Federation federal program “Safe High-quality Roads”, “Best Available Technologies”, which accords with the concept of ESG-investing (Environmental, Social and Governance).

2 Experimental model and equipment

Based on the Federal State Autonomous Educational Institution of Higher Education “Russian University of Transport” (MIIT) research laboratory, the authors’ team of the department “Bridges and Tunnels” has developed an experimental model of a bridge deck pavement with a size of $\approx 1.15 \text{ m}^2$, built on a scale of 1:20 in relation to the size of the object being modeled (Figures 1, 2).

The model is a rectangular heat- and waterproofing concrete slab with plywood framework, with the plan dimensions of $1520 \times 755 \text{ mm}$ and a height of 220 mm .

The heat exchanger pipeline made from metal-polymer pipe $d 20 \times 2 \text{ mm}$ is laid in a serpentine course.

Temperature parameters were read from the surface of the experimental model with an infrared pyrometer.

The schematic diagram of the installation for the thermal stabilization is shown in Figure 3.

In the experiment the assembled unit was responsible for the thermal stabilization of the bridge deck pavement research model, in which the heating of the heat-transfer agent (water) in the closed circulation circuit of the model slab was performed according to the heat exchange scheme in a heat-insulated heat exchange reservoir. Heat was injected into this heat exchanger due to heat transfer performed by the compressor. The heat was taken away by the compressor from another heat exchanger simulating a geothermal source with a maintained temperature of $11 \pm 1^\circ \text{C}$. The thermostating (thermal recharge) of this heat exchanger was performed by a flow heater.

Preliminary evaluations of heat exchangers were performed according to the Equation [9]:

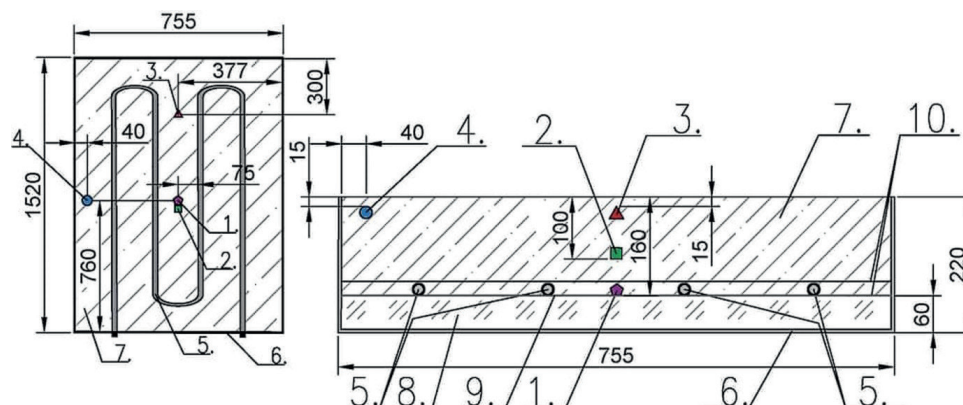
$$Nu_s = 1.4 \left(Re_p \frac{d}{l} \right)^{0.4} \cdot Pr_p^{0.33} \cdot (Pr_p / Pr_r)^{0.25}, \quad (1)$$

where: Nu_s - Nusselt number for the system;

Re_p - Reynolds number for the flow of water in the pipe;

Pr_p - Prandtl criterion for water in the pipe (6.52 at 22°C);

Pr_r - Prandtl criterion for water in a reservoir (3.93 at



1-4 - Remote thermal sensors; 5 - Metal-polymer pipe $d 20 \times 2 \text{ mm}$; 6 - Plywood framework; 7 - Sand-gravel concrete; 8 - Thermal insulation sheet; 9 - Polyethylene film 0.3 mm ; 10 - Structural steel netting $70 \times 70 \text{ mm}$

Figure 1 Scheme of the experimental model for the bridge deck pavement and the arrangement of remote temperature sensors

