FEM MODELLING OF THE TEMPERATURE INFLUENCE ON THE STRESS-STRAIN STATE OF THE PAVEMENT

Alexandr Shimanovsky[1], Abdujabbor Karabayev[2], Iryna Krakava[1], Volha Tsyhanok[1], Ibragim Sodikov[2], Abduvokhid Yunusov[3,*]

[1]Department of Technical Physics and Engineering Mechanics, Belarusian State University of Transport, Gomel, Belarus
[2]Department of Urban Roads and Streets, Faculty of Highway Engineering, Tashkent State Transport University, Tashkent, Uzbekistan
[3]Department of the Traffic Engineering and Management, School of Engineering, Kimyo International University in Tashkent, Tashkent, Uzbekistan

*E-mail of corresponding author: abduvokhid.yunusov@gmail.com

Alexandr Shimanovsky 0000-0001-8550-1725,
Abdujabbor Karabayev 0000-0002-9880-8547,
Iryna Krakava 0000-0002-8750-1806,
Volha Tsyhanok 0000-0001-8032-2285,
Ibragim Sodikov 0000-0002-2595-288X,
Abduvokhid Yunusov 0000-0002-5569-4172

Resume

The highways that are used in the countries with a sharp continental and a hot climate operate in the conditions when the pavement temperature changes along its height. This fact can lead to a significant increase in stresses in the layers of the road structure. In this paper is suggested an approach to solution of the joint problem of the pavement deformation and the heat propagation in it by a finite element modelling technique. The ANSYS software package was applied to solve the described problem. It is shown that an increase in the road surface temperature leads to a significant increase in the von Mises-equivalent stresses in the asphalt concrete upper layer and that is the cause for the ruts formation. Computational results also showed that at low temperatures of the road surface, the significant tensile stresses arise in its upper layers and that leads to formation of cracks.

Article info

Received 18 July 2022
Accepted 15 November 2022
Online 12 December 2022

Keywords:

road pavement
asphalt concrete
temperature
stress-strain state
finite element modeling

Available online: https://doi.org/10.26552/com.C.2023.011

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Introduction

When vehicles pass through the highways, the roads are under the action of cyclic loads. Large flows of vehicles of various masses lead to accumulation of the residual deformations in various elements of the pavement; this subsequently causes damages of its surface. Climatic conditions have a significant impact on the strength of roads, as well. Seasonal fluctuations in air temperature throughout the year, as well as its jumps due to sharp changes in weather conditions for several days, lead to a change in the stress-strain state of the pavement layers [1-2]. The climate of Uzbekistan is sharp continental and it is characterized by a dry hot climate. The summer in Uzbekistan is dry and hot, the average temperature in July in the flat part of the country is +26 °C to +30 °C and in the south of the country it reaches +31 °C to +32 °C. The absolute maximum of the air temperature in Tashkent is +44 °C, in Termez - +50 °C. The surface of the asphalt concrete pavement is heated up to +75 °C to +80 °C. In this regard, it becomes necessary to assess the effect of uneven temperature distribution in the road structure on stresses in it and its deformations. The similar analysis is also in demand in other countries, including the European ones, due to the climate changes [3-5].

Nowadays, the significant number of experimental studies, related to the analysis of the temperature distribution along the pavement height, have been carried out. The authors of the paper [6] present the results of measuring the temperature and moisture of the pavement upper layer on the island of Bali (Indonesia). It is shown that during the day the change in the temperature of the surface layer can reach

35 °C. In the article [7] there are presented the results of experiments performed in order to determine the temperature, moisture, stresses and strains in the pavement of an experimental road section in Lithuania. The above information shows that during the calendar year the range of temperature changes in the road surface layer is more than 65 °C. At the same time, the temperature difference at the surface and at the base of the pavement at a particular point in time can reach 20 °C or more. The measurement results also showed that the stresses in the upper layer of the road surface during the passage of cars do not, as a rule, exceed 250 kPa. In the paper [8] there are presented the experimental results of the determining the temperature in the layers of the pavement in Slovakia. In [9], a two-layer pavement was modeled to determine the effect of ambient temperature in summer on an asphalt concrete pavement, taking into account the traffic load.

In the paper [10] there are investigated the factors that determine the temperature value on the pavement surface. The dependences demonstrating the effect of thermal conductivity on the pavement temperature are given. A technique that allows to calculate the pavement temperature depending on the meteorological conditions typical for Sweden at different times of the year is described in [11]. The authors of papers [12-13] propose a method for determining the temperatures in pavement elements based on parameters that determine the meteorological situation in the place under consideration.

