Calculation of the risk of destruction of the pavement by permissible stresses in monolithic layers

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Abstract. The article presents a calculation of the strength of the road structure according to the allowable tensile stresses during bending in monolithic layers. The test is carried out according to the criterion of maximum tensile stresses on the sole of the layer along the load axis. The continuity of monolithic layers will not be violated if the tensile stresses during repeated bending do not exceed the permissible stresses (for the material of this layer), established taking into account fatigue phenomena. Therefore, for layers with an organic binder, the test is carried out according to the criterion of maximum tensile stresses on the sole of the layer along the load axis. This work is aimed at establishing the probability of cracks in the monolithic layer during bending, depending on the qualitative condition of the structures and changes in soil moisture of the roadbed in the spring period. It is taken into account that the distribution of tensile stresses in a monolithic layer during bending does not contradict the normal distribution law.

Keywords: highway, road surface, design, risk, transport load, damage, crack, bending tension.

Introduction

The failure of the pavement associated with insufficient strength can occur for many reasons and, in particular, as a result of fatigue failures of monolithic layers under the influence of tensile stresses from repeated application of a transport load. And, as a consequence, the subsequent intensive deterioration of the transport and operational properties of the pavement before the expiration of

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its service life. Therefore, the strength calculation is performed according to the allowable tensile stresses during bending in monolithic layers.

The deflection of the pavement occurs under the influence of the movement of vehicles. Its value depends on temperature, humidity and other factors. Therefore, the coating layers experience different compressive and tensile stresses, which vary over time.

The continuity of monolithic layers will not be violated if the tensile stresses during repeated bending do not exceed the permissible stresses (for the material of this layer), established taking into account fatigue phenomena. Therefore, for layers with an organic binder, the test is carried out according to the criterion of maximum tensile stresses on the sole of the layer along the load axis.

This work is aimed at establishing the probability of cracks in the monolithic layer during bending, depending on the qualitative condition of the structures and changes in soil moisture of the roadbed in the spring period. It is taken into account that the distribution of tensile stresses in a monolithic layer during bending does not contradict the normal distribution law.

Methods

In this study , standard roadway structures are checked for cracks during bending , taking into account the work [1-8].

The album of standard structures of non-rigid road coverings in various climatic zones is aimed at meeting the requirements of TR CU 014/2011, Federal Law of the Russian Federation No. 384-FZ of December 30, 2009 "Technical Regulations on the safety of buildings and structures" and other applicable regulatory documents. Therefore, standard designs of non-rigid road clothes should provide a level of reliability acceptable for the declared category [9-15].

A list of articles from foreign scientometric databases of representatives of the scientific school of Professor V.V.Ushakov is presented in [16-18].

27 road clothes corresponding to IB, II and III technical categories for I, II and III road-climatic zones were selected from the album, which were calculated according to PNST 542-2021, and then according to the formulas of risk theory.

An example of the calculation is provided below.

Example of calculation of non-rigid pavement using the mathematical apparatus of risk theory

The risk of cracks in a monolithic layer during bending can be determined by the formula:

$$r = 0,5 - \Phi\left(\frac{\sigma_{\text{КР}} - \sigma_r}{\sqrt{m_{\text{КР}}^2 + m_r^2}}\right)$$

where $\sigma_{\text{КР}}$ is the critical (maximum) tensile stress in a monolithic layer, at the occurrence of which the probability of cracks is 50%, MPa;

σ_r is the largest tensile stress in the layer under consideration, MPa;

$m_{\text{КР}}$ and m_r are the standard deviations of the parameters $\sigma_{\text{М}}$ *and* σ_r, MPa.

The calculated tensile stress is determined by the formula 20, PNST 542-2021:

$$\sigma_r = \underline{\sigma_r} * p * k_{\text{в}} ,$$

where σ_r is the tensile stress from a single load (Figure 5 PNST 542-2021), determined by the nomogram Fig.52 for a smooth contact with an underlying layer of loose material, or by the nomogram Figure E.51 for a soldered contact, MPa;

$k_в$ is a coefficient that takes into account the features of the stress state of the coating of the structure under the paired cylinder;

p is the calculated pressure from the wheel on the coating, MPa.