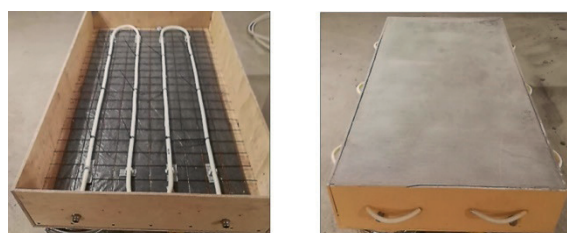
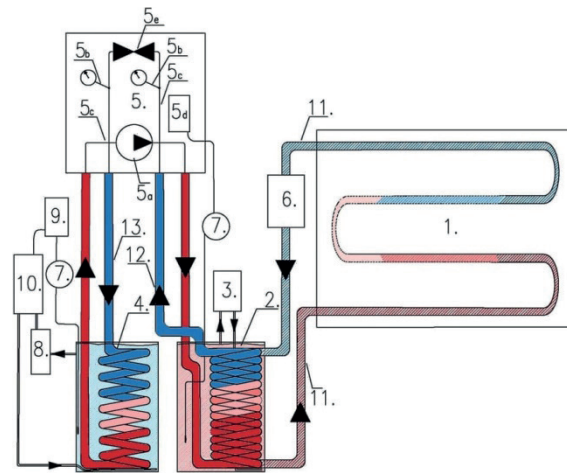


Figure 2 View of the bridge deck pavement experimental model before and after the sand-concrete filling



1 - Model slab; 2 - Heating circuit heat exchanger; 3, 8 - Mixers; 4 - Heat exchanger for heat recovery circuit;
5 - Compressor block; 6 - Circulation pump; 7 - Thermostat; 9 - Power contactor; 10 - Instantaneous water heater;
11 - Heating circuit of the model slab; 12 - Compressor heat supply circuit (condenser);
13 - Compressor heat removal circuit (evaporator)

Figure 3 Installation schematic diagram



Figure 4 View of the bridge deck pavement experimental model before and after the research experiment with imitation of icing

45 °C);

d - pipe diameter, m;

l - pipe length, m.

Amendment for the pipe curvature was made by introducing a correction factor as a multiplier, which is determined for the coil pipes by the ratio:

$$\epsilon_r = 1 + 1.77 \frac{d}{R}, \quad (2)$$

where: d - pipe diameter (1.5·10⁻² m);

R - coil radius (0.2 m).

Calculations have shown that a copper tubular heat exchanger with a diameter of 15 mm and a length of 15 m is sufficient to remove/return heat at the level of 7 kW.

The temperature of 45 °C in the heat exchanger of the model slab was kept constant using a thermostat. The temperature of 11±1 °C, kept constant in the compressor heat exchanger, simulates the real temperature of geothermal sources. Thus, the selected thermal mode of the installation corresponds to the standard thermal load, as close as possible to full-scale conditions.

The water volume in the circuit of the pattern slab was about 6 liters, in the heat exchangers tanks it was about 80 liters.

Such a scheme of the experimental unit was necessary for testing the model's construction parts and the thermophysical assessment of the entire scheme as a whole, including thermal loads and losses.

3 Experimental part

The pattern slab was moved outdoor (at a temperature of -17 °C) 20 hours before the start of the experiment, the surface was covered with water, thereby simulating the icing of the bridge deck pavement. The thickness of the ice cover ranged from 0.7 to 1.5 mm, the longitudinal slope of the surface was 30 ‰ (Figure 4).

The wind speed on the day of measurements was 3-5 m/s.

