DESIGNING AND CONSTRUCTION OF ROADS, SUBWAYS, AIRFIELDS, BRIDGES AND TRANSPORT TUNNELS

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EXPERIMENTAL DETERMINATION OF STRESS-STRAIN STATE OF ASPHALT PAVEMENT ON METAL BRIDGES

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Statement of the problem. Currently bridge surfacings are not designed but assigned with no consideration of the features of operation of an artificial structure. This might be the reason why bridge pavement has a short service life. In order to calculate bridge surfacings, it is necessary to know its stress-strain state under the action of a moving load that depends on its material and mechanical characteristics. This article is devoted to a practical application of a model for calculating a asphalt deformation modulus and Poisson's ratio.
Results. The data obtained as part of some experiments on artificial structures to determine the stress-strain of surfacings indicate that the resulting assumptions meet the actual operating conditions.
Conclusions. The dependences for determining a deformation modulus and Poisson's ratio of asphalt concrete, which would allow them to be applied for developing the methods for calculating an asphalt concrete on an orthotropic steel decks of metal bridges.

Keywords: bridge, superstructure, orthotropic steel deck, stress-strain state, surfacing, asphalt, modulus of deformation, Poisson's ratio.

Introduction. Construction parameters of elements perceiving efforts of any loads are generally specified based on calculation results to identify stress-strains of some structures. E.g., this is the case for designing bearing elements of span structures of bridges as well as of non-rigid surfacing. One of the loads here are transport vehicles and if a surfacing itself is a bearing element, on bridges it serves only to transmit an external impact onto the bearing elements of a highway and then onto the main beams/girders without increasing the bearing capacity of a structure.

Based on the fact that it is necessary to calculate surfacing according to a moving load, it leaves no doubt. The result of many years of studies and thus improvement of the relevant regulations is currently Industry Road Norms (IRN) 218.046-01 “Designing Non-Rigid Surfacing”.

It is not quite the case for bridges. Since highway surfacing here is not an immediate bearing element, it does not appear absolutely necessary to calculate it. It is proved in the regulations in Set of Rules (СП) 35.13330.2011 “Bridges and Pipes” prescribing that the parameters of a surfacig should be specified according to a structure regardless of its operational features on a span. However, highway surfacing perceives an immediate transport load and is deformed along with an an orthotropic or ferroconcrete plate of a highway. If some of the parameters of asphalt concrete that is typical of its stress-strain is over its limit, there is a defect of a material, which leads to degradation of operational characteristics of a structure and further repairs.

One of the common defects of surfacing on an orthotropic plate of span structures of metal bridges are cracks at the largest local rigidity points of a structure (over the walls of main and transverse beams). This is what occurred in the bridges over the Mzymta River (Fig. 1) and some other structures [2, 10, 19—21]. In a surfacing on a ferroconcrete plate of a highway there were no such cracks due to its considerably large rigidity. Therefore it is only of interest to examine highway surfacing on an orthotropic plate.

Fig. 1. Transverse cracks in a surfacing over the walls of main beams of the bridges through the Mzymta River

We believe that this defect was caused by excessively large transverse stretching strains in asphalt concrete compared to the strength of the material. It does not currently appear easy to identify the stress-strain of the surfacing as there are no legal regulations for the methods of calculating highway surfacing that is proved with experimental data. Therefore determining the stress-strain of a surfacing on an orthotropic plate of bridge spans is an important issue that has to be addressed in order to develop the methods to result in a defect-free life cycle of highway surfacing.

1. Calculation model for determining the characteristics of asphalt concrete. Asphalt concrete is an elastic-viscoplastic material, i.e. deformation and an applied load depend on the temperature *t*, time of load application τ and stress-strain of a material (Fig. 2).

a) viscoplatic deformation b) effort-deformation ratio

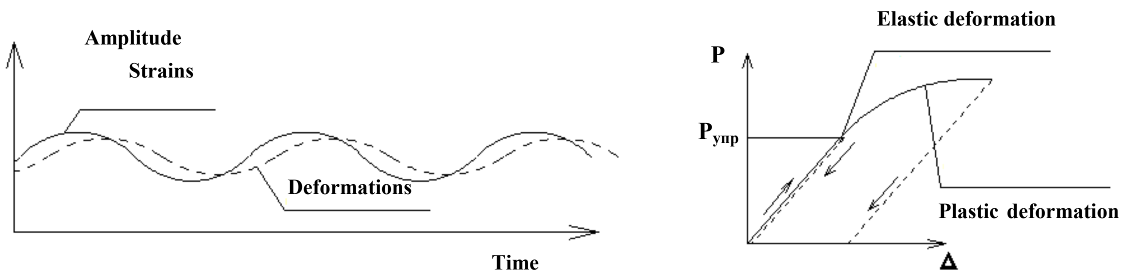

Fig. 2. Elastic-viscoplastic deformation of asphalt concrete

In order to determine the stress-strain of asphalt concrete under a load, it is necessary to know its deformation modulus *E* and Poisson coefficient μ that depend on the temperature as well as time of loading. However, in the current regulations IRN (ОДН) 218.046-01 the deformation modulus of a material for calculating compressive stretching are specified only at $t = 0\ ^0$C and τ = 0.1 c. Poisson coefficient is not regulated. Therefore in calculating it becomes challenging to identify the above characteristics in all possible ranges of temperature changes and times of loading.