The standard deviation of the greatest tensile stress in the layer under consideration is determined by the formula (3):

$$m_r = C_v^{\sigma_r} * \sigma_r$$

where is the coefficient of variation of tensile stresses during bending in a monolithic layer.

The critical tensile stress in a monolithic layer, at which the probability of cracks is 50%, is calculated by the formula:

$$\sigma_{КР} = 2R_N - \frac{\sqrt{R_N^2 + \left|25\left(C_V^{\sigma_{КР}}\right)^2 - 1\right|\left(R_N^2 - 25m_N^2\right)} - R_N}{25\left(C_V^{\sigma_{КР}}\right)^2 - 1}$$

where $C_V^{\sigma_{КР}}$ is the coefficient of variation of the critical tensile voltage;

R_N is the ultimate tensile stress of the layer material, taking into account fatigue phenomena, MPa;

m_N is the standard deviation of the permissible tensile stress of the material, MPa;

$$m_N = 0,1 * R_N ,$$

where 0,1 is the coefficient of variation in the strength of asphalt concrete.

The standard deviation of the critical tensile stress is determined by the formula:

$$m_{КР} = C_V^{\sigma_{КР}} * \sigma_{КР} .$$

The coefficient of variation of the critical tensile stress is determined by the formula:

$$C_V^{\sigma_r} = 0,35\left(C_V^{E_B} - 0,15\right) + 0,40\left(C_V^{E_H} - 0,2\right) + 0,75\left(C_V^{h} - 0,15\right) + 4,79 * 10^{-5} * E_B - 1,05 * 10^{-3} * E_H + 1,64 * 10^{-2} * h$$

where E_B and E_H are the elastic modulus of the upper and lower layers, MPa;

h is the thickness of the top layer, cm;

$C_V^{E_B}$ - coefficient of variation of the elastic modulus of the upper layer;

$C_V^{E_H}$ - coefficient of variation of the elastic modulus of the lower layer;

C_V^{h} is the coefficient of variation of the total thickness of asphalt concrete layers.

The modulus of elasticity of the upper layer of the model is calculated as a weighted average according to the formula 16, PNST 542-2021:

$$E_в = \frac{\sum_{i=1}^{n} E_i \bullet h_i}{\sum_{i=1}^{n} h_i}$$

where n is the number of layers of pavement;

E_i is the elastic modulus of the i-th layer;

h_i is the thickness of the i-th layer.

During new construction or major repairs with the replacement of all layers of asphalt concrete, the lower layer of the model is the part of the structure located below the package of asphalt concrete layers, including the soil of the working layer of the roadbed.

During repairs (replacement of two or more layers of coating), the lower layer of the model is the lower existing layer of asphalt concrete, if available.

The total modulus of elasticity of the lower layers is determined using a nomogram Figure E.1 PNST 542-2021

The strength of the monolithic layer material under repeated stretching during bending is determined by the formula 18, PNST 542-2021, taking into account the ODM 218.05.001-2009:

$$R_n = R_0 \bullet k_1 \bullet k_2 \bullet \left(1 - \gamma_r \cdot t\right)$$

where R_0 is the normative value of the ultimate tensile resistance during bending at the calculated low spring temperature with a single load application (Table G.5, appendix G PNST 542-2021), MPa;

k_1 is a coefficient that takes into account the decrease in strength due to fatigue phenomena with repeated application of the load, (formula 19, PNST 542-2021, taking into account ODM 218.05.001-2009):

$$k_1 = \frac{\alpha}{\sqrt[m]{\Sigma N_p \bullet k_{np}}}$$

k_2 is a coefficient that takes into account the decrease in strength over time from the effects of weather and climatic factors (Table 8 PNST 542-2021);

γ_r is the coefficient of variation of tensile strength equal to 0.1;

t is the coefficient of standard deviation (Table B.3, PNST 542-2021).

k_a is the coefficient that takes into account the increase in strength due to the reinforcement of the layer with a geogrid (ODM 218.05.001-2009, Table 8);

k_{np} is a coefficient that takes into account the reduction of the effect of fatigue processes on strength due to the reinforcement of asphalt concrete pavement with a geogrid (ODM 218.05.001-2009, Table 8);

The structural strength coefficient obtained by calculation is equal to:

$$K_{\text{пр}} = \frac{R_N}{\sigma}$$

Initial data

The initial data are shown in Table 1.