The temperature difference of the heat-transfer agent in the supply and return branches in the established stationary mode (after ~ 4 hours from the start of the experiment) was 0.3-0.4 °C. The graph of the change in the temperature difference of the heat-transfer agent over time (similar dependency with the heating power removed by the external circuit) is shown in Figure 5. The estimated power output varied in the

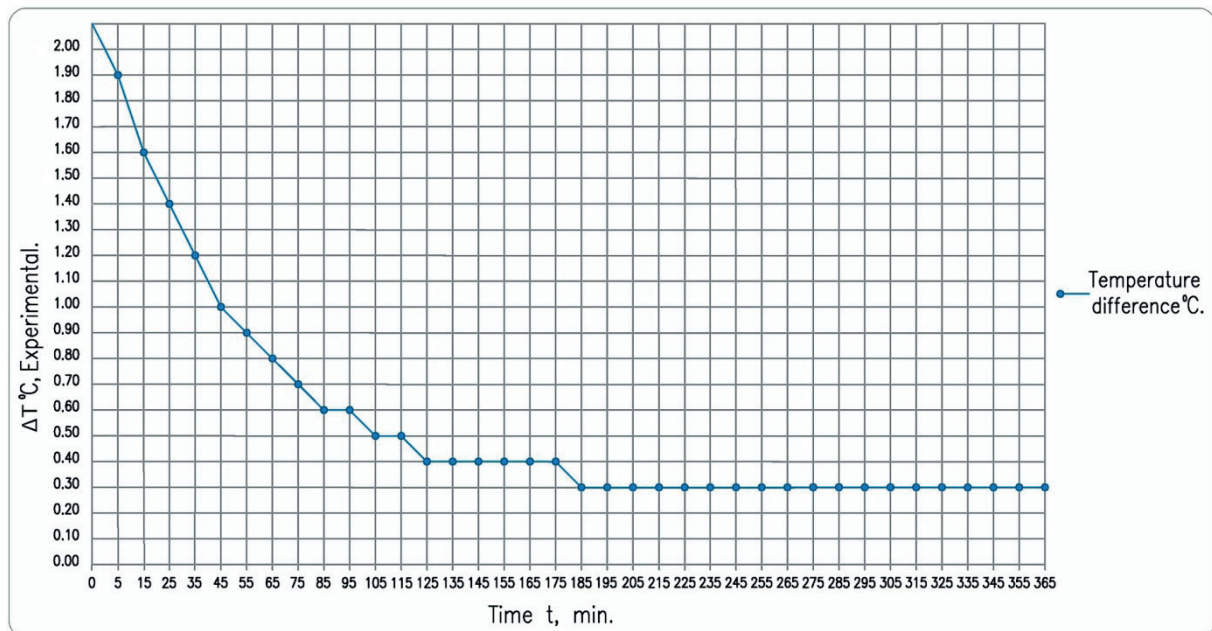


Figure 5 Graph of the change in the temperature difference of the heat-transfer agent (forward /reverse flow) in time