The character of deformation of asphalt concrete in different conditions is the subject of study by many scholars in this country and around the world. They often have their own view on the deformation mechanism of the material, which led to diversity of calculation models for calculating the deformation modulus.

Some of such dependencies have been investigated and analyzed [17, 18] resulting in the decision to employ a model by D. Christensen and the co-authors used along with the formula for determining a modulus of deformation (or rigidity as agreed on by the authors) of bitumen obtained by B. S. Radovskiy and B. B. Teltayev [11]. Let us look at it in more detail.

Asphalt concrete is a composite material. Thus according to the rule of mixtures by Reiss and Voigt its deformation modulus [11] first of all ranges between those of the components making it up and secondly depends on the volume of a mixture taken up by each component. The character of the connection at the contact of a matrix and inclusions also has a considerable influence on the deformation modulus: if this connection is weak, tangential strains along the contact are not transmitted and the components are thus deformed "sequentially", i.e. transverse deformations of the components of a mixture are summed (which can apply for asphalt concrete at high temperatures). If this connection is significant, the reverse happens.

In 1962 T. Hirsch set forth a formula for determining the deformation modulus of cement concrete based on the rule of mixtures by Reiss and Voigt considering the effect of the connection at the contact of inclusions and matrix [11]:

$$\frac{1}{E_c} = \frac{k}{E_1 c_1 + E_2 c_2} + (1-k)\left(\frac{c_1}{E_1} + \frac{c_2}{E_2}\right), \tag{1}$$

where E_c is a deformation modulus of a composite material; E_1 is a deformation modulus of the first component; E_2 is a deformation modulus of the second component; c_1 is a volumetric proportion of the first component in a mixture; c_2 is a volumetric proportion of the second component in a mixture; k is an empirical component ranging from 0 to 1 that characterizes the connection at the contact of a matrix and filler that show how close a deformation modulus of a composite material is to the lower or upper boundary of a possible range. The dependence by T. Hirsch was improved for asphalt concrete by D. Christensen, T. Pellinen and R. Bonaquist [11]. The empirical coefficient k is presented as the contact function P_c that characterizes the contribution of each component into the deformation modulus of asphalt concrete:

$$P_c = \frac{\left(P_0 + E_b \dfrac{VFA}{VMA}\right)^{P_1}}{P_2 + \left(E_b \dfrac{VFA}{VMA}\right)^{P_1}}, \tag{2}$$

where P_0, P_1, P_2 are empirical coefficients; E_b is a rigidity modulus of a binder; VMA is the porosity of a mineral material (in units); VFA is the proportion of pores between the grains filled with a binder.

The formula itself for calculating a deformation modulus of asphalt concrete is as follows:

$$E_{mix} = P_c[E_{agg} \cdot (1-VMA) + E_b \cdot VMA \cdot VFA] + \frac{1-P_c}{\dfrac{(1-VMA)}{E_{agg}} + \dfrac{VMA}{E_b \cdot VFA}}, \tag{3}$$

where E_{agg} is a deformation modulus of a stone material.

The deformation modulus of a binder can be determined by means of a dependence identified by B. B. Teltayev and B. S. Radovskiy [11]:

$$E(t) = E_g\left[1 + \left(\frac{E_g t}{3\eta}\right)^b\right]^{-\left(1+\frac{1}{b}\right)}, \tag{4}$$

where E_g is a rigidity modulus of a binder in a glass condition; t is time of a load impact; η is the viscosity of bitumen depending on the temperature and time of a load impact; b is the parameter depending on the penetration index of bitumen.

Strictly speaking, $E(t)$ in the dependence (4) is not a modulus of rigidity but of relaxation of bitumen as it is inserted into the formula (3) E_{mix} which becomes the modulus of relaxation of asphalt concrete. ановится However, in order to avoid confusion, the above terminology is used.

Since the above calculation model reflects the character of the interaction of the components of asphalt concrete using the contact function P_c, the calculated values of the deformation modulus of this composite material indirectly characterize the ratio between longitudinal and transverse deformations of a mixture (i.e. the higher E_{mix} is, the stronger at the connection is between the components and the transverse deformations are thus smaller). Therefore between the values of E_{mix} and μ there should be a correlation dependence that can be specified according to the mechanical and empirical method of designing surfacing [9, 24]:

$$\mu = 0.15 + \frac{0.35}{1 + e^{-12.452 + 2.291 \cdot \lg E^*}}, \quad (5)$$

where E^* is a complex modulus of asphalt concrete, *psi* (1 *psi* = 0.00689 MPa) which can be the values of the deformation modulus E_{mix}.

2. Experimental studies of the stress-strain of asphalt concrete. In order to evaluate the correspondence of the above calculation model to the actual character of deformation of asphalt concrete, it is essential to test it in practice. As an option, the stress-strain of road surfacing in artificial structures can be identified under the impact of actual moving vehicles as we did for the current study.