Table 1 Initial data

Name	Thickness, cm	Bending modulus, MPa	Humidity, fractions of a unit of	DKZ	m	α
SHCHMA-16 on BND 50/70	5,0	6450,0	0,683	II	6,00	5,0
A22Nn on BND 50/70	9,0	7200,0			6,00	5,0
Geogrid АРМДОР100	0	-			-	-

A32On on BND 50/70	12.0	6100,0			5,10	5,0
Crushed-sand, treated with liquid organic binders	22,0	450,0			-	-
Crushed stone mixture C5, grain size 40 mm 40 мм	25,0	260,0			-	-
Geotextile GEOSPAN TN 80	0	-			-	-
Crushed stone mixture C4, grain size 80 mm	35,0	275,0			-	-
Composite material STABARM SK 45/45	0	-			-	-
Light loam (angle inside. friction – 6,02)		44,12				

Results

Design load – A-11,5 (P = 0,8 MPa).

The period of work on major repairs, years – 24.

The term of repair work, years – 12.

Design load parameters:

Wheel load Q = 57,5 kN;

Tire pressure P = 0,8 MPa;

The diameter of the wheel stamp D = 34,5 cm.

The total estimated number of load applications is set initially and is 76209529.22 auth.

The thickness of the upper layer of the model is assumed to be equal to the sum of the thicknesses included in the package of asphalt concrete layers – 26,0 cm.

Identify. The risk of destruction of monolithic layers from stretching during bending.

Solving the problem. Let's determine the calculated tensile stress.

The modulus of elasticity of the upper layer of the model is calculated as a weighted average according to the formula 16, PNST 542-2021:

$$E_{в} = \frac{\sum_{i=1}^{n} E_i \bullet h_i}{\sum_{i=1}^{n} h_i} = \frac{6450*5+7200*9+6100*12}{26} = 6548,08 \text{ МР.}$$

The total modulus of elasticity of the lower layers is determined using the nomogram Figure E.1 PNST 542-2021:

$$\frac{E_1}{E_2} = \frac{191,17}{450} = 0,425, \quad \frac{h}{D} = \frac{22}{34,5} = 0,638, \quad \frac{E_{общ}}{E_{в}} = 0,6400, \; E_6 = 288,0 \text{ MPa}$$

$$\frac{E_1}{E_2} = \frac{127,9}{260} = 0,492, \quad \frac{h}{D} = \frac{25}{34,5} = 0,725, \quad \frac{E_{общ}}{E_{в}} = 0,7152, \; E_5 = 191,17 \text{ MPa}$$

$$\frac{E_1}{E_2} = \frac{44,12}{275} = 0,16, \quad \frac{h}{D} = \frac{35}{34,5} = 1,014, \quad \frac{E_{общ}}{E_{в}} = 0,4562, \; E_3 = 127,9 \text{ MPa}$$

$$E_1 = 44,12 \text{ MPa}$$

The total modulus of elasticity of the lower layers is 288.0 MPa.

The calculated tensile stress is determined by the formula 20, PNST 542-2021:

$$\frac{h}{D}=\frac{26}{34,5}=0,754,\ \frac{E_{в}}{E_{общ.осн}}=\frac{6548,08}{288}=22,736,\ \underline{\sigma}_r=1,196,$$

$$\sigma_r=\underline{\sigma}_r \bullet p \bullet k_{в}=1,196\cdot 0,80\cdot 0,85=0,813 \text{ MPa}.$$