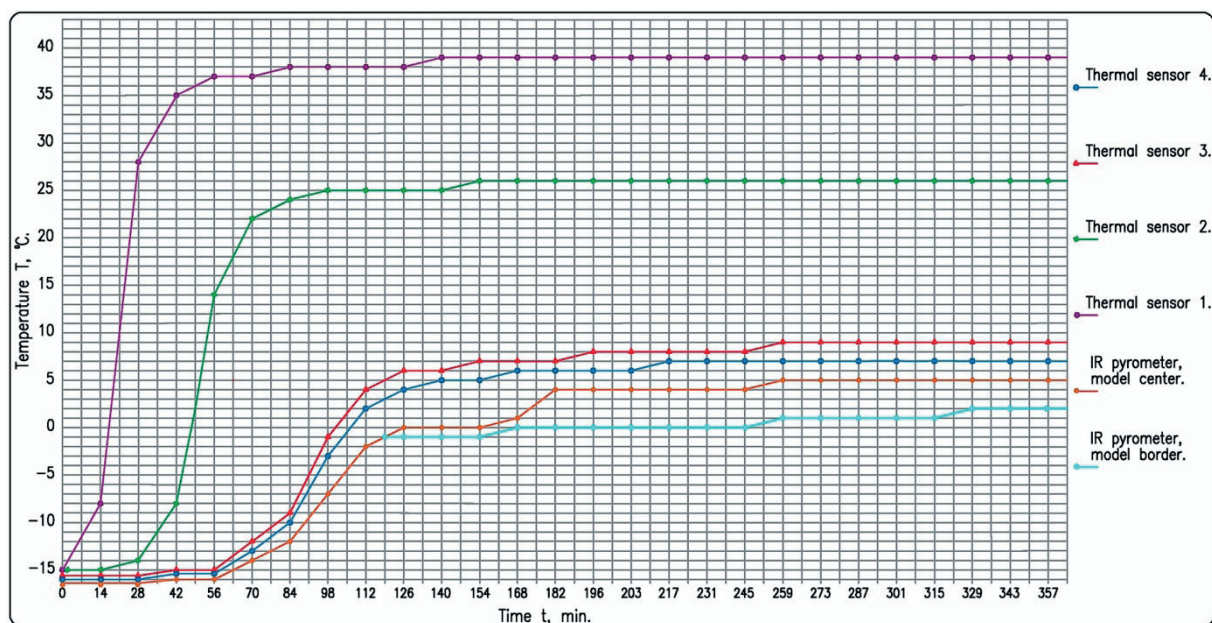


Figure 6 Graph of the temperature changes process on surfaces and in layers over time on the bridge deck pavement experimental model

approximate range from 4.2 to 0.5 kW.

The results of the experiment showed that the beginning of ice melting occurred after $t_{exp} \approx 2$ -2.5 hours and it took $t_{exp} \approx 4$ -4.5 hours to completely surface thawing of the bridge deck pavement experimental model (Figure 6).

As follows from the shown graphs of the change in the temperature difference (Figures 5, 6), the process of the heat wave dispersion in the solid is non-stationary and, in general, can be described by a rather complex system of differential equations with definite boundary conditions [10].

After 4-4.5 hours of the experiment to be started,

the heat transfer process assumes the character of a stationary one.

After 6 hours from the beginning of the research the experiment is terminated and accomplished.

4 Analytical solution

To describe the process of thermal stabilization of the bridge deck pavement experimental model in winter during the surface ice thawing, estimated calculations of the heat flows were performed to establish a correlation with the above mentioned experimental results.

Since the calculations are evaluative, the following assumptions were made:

1. In the period after the set of a stationary heat flow, the temperature dependence on the vertical coordinates is described by a linear dependence; the temperature gradient is constant;
2. Radiation thermal emission from the heated surface of the unit into the environment is not taken into account due to insignificance;
3. To account for the uneven heating along the horizontal coordinate, a concrete block can be represented as a superposition of 3 elements insulated along the perimeter and not interacting with each other through the side walls;
4. The heat transfer equations are considered in integral form;
5. Heating of the unit bottom part is uniform over the entire surface;
6. The values of thermodynamic coefficients are taken as averaged tabular [11].

Taking into account the accepted assumptions, the allocation scheme of the stationary heat flow for a parallelepiped with thermally insulated side walls (excluding phase transitions) consists of:

1. Heat transfer from the heater through the concrete solid to the surface;
2. Convective heat transfer from the block surface to the air.

Thus, the equation of the system stationary state for each highlighted element must satisfy the equality of two heat flows - heat-conducting through the volume of the concrete parallelepiped (Fourier equation) and then convective through the surface layer (Newton-Richman equation):

$$P = (\lambda \cdot S \cdot (T_2 - T_1)) / h = \alpha \cdot S \cdot (T_1 - T_a), \quad (3)$$

where:

P - total heat-loss power (heat flow), W;

S - the cross-sectional area of the parallelepiped (block), m^2 ;

T_2 - the temperature of the heated (bottom) block surface, K;

T_1 - the temperature of the cooled (top) block surface, K;

T_a - ambient air temperature, K;

h - block height, m;

λ - coefficient of thermal conductivity (specific conductivity), W/(m·K);

α - heat transfer coefficient, W/($m^2 \cdot K$).

