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Design Procedure by Strength Criteria of Asphalt Layers on a Rigid Base Taking into Account the Simultaneous Action of External Loads and Thermal Stresses

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Abstract

The article gives the definition of a generalized solution of the thermal stress in the asphalt layer on a rigid base at heating and cooling, taking into account the rheological properties of asphalt concrete pavement. The equation for determining the stress state of the asphalt layer on a rigid base caused by the combined effect of temperature deformation and external load is presented. The design procedure by the strength criteria of asphalt layers on a rigid base, taking into account the adhesion strength of the asphalt layer and the rigid base, the temperature cracking resistance, as well as the shear resistance of the asphalt layer is given.

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Keywords: asphalt layer; rigid base; stress-strain state; temperature deformation; strength criteria.

1. Introduction

One of the design solutions for new construction or repair of the hard road pavement is blacktopping. This solution makes it easier to perform repair work to improve the smoothness and friction coefficient of rigid pavement, improve the comfort and safety of traffic, to improve the hygiene and environmental condition: dust-free, ease of mechanical cleaning, drainage of surface water, etc. (ВБН В.2.3–218–532:2007… 2007).

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When in operation the asphalt layer is influenced by the action of the external load caused by vehicles. External load is characterized by vertical pressure and horizontal force. Horizontal force is the reaction of traction effort or braking force under vehicle wheels.

During heating and cooling of the asphalt layer there occur thermal stresses. Thermal stresses in the asphalt layer on a rigid base develop as the cement slab (provided that there is a reliable adhesion between the asphalt layer and the cement concrete slab) restricts the free thermal deformation of the asphalt layer (Ischenko 2003; Dorozhko et al. 2014; Fedotov 2007).

The asphalt layer on a rigid base is located in a complex stress-strain state, as the association of thermal stresses and strains from the action of traffic load is possible. Combining of thermal stresses and strains from the action of traffic load can lead to destruction and additional spending of funds on premature repairs.

Consequently, there is a need to develop a procedure for calculating the asphalt layers on a rigid foundation by the strength criteria, taking into account the simultaneous action of external load and thermal stresses.

2. Analysis of recent research and publications


First, the calculation of temperature stresses in the asphalt layers is performed only for the mode of structure cooling, i.e. analysis of thermal cracking resistance at brittle fracture state of the material. But thermal stresses also occur at heating of a structure; hence deformation and destruction inherent for the plastic state of the material are not taken into account (layering, rutting, landslide, bulging).

Herewith, the temperature stresses when combined with stresses caused by external loads can lead to plastic deformation and destruction, because at high operating temperatures the strength of the asphalt layer and the strength of interlayer adhesion of the asphalt and cement-concrete are reduced. In addition, the temperature coefficient of linear expansion of the asphalt-concrete is different for the mode of heating and cooling, which should also be considered.

Second, the estimation of temperature stress in asphalt layers is based on considering only the difference of coefficients of thermal expansion of the asphalt-concrete and cement material, but does not take into account the impact of stress caused by the cement slab warping and the forces of friction-clutching of the plate at its base.

3. Determination of thermal stresses in the asphalt layer on a rigid base

The values of thermal deformations of the asphalt layer and cement slab depend on the coefficients of heat-deformability (TCLE) of these materials and temperature gradients; at this TCLE of the asphalt-concrete is several times higher than that of the cement-concrete (Fedotov 2007; Dorozhko et al. 2013; Afinogenov 2004).

For accepted condition of reliable asphalt layer adhesion with the cement slab temperature deformations at the contact of layers, regardless of the layers material, coefficients of layers heat-deformability and temperature gradient will be the same (Dorozhko et al. 2014). At the same time the asphalt layer is thinner and has a significantly lower modulus of elasticity than the cement slab, therefore the asphalt layer is forced to deform as well as the cement slab at the base (Dorozhko et al. 2014). Therefore, when the temperature of the composite slab changes, in the asphalt layer there occur unrealized deformations and the corresponding thermal stresses.

Thermal stresses in the asphalt layer should be determined by the value of non-realized temperature deformation in accordance with the solutions given in (Dorozhko et al. 2014):