The experiments were conducted in four bridge crossings:

— № 1 is a steel ferroconcrete pipeway in Krasnoyarsk (Fig. 3a);

— № 2 is a bridge through the Tobol River in Tuymen region (Fig. 3b);

— № 3 is a bridge through the Pregolya River in Kaliningrad (Fig. 3c);

— № 4 is a bridge through the Kondoma River in Kemerovo region (Fig. 3d).

The main bearing elements of the investigated artificial structures are presented with metal solid wall beams of a double-tee and box section with the spans from 14.8 to 126 m. The bearing structures of the roadway are ferroconcrete or orthotropic plates with band/box transverse ribs. The structure of the roadway is made up of a hydro insulation layer + concrete of different types (dense, stone mastic, cast).

At the time of the experiments all the structures were at the final stages of construction, thus there were not any defects in the surfacing. Therefore the areas for setting up the measurement equipment were selected based on the experience of the operation of other bridges as well as the results of the preliminary calculations. The sensor reading the transverse deformations of the upper fiber of an asphalt concrete surfacing were placed over the walls of the main beams.

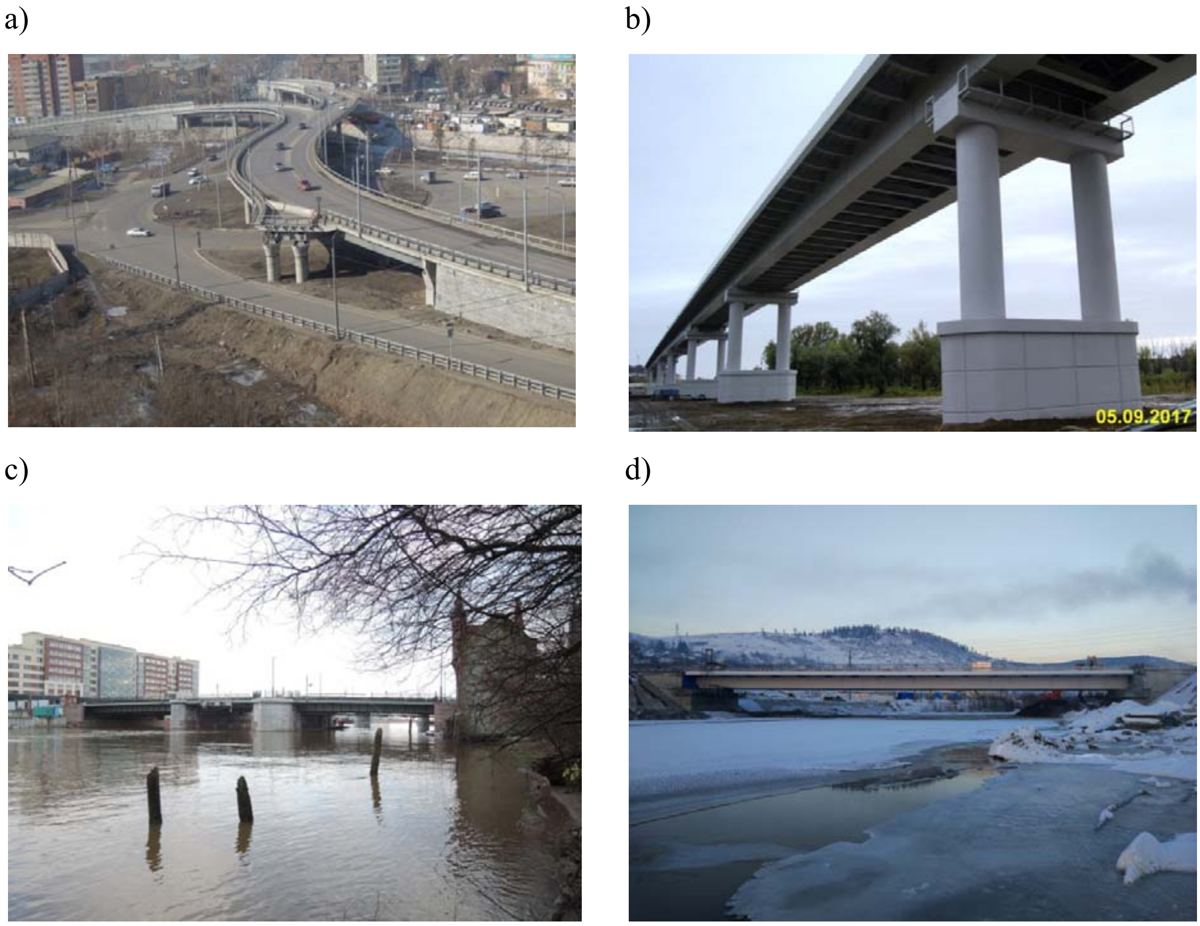

Fig. 3. Structures where the stress-strain of a road surfacing was experimentally identified

As a testing load single dump trucks were presented with the full mass from 27 to 42 tons. The principal scheme of the vehicle used for loading the road surfacing is presented in Fig. 4.