From this equation it is possible to find the surface temperature of the block with an established heat transfer process:

$$T_1 = (\lambda \cdot T_2 + h \cdot \alpha \cdot T_a) / (h \cdot \alpha + \lambda). \quad (4)$$

The heat transfer coefficient α - is calculated in accordance with requirements of the Russian Federation building regulations code (SNiP 2.03.04.84 part 2)

according to the formula:

$$\alpha = 5.8 + 11.6\sqrt{v}, \quad (5)$$

where

v - wind speed in m/s.

According to equation (4), the calculated temperature of the top block surface should be set at +5.7 °C, which correlates with the experimental data of ≈5.0-5.5 °C in the central part and confirms the correctness of the estimating calculations.

The steady-state specific heat flow P (specific heat consumption) will be - about 0.5 kW/m² in accordance with equation (3).

The specific amount of heat given off by the heat-transfer agent over a period of time Δt will be:

$$Q = V_{sp} \cdot \rho \cdot C_{sp} \cdot \Delta T \cdot \Delta t \quad (6)$$

where:

Q - the total amount of heat given, J;

V_{sp} - specific volume (flow rate) of the passing heat-transfer agent, m³;

ρ - the heat-transfer agent density, kg/m³;

C_{sp} - specific heat capacity of the heat-transfer agent, kJ/(kg·deg);

ΔT - change in the temperature of the heat-transfer agent, K.

Thence it is possible to assess the evaluated flow rate of the heat-transfer agent for the steady-state stationary mode of the heat transfer, which should be 1.64 m³/hour. During the time from the 4th to the 6th hour, the leaked volume of the heat-transfer agent was 3.55 m³, which correlates with the calculated 3.28 m³.

The process of melting the surface snow/ice layer, which requires additional heat spending, is divided into 3 stages:

- ice heating from T_a to 0 °C;
- phase transition;
- water heating from 0 °C to T_1

The evaluated value of the correction for the specific heat losses related to the melting of the surface ice layer of a thickness of 1 mm is about 95 W·h.

If one takes the above calculated specific power for a steady heat exchange flow of 500 W/m² (i.e., power consumption of 0.5 kW·h /m²), then the energy consumption increases to about 0.6 kW·h /m² or by 20% in the case of melting of a thin (1 mm) ice crust.

Assuming the density of freshly fallen dry snow of 40-60 kg/m³ [12], one can say that power consumption increases by 20% for every 15mm of precipitation in winter at temperatures below -10 °C.

In the stationary mode, the energy consumption of the entire model object for the last 2 hours of the experiment should be ~ 1.15 kW·h (specific heat extraction power ~ 500 W/m², slab surface area ~ 1.15 m², measurement time - 2 hours). The experimentally recorded integral energy consumption of the compressor

(measured by a direct-on electric meter) was 0.33 kW·h. Thus, the increasing coefficient of the heat pump in the experiment was ~ 3.5.

5 Computer simulation model

With the introduction of thermal stabilization technology, the load-bearing spans and surface layers of the roadway are staying under conditions of significantly different temperature loadings. This imbalance can lead to material's degradation, materialized in the appearance of cracks in the pavement. In order to analyze the reasonable need to install additional elements in the roadway structure, computer modeling for the experimental model was performed in the LIRA-CAD-2018 software package [13], with subsequent extrapolation to the real span section.

An increase in temperature leads to the transition of atoms (molecules) to a higher energy level, which means an increase in the oscillating atoms' amplitudes of when heated. However, the oscillation anharmonicity caused by the asymmetry of the real potential energy curve of the atoms' interaction leads to an increase in the distance between atoms and, accordingly, to the thermal expansion of solids [14].

The fundamental law of thermal expansion states that a body with a linear dimension L in the corresponding measurement, when its temperature increases by ΔT and there are no external mechanical forces, expands by an amount ΔL equal to:

$$\Delta L = \alpha \cdot L \cdot \Delta T, \quad (7)$$

where:

α - coefficient of linear thermal expansion.