\[
\sigma_{\alpha\delta} = \frac{R_{\alpha\delta}}{(1 - \mu_{\alpha\delta})} \left[ \alpha_{\alpha\delta} \cdot \left( \frac{\Delta t_{\alpha\delta}^n + \Delta t_{\alpha\delta}^v}{2} \right) - \left( \alpha_{\alpha\delta} \cdot \left[ \Delta t_{\alpha\delta}^{cp} * + \frac{1}{3} (\Delta t_{\alpha\delta}^n - \Delta t_{\alpha\delta}^{cp}) \right] \right) \right] - \left( \frac{\rho \cdot f + 0.5 \cdot C}{E_{\alpha\delta}} \right) (1 - \mu_{\alpha\delta})
\]
where $\sigma_{as}$ – thermal stresses in the asphalt layer, MPa; $R_{\mu_{as}}$ – relaxation function of the asphalt concrete at the temperature of (t) (Dongre et al. 2005), MPa; $\alpha_{as}$ – temperature coefficient of linear expansion of the asphalt concrete °C$^{-1}$; $\Delta T_{as}$, $\Delta t_{as}$ – temperature gradient (temperature difference) of the top and bottom of the asphalt concrete slab respectively, °C; $\alpha_{cc}$ – temperature coefficient of linear expansion of cement concrete, °C$^{-1}$; $\Delta t_{cc}$, $\Delta t_{cc}^{*}$ – temperature gradient (temperature difference) of the top and middle of cement concrete slabs respectively, °C; $\rho$ – specific pressure on the sole of the plate caused by the weight of the composite slab and estimated vehicle, MPa; $f$ – friction coefficient between the cement concrete slab and the base; $C$ – adhesion coefficient of the cement concrete slab and the base; $\mu_{as}$ – Poisson’s ratio of cement concrete; $\mu_{as}$ – Poisson’s ratio of asphalt concrete; $E_{as}$ – elasticity modulus of cement concrete, MPa; $t_{as}$ – temperature of the top of cement concrete slab, °C; $t_{as}^{n}$ – temperature of the bottom of cement concrete slab, °C; $m$ – coefficient of tension measure.

Thermal stresses in the asphalt layer on a rigid base are different for both modes of heating and cooling because the temperature coefficient of linear expansion of the asphalt concrete at heating and cooling is different.

Thermal stresses arising due to unrealized thermal deformation of the asphalt layer have two functions [Dorozhko et al. 2014]:

- Firstly, on the contact of the asphalt layer and cement concrete slab, i.e. at the contact of layers they are tangential stresses. This is because the shearing forces that impede the free deformation of the asphalt layer are applied directly to the contact zone of the asphalt concrete layer and cement concrete slab. The contact of layers can consist of the tack coat, the membrane, the waterproofing layer, etc.
- Secondly, on the bottom surface of the asphalt concrete layer they are horizontal thermal stresses acting directly in the “body” of the asphalt concrete layer. This is due to the forced deformation of the bottom surface of the layer in the horizontal plane.

In literature sources TCLE of bituminous asphalt is mainly given to address the problems of temperature fracture toughness and the experimentally numerical TFLE values were determined in the cooling mode for the temperature range from +20 °C to –20 °C (–30 °C) (Ischenko). Therefore, there is a need for a pilot study to determine the numerical TFLE value for different types of asphalt concrete at heating and cooling in the range of positive temperatures between 0 °C and above.

4. Experimental determination of asphalt concrete TFLE during heating and cooling

With the requirements for determining the TFLE of solids and specific requirements for asphalt concrete there was developed the following dilatometer circuit designed for measurements during heating and cooling (Fig. 1).

TFLE of the asphalt concrete is different for various temperature ranges (Ischenko 2003). As a result of analysis of the published data of previous studies and performance of search experiments there were accepted the following temperature ranges within which TFLE can be considered constant: from 0 °C to +5 °C, +5 °C to 20 °C, +20 °C to +40 °C. Maximum temperature +40 °C is selected in such a way to avoid heating of the sample at temperature not exceeding the softening point of the bitumen.

To determine the average differential asphalt-concrete TFLE in the temperature range they use the dependence (Ischenko 2003):

$$\alpha = \frac{1}{L_4} \cdot \frac{L_2 - L_1}{t_2 - t_1},$$

(2)
where $L_1$ – the amount of sample at the beginning of the test, at temperature $t_1$; $L_2$ – sample size at the end of the test, at temperature $t_2$.

During the test there were selected at least 3 samples of the same type, to account for the structural heterogeneity of asphalt concrete and possible faults during the formation.

After checking for blunders there were estimated the values of the confidence interval for the mean TFLE value. The results obtained during testing are summarized in Table 1.