The authors of [14] provide an overview of studies on determining temperatures in the pavement and present various empirical models and analytical dependencies that make it possible to establish the distribution picture for the physical, mechanical and geometric temperatures for different road parameters and environmental conditions.

In [15], a simplified model is proposed to describe the thermo-viscoelastic deformation of the road surface under the action of a moving load from tires. Comparison of the calculation results to the experiment demonstrated a satisfactory accuracy of the obtained results. It is noted that for a more precise determination of the maximum deformations, a detailed investigation of the base deformation features is required.

In the work [16] there are analyzed the distribution patterns of temperature, moisture, stresses and strains in the pavement and subgrade of a highway located in the northern part of Kazakhstan during one year, in particular, during the cold period. The distribution of temperature and the moisture was studied experimentally using special sensors. It is shown that in the winter the elasticity modulus of the asphalt concrete layers and the upper part of the subgrade increases significantly: up to 18,000 MPa and 10,000 MPa, respectively. Stress and strain calculations were performed using a mathematical model of an elastic multilayer half-space. It has been established that all the stress and strain components at the points of the pavement and subgrade change significantly during the annual cycle. Similar results were obtained by Lithuanian scientists [17].

In recent research, there are many investigations performed by scientists from different countries where the stress-strain state of the road surface and the formation of various defects in road structures are studied. In [18], it was considered a multilayer system as one- or two-layer and the author established the depth where the stresses from the load action are almost unchanged. The authors of the article [19] used the Drucker-Prager model of the material elastic-plastic deformation to establish the effective equivalent stresses and strains in the coating at maximum operational loads. The problem was solved using the finite element model in the ANSYS software package. The results of the developed and optimized compositions of a complex organic binder based on Dzharkurgan oil, viscous bitumen and gossypol resin with structure-forming additives are given in [20-21]. These compositions ensured the latter's strength in the range of 1.1-1.5 MPa.

The authors of paper [22] demonstrate the results of determining the allowable temperature gradients for a cement concrete pavement that do not allow formation of microcracks on their surface. The finite-difference method implemented in the PARUS software was used to study the stress state. The analysis used a strength criterion based on the process of formation and development of microcracks in concrete. Similar studies were carried out in [23]. In investigations [24-25] there were considered the peculiarities of the non-elastic deformation of the materials of the asphalt-concrete surfaces, as well as the approaches that are supposed to take into consideration the found effects at the process of computer simulation. However, those calculations did not consider the effect of the load from a passing car.

The stress-strain state analysis of the pavement system under moving aircraft loads is performed in investigation [26]. It is demonstrated that the Mises model allows to obtain the stress results that are the closest to the experimental data. The finite element method is applied for determining the stresses in asphalt pavements due to action of the moving load in papers [27-28]. It is shown that this method allows to get the results that are close to the experimental ones.

In papers [29-30] there are demonstrated the results of the finite element modeling of the stress-strain state of the cement concrete pavement under the action of passing vehicles for various temperatures of the pavement.

Thus, the performed analysis allows to obtain a large amount of information on the experimental determination of temperatures, stresses and deformations in the road surfaces. In addition, the methods for calculating temperatures in the road material were developed in sufficient details. However, no investigations were found with calculations of the

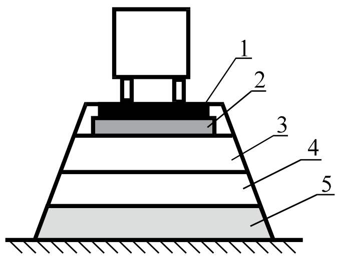


Figure 1 *Estimated model of the road surface: 1 - dense asphalt concrete, 2 - porous asphalt concrete, 3 - highly porous asphalt concrete, 4 - gravel mixture, 5 - dusty sandy loam*

Table 1 *Physical and mechanical properties of pavement layer materials*

Layer Number	Thickness layer (mm)	Density (kg/m^3)	Young modulus (MPa)	Poisson's ratio	Coefficient thermal expansion (1/K)	Specific heat (kJ/kg·K)	Thermal conductivity (W/m·K)
1	60	2300	3200	0.30	10^{-5}	1.65	1.40
2	90	2300	2000	0.25	10^{-5}	1.65	1.25
3	120	2000	2000	0.25	10^{-5}	1.65	1.00
4	400	1700	205	0.15	10^{-5}	1.00	0.64
5	-	1600	46	0.35	1.18×10^{-5}	1.10	0.62

pavement stress-strain state under the loads from moving vehicles, taking into account the peculiarities of the temperature distribution along the pavement height.