Asphalt concrete pavements arranged on a rigid (cement concrete) base have a coefficient of linear thermal expansion several times different from the concrete of the base bearing layer, therefore, reflected cracks appear atop the joints and cracks of the rigid base, which are intensively developing, lead to untimely destruction of the pavement.

The most radical way to rapidly retard of the asphalt concrete pavements cracking processes is to reinforce them with flexible rolled geogrids in combination with solid nonwoven geotextiles [15].

In the software package, the model of the road pavement piece with the base heating possibility is adopted in the dimensions of 1520 × 755 mm. The grid of the model nodes is adopted 75×75 mm. The layers of the road pavement fragment are modeled by linking a set of isosceles rectangular triangles with 75 mm legs made using the finite element No. 42 (triangular plate) into three composite slabs of 1520 × 755 mm. The nodes of composite slabs modeling the road pavement layers are connected by rod elements made of rod finite element No. 10, which is assigned infinitely large stiffness to imitate the joint effort of composite slabs. Figure 7 shows a general view of the calculation scheme in plane and in axonometry.

The model of the road pavement fragment is fixed by each bottom layer node from movement along the Z axis. For the possibility of modeling the slab deformations from temperature influences, the border line of the bottom slab nodes located along the slab long side is fixed to avoid displacing along the Y axis and the border line of nodes located along the short side of the slab is fixed to avoid displacing along the X axis. The fastenings combination allows the slab model to deform easily from temperature influences in the XOY plane. The scheme for fixing the nodes of the bottom slab is shown in Figure 8.

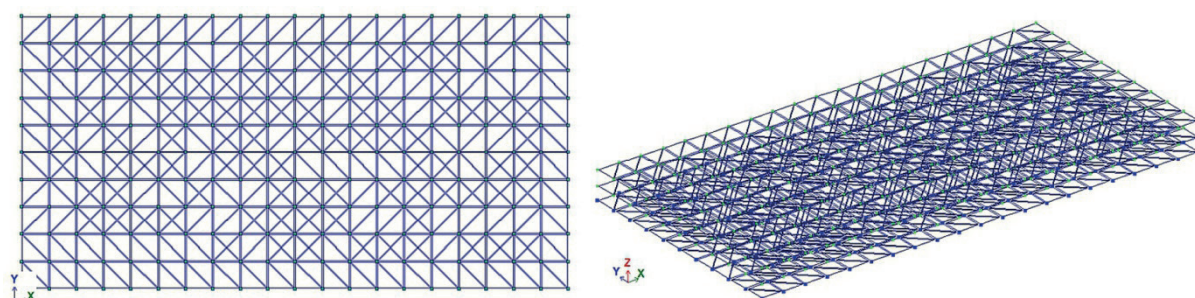


Figure 7 General view of the design scheme in plan and axonometry (LIRA-CAD-2018)

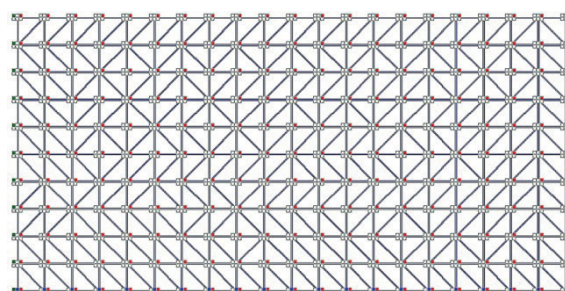


Figure 8 The scheme for fixing the nodes of the model bottom slab (LIRA-CAD-2018)