<table>
<thead>
<tr>
<th>Type of asphalt concrete</th>
<th>Temperature mode</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>heating, °C</td>
<td>cooling, °C</td>
</tr>
<tr>
<td></td>
<td>$0 \rightarrow +5$</td>
<td>$+5 \rightarrow +20$</td>
</tr>
<tr>
<td>Fine-grained, type B</td>
<td>(28.8±31.2)·10^{-6}</td>
<td>(26.9±29.1)·10^{-6}</td>
</tr>
<tr>
<td>Grain size to 20 mm, BND</td>
<td>(24.9±27.1)·10^{-6}</td>
<td>(23.8±26.2)·10^{-6}</td>
</tr>
<tr>
<td>SMA – 5, 60/90</td>
<td>(30.7±33.3)·10^{-6}</td>
<td>(26.9±29.1)·10^{-6}</td>
</tr>
<tr>
<td>7.2% bitumen</td>
<td>(24.9±27.1)·10^{-6}</td>
<td>(23.8±26.2)·10^{-6}</td>
</tr>
<tr>
<td>SMA – 5 90/130</td>
<td>(24.9±27.1)·10^{-6}</td>
<td>(19.8±22.2)·10^{-6}</td>
</tr>
<tr>
<td>6.2% of bitumen</td>
<td>(24.9±27.1)·10^{-6}</td>
<td>(19.8±22.2)·10^{-6}</td>
</tr>
</tbody>
</table>

Analyzing the test results, there was revealed the law that TFLE of the asphalt concrete of different types is different at heating and cooling, and is different for different temperature ranges. This is due to the fact that when
the temperature changes, the properties of the bitumen and as a consequence those of the asphalt concrete change. From the results of the test conducted it can be concluded that when estimating the thermal stress in asphalt layers on a rigid base one must take into account what mode (heating or cooling) a structure works in and within which temperature range.

5. The stress-strain state of asphalt layer on a rigid base under the simultaneous action of thermal stresses and external load

Stresses arising from the simultaneous action of external load and temperature deformation cannot be defined by the total of these two factors deformation. This is due to the effect that the time of external load action and temperature deformation are significantly different (Ryapuhin et al. 2013).

Thermal deformation occurs over a long time (hours, days). During this time, the temperature and the properties of asphalt layer change, so when calculating thermal stresses there arises the need to take into account the stress relaxation.

External load acts during a shorter period of time (estimated period of dynamic loading action is 0.1 sec., that of the static load is 600 sec.) (ВБН В.2.3-218-186-2004. 2004) as opposed to the time of temperature deformation.

It is necessary to take into account that the stress-strain state of asphalt concrete depends on the time of load action or deformation.

The components of the stress state (σ, σx, σy, τxz, τxy, τyz) and the principal stresses caused by the action of external load is calculated by the solution of elasticity theory. For this purpose one can use the finite element method.

To determine the stresses arising in the asphalt concrete layer on a rigid base caused by the simultaneous action of external load and temperature deformation, it is proposed to use the principle of superposition (Ryapuhin et al. 2013). Based on the principle of superposition, stresses arising due to various factors are summarized. Upon that, stresses resulting from the action of the external load and thermal deformation are calculated separately with respect to the time of load action and changes in the properties of asphalt concrete during this time.

Since thermal stresses in the stress-strain state of a thin layer of asphalt on a rigid base have two functions: tangential stresses at the contact of layers and horizontal stresses at the bottom of asphalt concrete, then by accepted principle of superposition:

- tangential stresses at the contact of layers:

  \[ \sum \tau = \tau_p + \tau_a \delta \quad , \]  

  where \( \tau_p \) – shear stresses at the contact of layers caused by the calculated (external) load, MPa; \( \tau_a \delta \) – tangential stresses at the contact of layers caused by thermal deformation, MPa.

- horizontal stresses on the lower surface of asphalt layer:

  \[ \sum \sigma = \sigma_p + \sigma_a \delta \quad , \]  

  where \( \sigma_p \) – the total horizontal stresses in the asphalt concrete layer caused by the calculated (external) load along axes “X” and “Y” in the Cartesian coordinate system, MPa; \( \sigma_a \delta \) – total horizontal thermal stresses in the asphalt layer caused by unrealized deformation along axes “X” and “Y” in the Cartesian coordinate system, MPa.

6. Calculation of the asphalt layer on a rigid base with simultaneous action of external load and thermal stresses by strength criteria

Structural failure of the material in any state of stress occurs when the value of the most hazardous factor reaches its limit. Adoption of the strength criterion makes it possible to compare a complex stress-strain state with a simple one (tension or compression) and set the safety factor.
For the asphalt concrete layer on a rigid base there were selected strength criteria, according to which there should be carried out calculations on the basis of obtained intensities of internal forces.

Asphalt layers are treated as monolithic visco-elastic-plastic ones, for which there is provided strength when exposed to external loads. In this case, the structure (asphalt layers) under the action of internal forces must behave as an elastic or visco-elastic body, which is in the process of initial distortion and high consumer quality of the coverage will be provided.

Under the influence of the external load and temperature deformation separation of the asphalt concrete layer of cement concrete slab is possible, since tangential stresses act at the contact of layers. Loss of traction leads to rapid destruction of the asphalt concrete layer. Design according to the criterion of ensuring adhesion at the contact of the asphalt concrete layer and cement concrete slab lies in comparing the active tangential stresses at the contact of layer with the strength of the shear contact (Ryapuhin et al. 2013):

\[ \Sigma \tau \leq \frac{\tau_k}{K_z}, \]  
(5)

where \( \Sigma \tau \) – Active tangential stresses at the contact of layers (Formula 3), MPa; \( \tau_k \) – Long-term shear strength at the contact of layers, MPa; \( K_z \) – the safety factor.