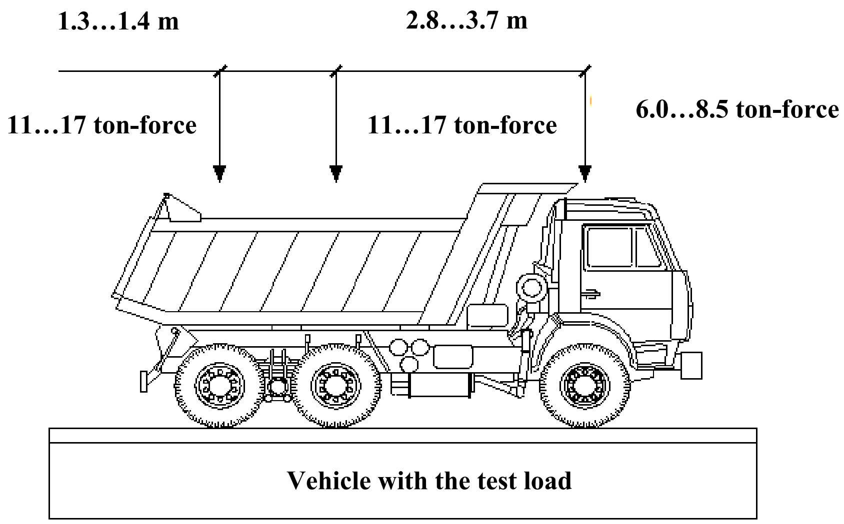

Fig. 4. Principal scheme of the test load

The parameters of the stress-strain of asphalt concrete were fixed using a measuring multi-functional complex "Tensor MS" developed by the Scientific Research Laboratory "Mosty" of the Siberian State Transport University (a certificate of the Federal Agency in Technical Regulation and Metrology for Measurement Equipment RU.C.34.007.A № 32603/1, valid till November, 22, 2018). Fig. 5 shows a measurement complex set up in the bridge roadway and ready to operate.

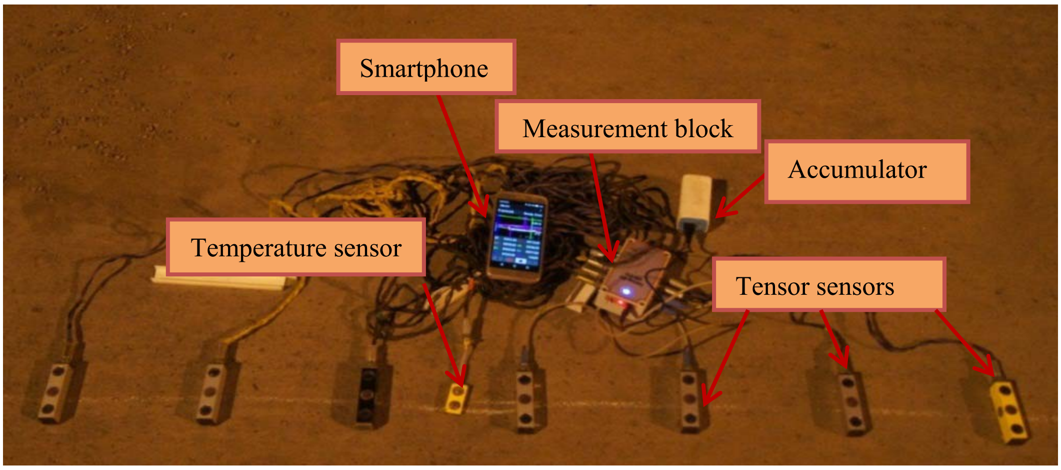

Fig. 5. Measurement complex "Tensor MS" in the operating condition

Throughout the course of the tests, a few options of loading the road surfacing: overpasses over the controlled sections with different speeds as well as stops over them different in time. The schemes for placing the dump truck in the overpass as well as the measurement equipment are shown in Fig. 6.

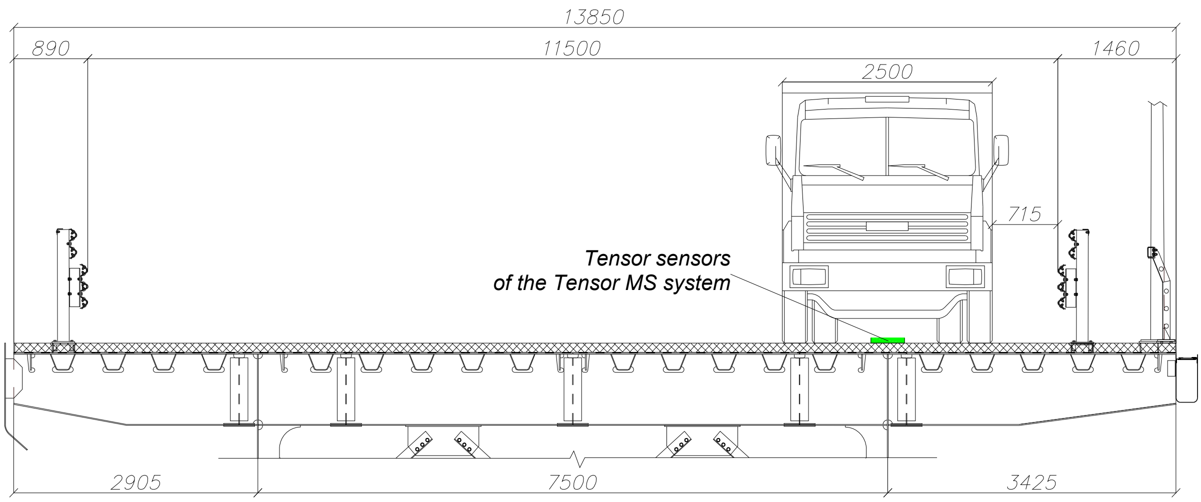

Fig. 6a. Example of placing the test load and measurement equipment in the roadway: scheme of placing the load and equipment in a transverse direction (the bridge through the Tobol River)