The purpose of the presented paper is to determine the influence of temperature distribution in the pavement on its stress-strain state. In this case, the algorithms developed earlier [31-32] are used to solve other technical problems.

2 Finite element model

As an example of the model the section of the first category road (according to the scale used in Uzbekistan) is considered, the corresponding scheme is shown in Figure 1. The used type of pavement includes four layers, which are made from various materials. The physical, mechanical and geometric characteristics of the layers used for the calculations are shown in the Table 1. The physical and mechanical parameters are taken from [33]. The thickness of the base (of the layer 5) was assumed to be 830 mm. The investigation demonstrated that in this case, it is possible to determine the stresses and deformations in the road surface with a sufficient degree of accuracy, therefore, no increase in its thickness was required.

The standard method for calculating the road surface assumes application of uniformly distributed pressure from the tires to the road section. When the vehicles move along the road, it is affected by several tires at the same time. Taking into account the periodicity of load application along the length and width of the pavement, a structural element containing a section that includes ¼ of the load application area is selected. Thus, a parallelepiped is taken as the calculation area, which includes several layers of the road surface with different physical and mechanical characteristics. The resulting geometric model is shown in Figure 2.

The finite element model of the selected pavement structural element was created using the ANSYS Mechanical software. To conduct a complex static and temperature analysis, the pavement layers were modeled by a 20-node Brick-element Coupled Field 226, which allows to consider the features of multiphysics analysis. The finite element mesh was created in a semi-automatic mode, the number of finite elements of the model was about 7000.

A uniformly distributed pressure of 600 kPa was applied to the model surface circle quarter of the 140 mm radius, this load simulated the force acting on the road from the tires. A symmetry condition is imposed to all the side surfaces of the parallelepiped as bonds; vertical movement is prohibited for the lower surface of the lower layer. In addition, for the pavement upper layer the different temperatures T_t were set from the range from - 20 to + 50 °C relative to the constant temperature of the lower surface of layer 5, which was assumed to be 0 °C. The selected range of temperature changes corresponds to the conditions of Uzbekistan, which is located in the sharply continental climate zone. In this paper, the change in Young's modulus depending on the increasing temperature is neglected. Therefore, for example, at the base temperature T_0 = 20 °C the real surface temperature of 70 °C corresponds to the T_t = 50 °C.

During the calculation, the solution of the coupled

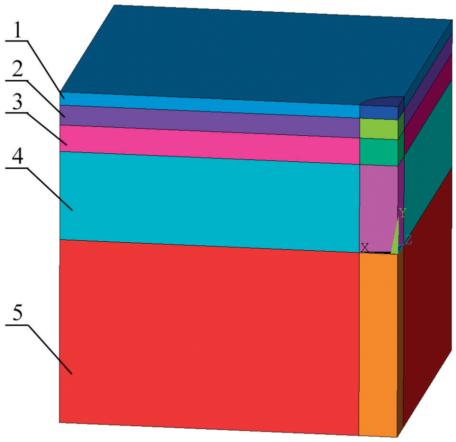


Figure 2 *Structural element of the pavement. The layers of the material correspond to the pavement layers shown in Figure 1*

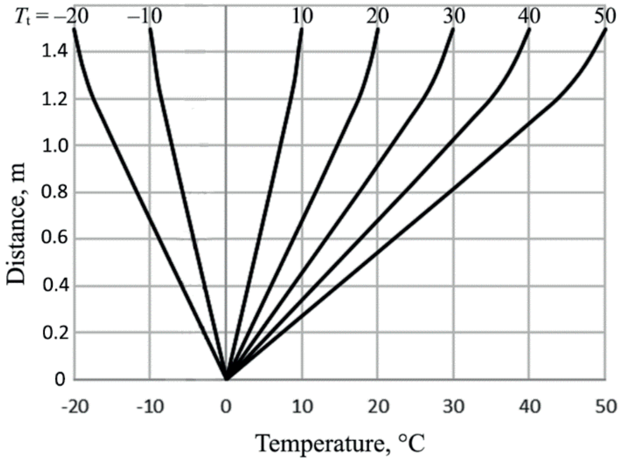


Figure 3 *The obtained temperature changes in the pavement layers at different surface temperatures T_t.*

thermoelastic constitutive equations [34] was performed:

$$\{\varepsilon\} = [D]^{-1}\{\sigma\} + \{\alpha\}\Delta T\,, \tag{1}$$

$$S = [\alpha]^T\{\sigma\} + \frac{\rho C_p}{T_0}\Delta T\,, \tag{2}$$

where: $\{\varepsilon\}$ - total strain vector; $[D]$ - elastic stiffness matrix; $\{\sigma\}$ - stress vector; $\{\alpha\}$ – vector of the thermal expansion coefficients; ΔT - temperature change relative to the reference temperature (it was assumed 0 °C); S - entropy density; ρ - density of a material; C_p - specific heat at constant stress; T_0 - absolute reference temperature (K).