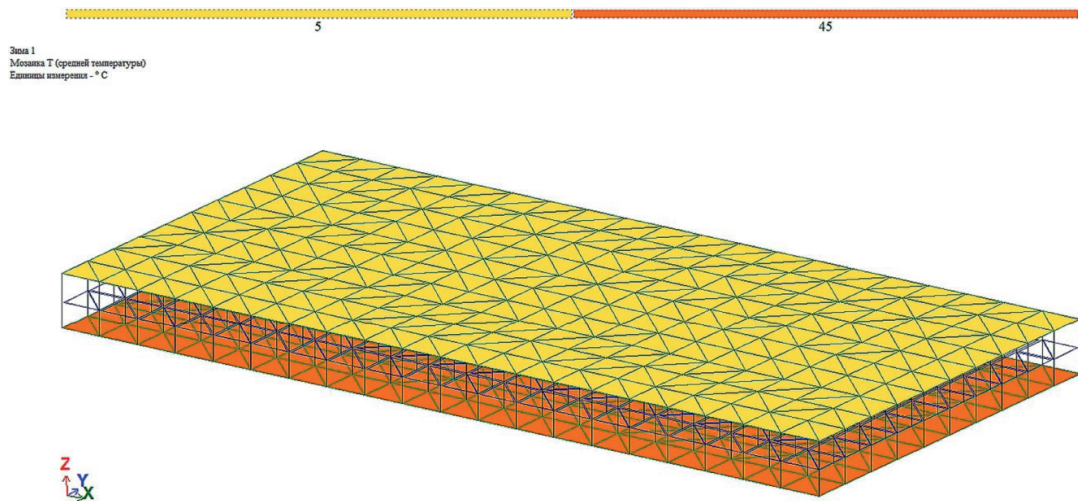


Figure 9 Mosaic of temperature loadings according to the “Winter-1” scheme (LIRA-CAD-2018)