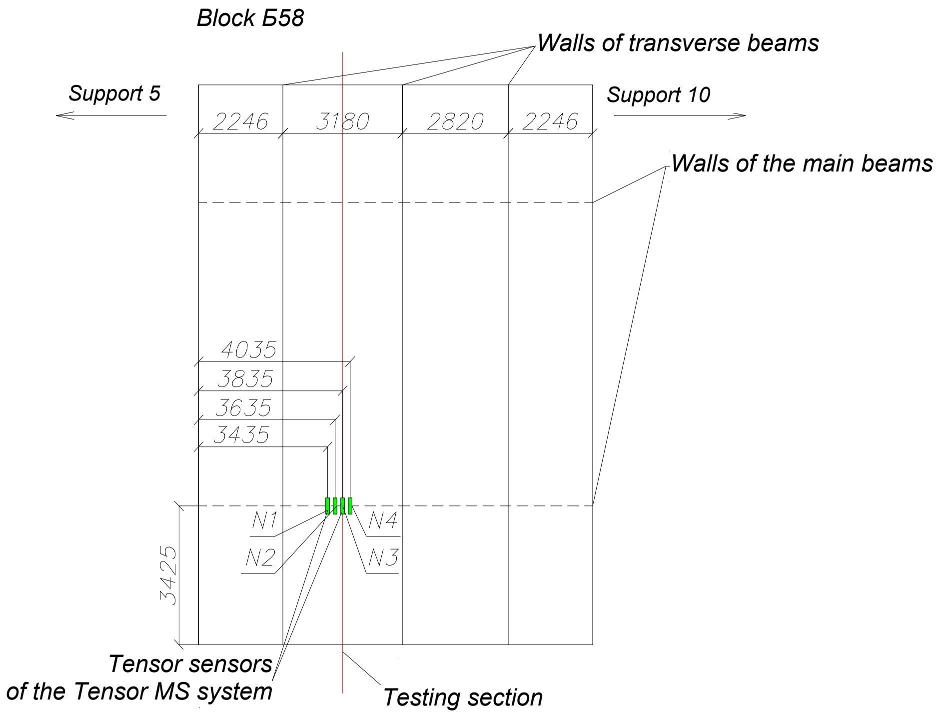

Fig. 6b. Example of placing the test load and measurement equipment in the roadway: scheme of placing the measurement equipment in the plan (the bridge through the Tobol River)

Based on the diversity of factors influencing the stress-strain of a road surfacing, a calculation model for mechanical characteristics of asphalt concrete should be tested in a maximum range of changing parameters, which was taken into account during the tests (Table 1).

Table 1

The parameters changing during the experiments

Parameter	Tested structure			
	№ 1 (Krasnoyarsk)	№ 2 (Tobol River)	№ 3 (Pregolya River)	№ 4 (Kondoma River)
Type of a roadway	Ferroconcrete plate with the thickness of 240 mm	Orthotropic plate with box stringers	Orthotropic plate with band stringers	Orthotropic plate with box stringers
Structure of a roadway	Hydroinsulation “Technoelastmost C” + + dense asphalt concrete of type B of Class I with the thickness 110 mm	Hydroinsulation “Technoelastmost C” + + dense asphalt concrete of type B of Class I with the thickness 60 mm + stone mastic asphalt –15 with the thickness 50 mm	Hydroinsulation “Technoelastmost C” + + cast asphalt concrete of Type I with the thickness 50 mm on a movable and 80 mm on stationary spans	Hydroinsulation “Mostoplast” + cast asphalt concrete of Type I with the thickness 105 mm

End of Table 1

Parameter	Tested structure			
	№ 1 (Krasnoyarsk)	№ 2 (Tobol River)	№ 3 (Pregolya River)	№ 4 (Kondoma River)
Tempera-ture, ^{0}C	–7	+15…+25	+3	–14
Load	Vehicle KamAZ-65115 with the mass of about 27 tons	Vehicle Volvo with the mass of about 38 tons	Vehicle Volvo with the mass of about 42 tons	Vehicle MAN with the mass of about 40 tons
Load impact type	One loading of 1.7 sec	Twelve loadings of 3.1…137.5 sec	Six loadings of 1.1…4.6 sec	Three loadings of 22…85.5 sec

The photos illustrating the tests are given in Fig. 7.

a) b)

Fig. 7. Tests of the bridge over the Tobol River:

a) spots for placing the sensors in the roadway; b) equipment in the roadway;

c) loading

According to the results of loading the roadway surfacing, the graphs of relative deformations of the asphalt concrete surfacing at control points were obtained. An example of this tensorgramm designed during the tests of asphalt concrete in the bridge through the Tobol River is given in Fig. 8. Note that transverse relative deformations of the surfacing on an orthotropic plate under the impact of vehicles obtained in summer season are almost twice (100 times) more than those on a ferroconcrete plate in winter season.