3 Calculation results and their analysis

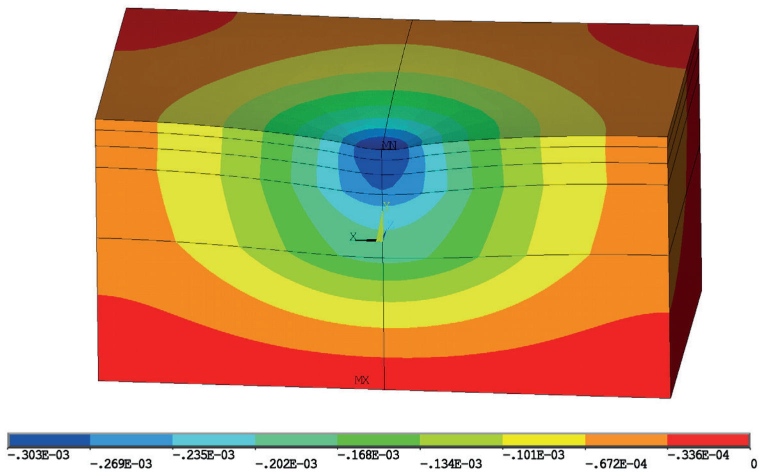
During the calculations, the distributions of temperature, stresses and strains in the pavement layers were obtained.

Figure 3 shows graphs demonstrating the calculated temperature changes along the road height at different temperatures of its surface. Their comparison to the experimental dependences presented in [16] shows a fairly good agreement.

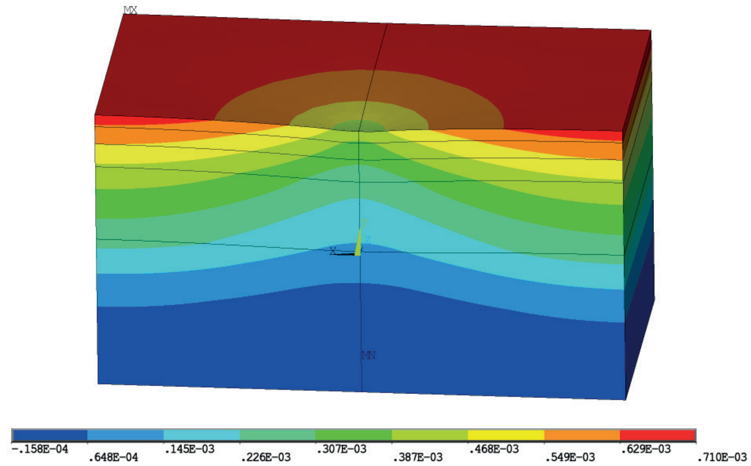
Figure 4 shows the distribution of deformations along the cross section of the road near the place of the load application. Under the applied load action, at the same temperature at all the points of the road surface, all the road surface layers are displaced downwards, as shown in Figure 4, a. When the pavement is heated, its thickness increases due to the thermal expansion. The application of the load from the tire weight leads to a decrease in deformations caused by heating and the total movement of the four upper layers of the pavement at high heating temperatures remains positive, i.e. they do not return to their original position.

There should also be noted that the difference between the largest and the smallest displacements of the model points in the case of pavement heating increases and for the temperature T_t = 50 °C the ratio is 2.4 times in comparison to the case of the not heated pavement, that fact indirectly indicates an increase in the uneven distribution of stresses over the volume.

Comparison of the von Mises equivalent stress patterns (Figure 5) confirms the conclusion presented



a)



b)