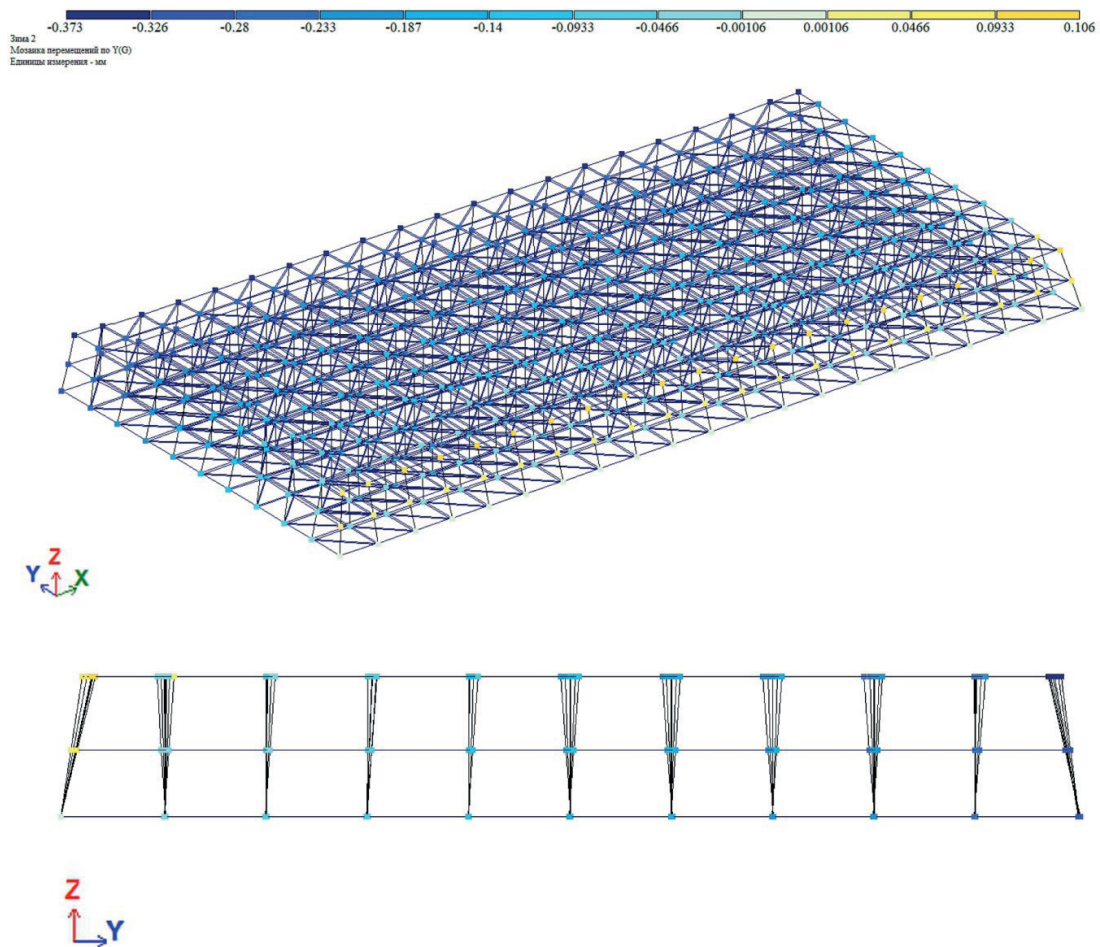


Figure 10 Calculation mosaics of model nodes displacements along the Y axis for temperature loadings of the “Winter-2” scheme (LIRA-CAD-2018)

Table 1 Displacement mosaic for model slab

Scheme	X-axis maximum	Y-axis maximum	X-axis summ	Y-axis summ
Winter-1	0.817	0.414		
Winter-2	-0.680	-0.373		
Winter mode			1.497	0.787

The design scheme contains two different temperature loadings:

- “Winter-1” - the transition from 45 °C in the bottom part of the slab to 5 °C in the top part at ambient temperature from -16 °C to -12 °C (heating mode).
- “Winter-2” - a slab in a stationary uniformly cooled state at the beginning of the experiment (the temperature of the bottom part is -16 °C, the top part is -16 °C).

Reference temperatures are taken from experimental data:

- 45 °C - corresponds to the heat-transfer agent temperature;
- 5 °C - plate surface temperature after completion of the ice melting process;
- -16 °C - temperature of the ambient air and the model at the beginning of the experiment.

In the LIRA-CAD-2018 software package the following conditions are accepted as normal: $T = 273.15$ K (0 °C), $P = 101\,325$ Pa (1 atm, 760 mm Hg)

The mosaic of temperature loading according to the “Winter-1” scheme is shown in Figure 9.

Each loading provides for both temperature effects on the bottom and top layers of the model and the effect on the plates of the slab's body.

As a result of computer simulation, calculated mosaics of the model nodes' displacements along the X and Y axes were obtained for all the variants of temperature loadings.

Figure 10 shows as an example a mosaic of the nodes' geometry deformation of the slab for the loading “Winter-2”.

The results of the displacement mosaics for a model slab with a length of 1520 mm are shown in Table 1 (according to the maximum values for each scheme and for the total values by period, mm).

Taking the standard span length of 64 m, one obtains

the possible range for additional thermal extensions of the bridge deck pavement for this gauge - up to +63 mm.

The obtained results confirm the need to install additional modular multiprofile deformation thermal joints during the thermostabilized blocks' assembly on the bridge deck pavement.

6 Conclusions

The results obtained in the experiment on the thermal stabilization of a bridge deck pavement prototype, in combination with the analysis of the efficiency of underground heat collectors [16], allow to capture the ability of the proposed method practical application.

As follows from the results of the experiment, with an average winter temperature range in the Central Russia, the power consumption to maintain the roadway in a safe condition is about 0.5 kW·h/m².

Further development of the thermal stabilization technology with application of the modern geothermal heat pumps with an efficiency coefficient of up to 4.5-5.5, in the future would reduce energy consumption by 4-5 times and reach 100-150 W/m² per hour.

The obtained experimental results are satisfactorily correlated to the calculated ones, which makes it possible to perform preliminary estimates in laboratory conditions.

The modelling of seasonal temperature loadings for the roadway on the bridge spans confirms the need to install additional compensatory thermal joints when using the thermal stabilization technique.

Overall, the obtained results indicate the economic efficiency and expediency of introduction and practical application of the thermal stabilization technology for the bridge structures' safe operation.

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