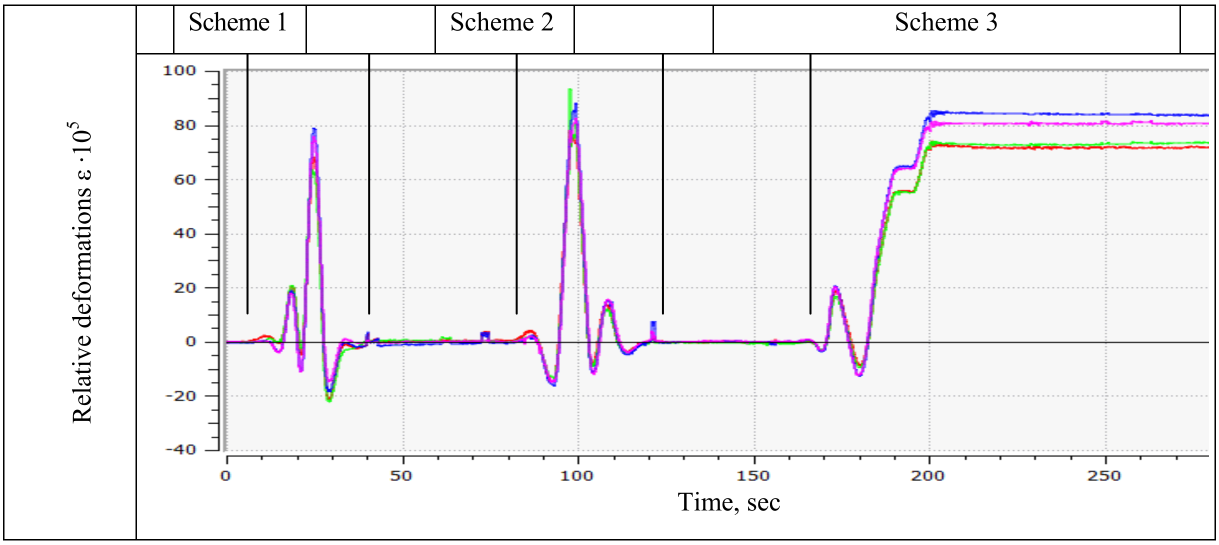

Fig. 8. Example of the graphs of relative deformations of the surfacing obtained during the tests:
(red line) are relative deformations at the spot of placing of the sensor № 1;
(green line) are relative deformations at the spot of placing of the sensor № 2;
(blue line) are relative deformations at the spot of placing of the sensor № 3;
(purple line) are relative deformations at the spot of placing of the sensor № 4

The next step following the experiments is to compare the obtained data with the calculation one. All the calculations were performed in a finite-element software *MidasCivil*. The metal structures were specified by means of plate finite elements and ferroconcrete, asphalt concrete and hydroinsulation with volumetric finite elements. One block of each span was modeled in detail as it was important to obtain local strains and deformations of the roadway surfacing at control point. An example of a finite-element model with an applied load is shown in Fig. 9.

The correspondence of the calculation model and actual operation of the structure can be evaluated using a construction coefficient given by the formula:

$$K_k = {}^{S_r}\!/_{S_k}, \tag{6}$$

where S_r is the parameter obtained as a result of actual impact of the test load; S_k is a calculation parameter from the test load.

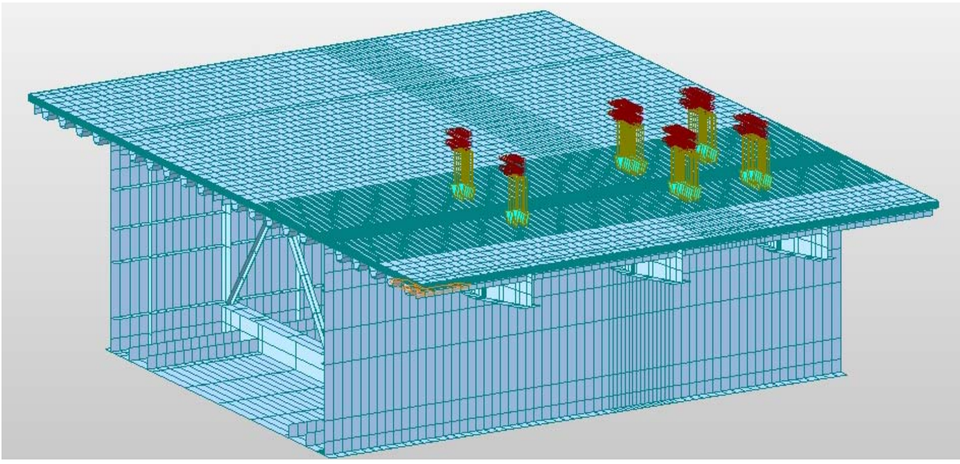

Fig. 9. Example of a finite-element model for calculating the stress-strain of a roadway surfacing

The results of comparing the calculation values of transverse relative deformations of the surfacing with the data obtained during the experiments are given in Table 2. Note that according to the current GOST (ГОСТ) the characteristics that the deformation modulus of asphalt concrete depends on can be in a certain range. Therefore for the calculations minimum and maximum possible deformation modules of a material were calculated and further used for comparisons.