Figure 4 *Pavement deflections at temperatures: a - T_t = 0 °C, b - T_t = 50 °C*

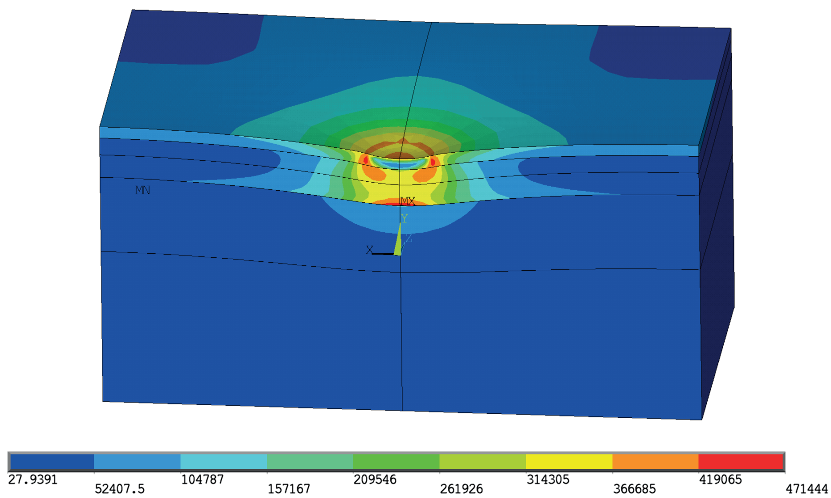
earlier in the strain analysis. At the same temperature of the road layers, the stresses in the three upper layers are distributed fairly evenly, so, it can be assumed that they work like a three-layer plate on an elastic base (Figure 5, a). In the case of the road upper layer heating the greatest stresses are concentrated in the upper layer of the road (Figure 5, b). The maximum stress values increase by a factor of 5.7 compared to the case without heating (up to 2.7 MPa). This causes formation of the ruts in the places where the tires pass. It should be noted that the presented calculation did not take into account the decrease in the asphalt concrete stiffness with an increase in temperature, which is observed in practice. Consequently, the track appears on the road not only due to a change in the mechanical characteristics of the road surface upper layer, but due to the redistribution of stresses due to the temperature deformations, as well.

Figures 6 and 7 show how the displacements and stresses in the layers of the road surface change when the heating temperature of its surface changes and the pressure force of the car tire is taken into account. The presented figures show that the greatest deformations are observed in the first and the second layers at a temperature of about 30 °C. At the same time, at temperatures above 20 °C, the base is practically not deformed. However, the greatest modulus values of deformations are observed when the air temperature decreases.

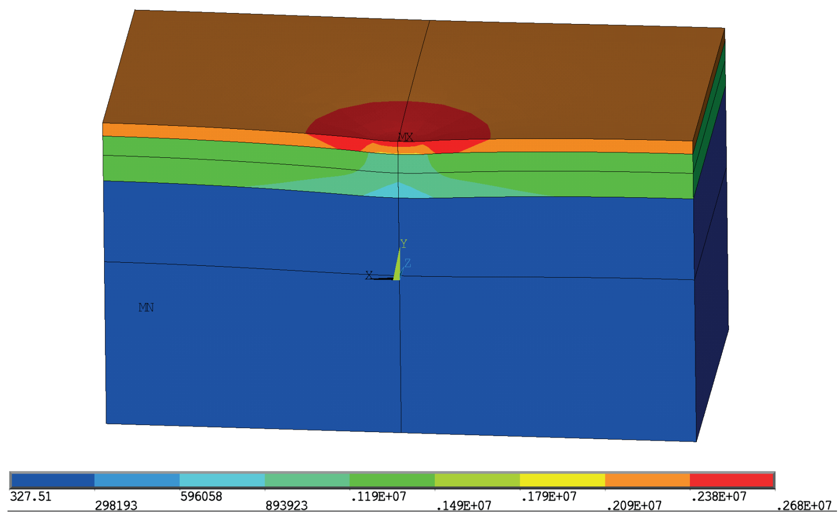
Graphs of the von Mises equivalent stresses changes demonstrate a significant increase in their values in the layer 1 material both with an increase and a decrease in the temperature. In the first case, this can lead to the formation of a rut and in the second case - to the road surface cracking.

4 Discussion and conclusions

The paper considers a technique for the finite element modeling of thermal elastic deformation of a road surface using an element that implements the possibility of the Coupled Fields analysis. Taking into account the actual distribution of temperatures in the pavement made it possible to establish that the presence of a temperature gradient leads to a significant increase



a)



b)

Figure 5 *Distribution of the von Mises equivalent stresses in the pavement layers at temperatures: a - T_t = 0 °C, b - T_t = 50 °C*