We will determine the strength of the monolithic layer material under repeated stretching during bending according to the formula 18, PNST 542-2021, taking into account the ODM 218.05.001-2009:

$$R_n=R_0 \bullet k_1 \bullet k_2 \bullet k_a \bullet \left(1-\gamma_r \cdot t\right)=9,30\cdot 0,1479\cdot 0,80\cdot 1,08\cdot(1-0,1\cdot 2,19)=0,924 \text{ МПа}$$

k_1 is a coefficient that takes into account the decrease in strength due to fatigue phenomena with repeated application of load, (formula 19, PNST 542-2021, taking into account ODM 218.05.001-2009):

$$k_1=\frac{\alpha}{\sqrt[m]{\Sigma N_p \bullet k_{np}}}=\frac{5,00}{\sqrt[5,10]{76209529,22\cdot 0,82}}=0,1479\ .$$

The calculation also takes into account the reinforcement of asphalt concrete with geosynthetic material, for this purpose the coefficients k_a= 1,08 are introduced, taking into account the increase in strength and k_{np}= 0,82, taking into account the decrease in the influence of fatigue processes.

The structural strength coefficient obtained by calculation is equal to:

$$K_{np}=\frac{R_N}{\sigma}=\frac{0,924}{0,813}=1,136\ .$$

The required strength coefficient is equal to 1,10.

We determine the coefficient of variation of the critical tensile stress by the formula for coefficients $C_V^{E_B}=0,002;\ C_V^{E_H}=0,002;\ C_V^{h}=0,002$:

$$C_V^{\sigma_r}=0,35\left(C_V^{E_B}-0,15\right)+0,40\left(C_V^{E_H}-0,2\right)+0,75\left(C_V^{h}-0,15\right)+4,79*10^{-5}*E_B-1,05*10^{-3}*E_H+1,64*10^{-2}*h=0,1957\ .$$

We determine the standard deviation of the greatest tensile stress in the layer under consideration by the formula:

$$m_r=C_v^{\sigma_r}*\sigma_r=0,1957*0,813=0,159 \text{ МПа}\ .$$

We determine the critical tensile stress in a monolithic layer, at which the probability of cracks is 50%, calculated by the formula:

$$\sigma_{КР}=2R_N-\frac{\sqrt{R_N^2+\left[25\left(C_V^{\sigma_{КР}}\right)^2-1\right]\left(R_N^2-25m_N^2\right)}-R_N}{25\left(C_V^{\sigma_{КР}}\right)^2-1}=2*0,924-\frac{\sqrt{0,924^2+\left[25(0,1957)^2-1\right]\left(0,924^2-25*0,092^2\right)}-0,924}{25(0,1957)^2-1}=1,50 \text{ МПа}$$

,

$$m_N=0,1*R_N=0,1*0,924=0,092 \text{ МПа}.$$

The standard deviation of the critical tensile stress is determined by the formula:

$$m_{КР}=C_V^{\sigma_{КР}}*\sigma_{КР}=0,1957*1,50=0,293 \text{ МПа}\ .$$

The risk of cracks in a monolithic layer during bending can be determined by the formula (1):

$$r=0,5-\Phi\left(\frac{\sigma_{КР}-\sigma_r}{\sqrt{m_{КР}^2+m_r^2}}\right)=0,5-\Phi\left(\frac{1,50-0,813}{\sqrt{0,293^2+0,356^2}}\right)=0,5-\Phi(2,06)=0,5-0,4803=0,0197.$$

The value of the risk of cracking when stretching the pavement corresponds to 2,78 m^2 per 10 m^2 or 27789 m^2 per 100,000 m^2.

This roadwear will correspond to a reliability value equal to P=1-r=1-0,0197=0,9803.

For the IB road of the technical category, the reliability is 0,98.

This roadwear meets the requirements of PNST 542-2021 and meets the reliability requirements for calculation using the mathematical apparatus of risk theory.

Conclusion

Based on the calculations obtained using risk theory formulas, most (more than 95%) of standard designs correspond to the level of specified reliability, despite the fact that all of them meet the requirements of PNST 542-2021. This may indicate that modern regulatory materials of a recommendatory nature do not take into account statistical methods of risk assessment. Consequently, the requirements of these regulatory documents are intentionally underestimated, which can lead to the construction of structures that do not actually meet the requirements of reliability.

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