Table 2

Results of comparing the experimental and calculation data

Steel ferroconcrete overpass in Krasnoyarsk				
Range of construction coefficients	Section 1			
	0.49…0.67			
Bridge through the Tobol River in Tyumen region				
Range of construction coefficients	Section 1	Section 2	Section 3	Section 4
	0.92…0.95	0.73…0.77	0.77…0.81	0.85…0.99
Bridge through the Pregolya River in Kaliningrad				
Range of construction coefficients	Section 1, Span 2		Section 2, Span 3	
	0.18…0.29		0.47…0.74	
Bridge through the Kondoma River in Kemerovo region				
Range of construction coefficients	Span 1			
	0.50…1.14			

Conclusions

1. Considering that the character of the operation of an asphalt concrete surfacing in artificial structures is not sufficiently studied and there are extremely few natural studies of stress-strain of bridge roadway surfacing, the results can be deemed satisfactory, i.e. construction coefficients are mostly in the range or about 0.5…1.

2. Therefore the results obtained during the experiments are overall in agreement with the calculation prerequisites of actual operation of structures. The tests of the dependencies for determining the mechanical characteristics of asphalt concrete allow them to be employed in further development of the methods of calculating asphalt concrete surfacing on an orthotropic plate of spans of metal bridges.

References

1. Belyaev N. N. [Experience in numerical simulation of asphalt concrete pavement on an orthotropic plate]. *Trudy pervogo vseross. dorozhn. kongressa* [Proc. of the first all-Russian road Congress]. Moscow, 2009, pp. 60—70.

2. Belyaev N. N. Problemy asfal'tobetonnykh pokrytii i puti ikh resheniya na primere KAD vokrug Sankt-Peterburga [Problems of asphalt concrete pavement and their solutions on the example of the ring ROAD around St. Petersburg]. *Dorogi. Innovatsii v stroitel'stve*, 2014, no. 39, pp. 60—63.

3. Gezentsvei L. B. e. a. *Dorozhnyi asfal'tobeton*. 2-e izd., pererab. i dop [Road asphalt concrete. 2nd ed.]. Moscow, Transport Publ., 1985. 350 p.

4. Zav'yalov M. A., Kirillov A. M. Modelirovanie izmeneniya modulya uprugosti asfal'tobetona pri nagruzhenii [Simulation of changes in the modulus of elasticity of asphalt concrete under loading]. *Inzhenerno-stroitel'nyi zhurnal*, 2015, no. 2, pp. 70—76.

5. Zolotarev V. A., Malyar V. V., Tkachuk Yu. P. Reologicheskaya model' asfal'tobetona [Rheological model of asphalt concrete]. *Sovremennoe promyshlennoe i grazhdanskoe stroitel'stvo*, 2006, no. 2, pp. 104—107.

6. Ivanov N. N. e. a. *Konstruirovanie i raschet nezhestkikh dorozhnykh odezhd* [Design and calculation of non-rigid pavement]. Moscow, Transport Publ., 1973. 317 p.

7. Kiryukhin G. N. Analiz vyazkoplastichnogo i khrupkogo razrusheniya asfal'tobetona [Analysis of viscoplastic and brittle fracture of asphalt concrete]. *Mir dorog*, 2013, no. 71, pp. 51—55.

8. Kiryukhin G. N. Obratimoe deformirovanie asfal'tobetona v zavisimosti ot uslovii nagru-zheniya [Reversible deformation of asphalt concrete depending on loading conditions]. *Dorogi i mosty*, 2017, no. 35, pp. 233—256.

9. Kiryukhin, G. N. Sovremennye podkhody k prognozirovaniyu dolgovechnosti asfal'tobetona v dorozhnykh pokrytiyakh [Modern approaches to forecasting the durability of asphalt concrete in road surfaces]. *Mir dorog*, 2017, no. 95, pp. 63—67.

10. Pokrovskii A. V. Kratkii obzor opyta primeneniya litykh polimerasfal'tobetonov na is-kusstvennykh sooruzheniyakh v severo-zapadnom regione RF [A brief review of the application of cast polymerisation on arti-

ficial structures in the North-West region of Russia]. *Internet-zhurnal «Naukovedenie»*. Available at: https://cyberleninka.ru/article/v/kratkiy-obzor-opyta-primeneniya-lityh-polimerasfaltobetonov-na-iskusstvennyh-sooruzheniyah-v-severo-zapadnom-regione-rf

11. Radovskii B. S., Teltaev B. B. *Vyazkouprugie kharakteristiki bituma i ikh otsenka po standartnym pokazatelyam* [Viscoelastic characteristics of bitumen and their evaluation by standard parameters]. Almaty, «Bilim» baspasy Publ., 2013. 152 p.

12. Radovskii B. S., Suprun A. S., Kozakov I. I. *Proektirovanie dorozhnykh odezhd dlya dvizheniya bol'shegruznykh avtomobilei* [Design of pavement for the movement of heavy vehicles]. Kiev, Budivel'nik Publ., 1989. 168 p.