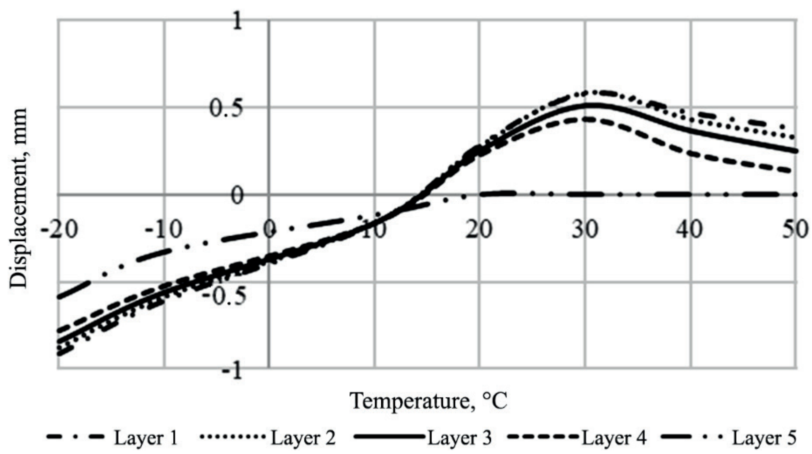


Figure 6 *Change in the maximum displacements in the layers of the road under the center of the contact area between the wheel and the road surface depending on the temperature of the upper layer T_t.*

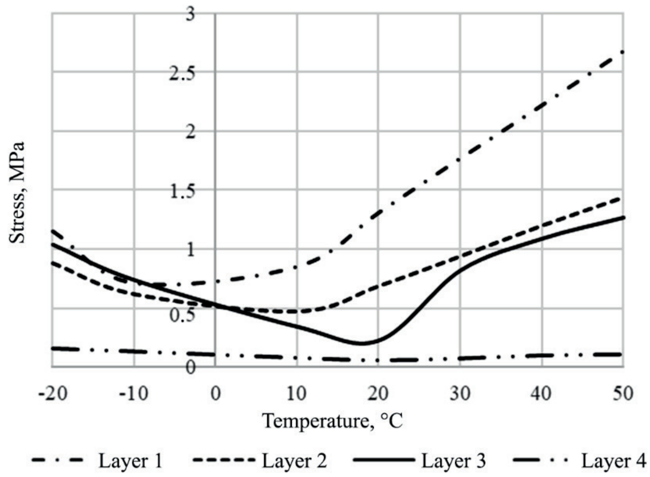


***Figure 7** Changes in the maximum von Mises equivalent stresses in the wheel-road contact zone depending on the temperature of the pavement top layer*

in the asphalt concrete pavement upper layer stresses. When the pavement surface is heated to 50 °C the maximal stresses in the upper layer of the road surface increase by 4 times compared to the case when the temperature of all the layers is the same. This fact is one of the reasons for formation of the ruts on the road at high air temperatures. At a low pavement surface temperature the most unfavorable situation is observed in the third layer of the pavement where the stresses are doubled. This leads to the pavement cracking at low temperatures.

The results presented in the paper were obtained for the model that does not consider the dependence of the materials mechanical characteristics on temperature. A decrease in the elastic modulus due to the temperature increase would lead to some decrease in the road surface upper layer stresses. To perform an appropriate quantitative analysis, the use of nonlinear equations for the deformation of materials is required and this kind of investigation is planned to be performed in the further work.

The proposed method for the pavements' calculation can be applied to the optimization of the geometric and physical parameters of pavements.

Grants and funding

The authors received no financial support for the research, authorship, and/or publication of this article.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] BOCHKARYOV, D. I., PETRUSEVICH, V. V. Evaluation of the effect of operational characteristics of asphalt concrete pavement on road safety. *Emergency Situations: Education and Science*. 2015, **10**(1), p. 40-44. ISSN 2072-2699.

[2] EFREMOV, S. V. The effect of temperature on durability in aggressive environments of asphalt concrete with granite and limestone crushed stone. *Bulletin of Kharkiv National Automobile and Highway University*. 2017, **79**, p. 123-128. eISSN 2219-5548.

[3] DECKY, M., REMISOVA, E., KOVALCIK, E., DIBDIAKOVA, J., HAJEK, M. Climatic characteristics of Slovakia in the years 1971 to 2011 from the aspect of pavement design. *IOP Conference Series: Earth and Environmental Science* [online]. 2017, **95**(2), 022056. ISSN 1755-1307, eISSN 1755-1315. Available from: https://doi.org/10.1088/1755-1315/95/2/022056

[4] ZUZULOVA, A., HODAKOVA, D., CAPAYOVA, S., SCHLOSSER, T., GROSEK, J. Climatic influences considered in pavement design methodology. In: Proceedings of 20th International Multidisciplinary Scientific GeoConference SGEM 2020: proceedings [online]. 2020. ISSN 1314-2704, ISBN 978-619-7603-09-5, p. 349-356. Available from: https://doi.org/10.5593/sgem2020/4.1/s19.044

[5] LEE, J. S., KIM, J. H., KWON, O. S., LEE, B. D. Asphalt binder performance grading of North Korea for superpave asphalt mix-design. *International Journal of Pavement Research and Technology* [online]. 2018, **11**(6), p. 647-654. ISSN 1996-6814. Available from: https://doi.org/10.1016/j.ijprt.2018.06.004