13. Smirnov A. V. *Dinamika dorozhnykh odezhd avtomobil'nykh dorog* [Dynamics of road pavement of roads]. Omsk, Zapadno-Sibirskoe kn. izd-vo, 1975. 182 p.

14. Teltaev B. B. Analiz raschetnykh znachenii modulya uprugosti asfal'tobetonov [Analysis of the calculated values of the modulus of elasticity of asphalt concrete]. *Dorozhnaya tekhnika*, 2010, pp. 130—137.

15. Teltaev B. B. Ob odnom sposobe postroeniya funktsii relaksatsii bituma [About one method of constructing functions of relaxation of bitumen]. *Doklady Natsional'noi akademii nauk Respubliki Kazakhstan*, 2015, no. 3, pp. 67—76.

16. Shcherbakov A. G. e. a. *Prikladnaya mekhanika dorozhnykh odezhd na mostovykh sooruzheniyakh* [Applied mechanics of road pavement on bridge structures]. Volgograd, VolgGASU Publ., 2006. 220 p.

17. Yashnov A. N., Polyakov S. Yu. [Analysis of computational models to determine the modulus of elasticity of asphalt concrete]. *Trudy IX Mezhdunarodnoi nauchno-tekhnicheskoi konferentsii «Politransportnye sistemy» po napravleniyu «Nauchnye problemy realizatsii transportnykh proektov v Sibiri i na Dal'nem Vostoke»* [Proc. of the IX international scientific and technical conference "political transport systems" in the direction of " Scientific problems of transport projects in Siberia and the far East»]. Novosibirsk, Izd-vo SGUPSa, 2017, pp. 73—79.

18. Yashnov A. N., Polyakov S. Yu. [On the problem of normalization of asphalt concrete coating properties on orthotropic plate of metal bridges]. *Sb. st. i dokladov ezhegodnoi nauchnoi sessii Assotsiatsii issledovatelei asfal'tobetona* [Collection of articles and reports of the annual scientific session of the Association of asphalt concrete researchers]. Moscow, MADI Publ., 2016, pp. 40—49.

19. Yashnov A. N., Polyakov S. Yu. Osobennosti rascheta nezhestkoi dorozhnoi odezhdy primenitel'no k usloviyam ekspluatatsii pokrytiya na ortotropnoi plite [Features of the calculation of non-rigid pavement in relation to the operating conditions of the coating on the orthotropic plate]. *Transport. Transportnye sooruzheniya. Ekologiya*, 2016, no. 1, pp. 142—157.

20. Yashnov A. N., Polyakov S. Yu. [Problems of purpose and operation of coatings on orthotropic plate of span structures of metal bridges]. *Trudy XLI Mezhdunarodnoi nauchno-prakticheskoi konferentsii «Innovatsionnye tekhnologii na transporte: obrazovanie, nauka, praktika»* [Proc. of the XLI International scientific and practical conference " Innovative technologies in transport: education, science, practice»]. Almaty, 2017, pp. 354—358.

21. Yashnov A. N., Polyakov S. Yu. [Characteristic cracks in the coating on the orthotropic plate of metal bridges and the ability to prevent them]. *Trudy XXI nauchno-metodicheskoi konferentsii VITU «Defekty zdanii i sooruzhenii. Usilenie stroitel'nykh konstruktsii (16 marta 2017 goda)»* [Proc. of the XXI scientific-methodical conference of VITU " Defects of buildings and structures. Strengthening of building structures (16 March 2017)»]. Saint-Petersburg, 2017, pp. 229—233.

22. Al-Khateeb Ghazi, Shenoy Aroon, Gibson Nelson, Harman Thomas A New Simplistic Model for Dynamic Modulus Predictions of Asphalt Paving Mixtures. Journal of the AAPT, 2006, vol. 75E. 40 p.

23. Flintsch G. W. e. a. Asphalt materials characterization in support of implementation of the proposed mechanistic-empirical pavement design guide. USA, Virginia Department of Transportation, 2007. 45 p. Available at: http://www.virginiadot.org/vtrc/main/online_reports/pdf/07-cr10.pdf

24. Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures. P. 2. Design Inputs. Ch. 2. Material characterization. USA, 2004. 83 p. Available at: http://onlinepubs.trb.org/ onlinepubs/archive/mepdg/Part2_Chapter2_Materials.pdf

25. Shahin M. Y., McCullough B. F. Prediction of low-temperature and thermal-fatigue cracking in flexible pavements: Report No. 123-14. USA, University of Texas, 1972. 225 p.

26. Xiao Y. Evaluation of Engineering Properties of Hot Mix Asphalt Concrete for the Mechanistic Empirical Pavement Design. USA, Florida State University, 2009. 183 p.

27. Yu J. Modification of Dynamic Modulus Predictive Models for Asphalt Mixtures Containing Recycled Asphalt Shingles. USA, Iowa State University, 2012. 156 p.

28. Seredin P. V., Lenshin A. S., Kashkarov V. M., Lukin A. N., Arsentiev I. N., Bondarev A. D., Tarasov I. S. Ultrathin nano-sized Al2O3 strips on the surface of por-Si. Materials Science in Semiconductor Processing, 2015, vol. 39, pp. 551—558. doi: 10.1016/j.mssp.2015.05.067.