[6] ARIAWAN, I. M. A., SUBAGIO, B. S., SETIADJI, B. H. Development of asphalt pavement temperature model for tropical climate conditions in West Bali region. *Procedia Engineering* [online]. 2015, **125**, p. 474-480. ISSN 1877-7058. Available from: https://doi.org/10.1016/j.proeng.2015.11.126

[7] CYGAS, D., LAURINAVICIUS, A., PALIUKAITE, M., MOTIEJUNAS, A., ZILIUTE, L., VAITKUS, A. Monitoring the mechanical and structural behavior of the pavement structure using electronic sensors. *Computer Aided Civil and Infrastructure Engineering* [online]. 2015, **30**(4), p. 317-328. eISSN 1467-8667. Available from: https://doi.org/10.1111/mice.12104

[8] TROJANOVA, M., DECKY, M., REMISOVA, E. The implication of climatic changes to asphalt pavement design. *Procedia Engineering* [online]. 2015, **111**, p. 770-776. ISSN 1877-7058. Available from: https://doi.org/10.1016/j.proeng.2015.07.144

[9] LI, Y., LIU, L., SUN, L. Temperature predictions for asphalt pavement with thick asphalt layer. *Construction and Building Materials* [online]. 2018, **160**, p. 802-809. ISSN 0950-0618. Available from: https://doi.org/10.1016/j.conbuildmat.2017.12.145

[10] CHEN, J., WANG, H., XIE, P. Pavement temperature prediction. Theoretical models and critical affecting factors. *Applied Thermal Engineering* [online]. 2019, **158**, 113755. ISSN 1359-4311. Available from: https://doi.org/10.1016/j.applthermaleng.2019.113755

[11] HERMANSSON, A. Mathematical model for paved surface summer and winter temperature: comparison of calculated and measured temperatures. *Cold Regions Science and Technology* [online]. 2004, **40**(1-2), p. 1-17. ISSN 0165-232X. Available from: https://doi.org/10.1016/j.coldregions.2004.03.001

[12] ALAVI, M. Z., POURANIAN, M. R., HAJJ, E. Y. Prediction of asphalt pavement temperature profile with finite control volume method. *Transportation Research Record: Journal of the Transportation Research Board* [online]. 2014, **2456**, p. 96-106. ISSN 0361-1981, eISSN 2169-4052. Available from: https://doi.org/10.3141/2456-10

[13] MINHOTO, M. J., PAIS, J. C., PEREIRA, P. A., PICADO-SANTOS, L. G. Predicting asphalt pavement temperature with a three-dimensional finite element method. *Transportation Research Record: Journal of the Transportation Research Board* [online], 2005, **1919**(1), p. 96-110. ISSN 0361-1981, eISSN 2169-4052. Available from: https://doi.org/10.1177/0361198105191900111

[14] ADWAN, I., MILAD, A., MEMON, Z. A., WIDYATMOKO, I., AHMAT ZANURI, N., MEMON, N. A., YUSOFF, N. I. M. Asphalt pavement temperature prediction models. A review. *Applied Sciences* [online], 2021, **11**(9), 3794. eISSN 2076-3417. Available from: https://doi.org/10.3390/app11093794

[15] HOMSI, F., BODIN, D., CHABOT, A., HORNYCH, P. Effect of temperature on asphalt pavement strain responses: APT data and thermo-viscoelastic pavement modelling. In: 17th AAPA International Flexible Pavements Conference: proceedings. 2017. p. 1-12.

[16] TELTAYEV, B. B., LIU, J., SUPPES, E. A. Distribution of temperature, moisture, stress and strain in the highway. *Magazine of Civil Engineering* [online] 2018, **83**(7), p. 102-113. ISSN 2712-8172. Available from: https://doi.org/10.18720/MCE.83.10

[17] VAITKUS, A., ZALIMIENE, L., ZIDANAVICIUTE, J., ZILIONIENE, D. Influence of temperature and moisture content on pavement bearing capacity with improved subgrade. *Materials* [online]. 2019, **12**(23), 3826. ISSN 1996-1944. Available from: https://doi.org/10.3390/ma12233826

[18] AFINOGENOV, A. O. Analysis of the stress-strain state for the subgrade soil mass of high-ways. *Bulletin of the Kuzbass State Technical University*. 2008, **3**, p. 109-111. ISSN 1999-4125

[19] YASTREMSKIY, D. A., CHEPUR, P. V., ABAYDULLINA, T. N. Numerical simulation of stress-strain state of road covering of the SMA with the use of stabilizing additives «Armide». *Fundamental Research*. 2016, **7**(2), p. 277-281. ISSN 1812-7339.

[20] KARABAEV, A. M. Asphalt concrete based on a complex organic binder. Monograph. Tashkent: YaTT Rizaev M.X., 2018.

[21] SADIKOV, I. S., KARABAEV, A. M., KAMILOV, A., MAKHKAMOV, B. R. Analysis of ways to improve the properties of cold asphalt concrete. In: Proceeding of the III Republican Scientific and Technical Conference "Problems of Introducing Innovative Projects into Production": proceedings. 2011. p. 265-267.

[22] PSHEMBAEV M. K., KOVALEV, Y. N., SHEVCHUK, L. I. Analysis of stress state in upper layer of road concrete pavement with temperature action. *Science and Technique* [online]. 2017, **16**(4), p. 282-288. ISSN 2227-1031. eISSN 2414-0392. Available from: https://doi.org/10.21122/2227-1031-2017-16-4-282-288

[23] TELTAYEV, B., AITBAYEV, K. Modeling of temperature field in flexible pavement. *Indian Geotechnical Journal* [online]. 2015, **45**(4), p. 371-377. ISSN 0971-9555, eISSN 2277-3347. Available from: https://doi.org/10.1007/s40098-014-0122-6

[24] CHOMICZ-KOWALSKA, A., MACIEJEWSKI, K. Performance and viscoelastic assessment of high-recycle rate cold foamed bitumen mixtures produced with different penetration binders for rehabilitation of deteriorated pavements. *Journal of Cleaner Production* [online]. 2020, **258**, 120517. ISSN 0959-6526. Available from: https://doi.org/10.1016/j.jclepro.2020.120517

[25] BASTOLA, R., SOULIMAN, M. I., MOHAMMED, Z. A. Preliminary finite element modeling of asphalt material using ANSYS. *Civil Engineering Beyond Limits* [online]. 2021, **1**, p. 21-27. eISSN 2687-5756. Available from: https://doi.org/10.36937/cebel.2021.001.005

[26] SUKUMARAN, B., WILLIS, M., CHAMALA, N. Three dimensional finite element modeling of flexible pavements. *Advances in Pavement Engineering* [online]. 2005, p. 1-12. Available from: https://doi.org/10.1061/40776(155)7

[27] HADI, M. N., BODHINAYAKE, B. C. Non-linear finite element analysis of flexible pavements. *Advances in Engineering Software* [online]. 2003, **34**(11-12), p. 657-662. ISSN 0965-9978. Available from: https://doi.org/10.1016/S0965-9978(03)00109-1

[28] LIU, P., WANG, D., OTTO, F., HU, J., OESER, M. Application of semi-analytical finite element method to evaluate asphalt pavement bearing capacity. *International Journal of Pavement Engineering* [online]. 2018, **19**(6), 479-488. ISSN 1029-8436, eISSN 1477-268X. Available from: https://doi.org/10.1080/10298436.2016.1175562

[29] DECKY, M., PAPANOVA Z., JUHAS, M., KUDELCIKOVA, M. Evaluation of the effect of average annual temperatures in Slovakia between 1971 and 2020 on stresses in rigid pavements. *Land* [online] 2022, **11**, 764. eISSN 2073-445X. Available from: https://doi.org/10.3390/land11060764

[30] DECKY, M., HODASOVA, K., PAPANOVA, Z., REMISOVA, E. Sustainable adaptive cycle pavements using composite foam concrete at high altitudes in Central Europe. *Sustainability* [online]. 2022, **14**(15), 9034. eISSN 2071-1050. Available from: https://doi.org/10.3390/su14159034

[31] SHIMANOVSKY, A. O., KRAKAVA, I. E., YAKUBOVICH, V. I., VARAZHUN, I. A. Cargo fastening on automobile transport considering its deformation. In: - Proceedings of the 22nd International Conference Transport Means: proceedings. Vol. 1. 2018. p. 192-196. ISSN 1822-296X, eISSN 2351-7034

[32] SHIMANOVSKY, A. O., KUZNIATSOVA, M. G., YAKUBOVICH, V. I. Dynamics of tank trucks with baffles for transportation of viscous liquids. *International Journal of Mechanical Engineering and Robotics Research*. 2018, **7**(4), p. 438-443. ISSN 2278-0149.

[33] Design of flexible road pavements. Industry Road Codes ODN 218.046-01. Moscow: Informavtodor, 2001.

[34] NYE, J. F. *Physical properties of crystals: their representation by tensors and matrices*. Oxford: Clarendon Press, 1957.