Upon cooling there can occur cracks in the asphalt layer.

The criterion of strength will be the tensile strength of asphalt concrete at temperature compression of plates and external load action. The condition of the tensile strength of asphalt layer on a rigid base at cooling (temperature fracture toughness) is expressed by (Ryapuhin et al. 2013):

\[ \sigma^t_x \leq \frac{R}{K_z}, \]  
(6)

where \( \sigma^t_x \) – active horizontal tensile stresses in the asphaltic concrete at the appropriate temperature, MPa; \( R \) – long-term tensile strength of the asphalt concrete layer under bending at appropriate temperature, MPa; \( K_z \) – the safety factor.

The plastic state of the asphalt concrete layer is characterized by deformations in the form of a tracks, sagging, and shifts. Taking into account the structural and textural features of the asphalt concrete as a rigid body, the generalized theory of Pisarenko-Lebedev (second) should be recognized to be the most appropriate one. Strength condition (Ryapuhin et al. 2013):

\[ \chi \sigma_{u} + (1 - \chi) \sigma_{1} A \left( \frac{3\sigma_{tp}}{\sigma_{u}} \right) < |\sigma^t|, \]  
(7)

\[ \chi = \frac{R_{\text{tens}}}{R_{\text{com}}}, \]  
(8)

where \( R_{\text{tens}} \) – asphalt concrete tensile strength, MPa; \( R_{\text{com}} \) – compressive strength of asphalt concrete MPa; \( \sigma_{u} \) – equivalent of strain according to the IVth theory of strength, MPa; \( |\sigma^t| \) – boundary stresses at simple compression; \( \sigma_{1} \) – principal stress, MPa; \( A \) – constant, which depends on the nature of defects present in the material, i.e. reflects the statistics of structurally inhomogeneous material.

\[ A = \frac{\frac{R_{\text{tens}}}{\tau_k} - 1,732 \cdot \chi}{1 - \chi}, \]  
(9)
where $\tau_k$ – the torsion strength of asphalt concrete, MPa.

At combined action of external load and temperature deformation one should take into account the changes of stress components $\Sigma \tau_{xz}$, $\Sigma \tau_{yz}$, $\Sigma \sigma_x$, $\Sigma \sigma_y$, which the value of principal stresses $\sigma_1$, $\sigma_2$, $\sigma_3$ will depend on. Specified principal stresses caused by the action of complex load are proposed to be determined from the known equation of the theory of elasticity (Bezukhov 1961):

\[
\sigma^3 - \sigma^2 \left( \sigma_x + \sigma_y + \sigma_z \right) + \sigma \left( \sigma_x \sigma_y + \sigma_y \sigma_z + \sigma_z \sigma_x \right) - \tau^2_{xz} - \tau^2_{yz} - \tau^2_{xy} - \tau^2_{\alpha} - \sigma_x \tau_{\alpha x} - \sigma_y \tau_{\alpha y} - \sigma_z \tau_{\alpha z} = 0.
\]  

Substituting in formula (9) certain numerical values of stress $\sigma$, $\Sigma \sigma_x$, $\Sigma \sigma_y$, $\Sigma \tau_{xz}$, $\Sigma \tau_{yz}$, $\Sigma \tau_{xy}$, we obtain a simplified cubic equation due to the simultaneous action of external load and temperature deformation:

\[
\sigma^3 + a \sigma^2 + b \sigma + c = 0.
\]  

Roots of the equation (11) will be the main stresses, which are necessary to know to calculate according to the criterion of strength of Pisarenko-Lebedev (second).

To test the validity of estimations according to the adopted criteria there was performed the estimation of strength of asphalt layers of a particular road section of highway R-51 (Kharkiv–Krasnograd–Pereschepine). The actual state of the asphalt pavement and the evaluation results are the same. In areas where they revealed insufficient adhesion (separation) of the lower layer of coating with the base, formation of rutting at the depth of more than 30 mm, the occurrence of transverse and longitudinal cracks it was proved by calculation that the structural strength against shift, resistance to cracking or adhesion strength of layers contact were not provided.

7. Conclusions

1. Stresses that arise from the action of thermal deformation, have two functions: they are horizontal stresses in the lower plane of the asphalt concrete layer and tangential stresses at the contact of asphalt concrete layer and cement concrete slab.

2. To account the simultaneous action of external load and temperature deformation, the principle of superposition is generally accepted, according to which stresses caused by a variety of factors (external load and thermal deformation) are determined separately based on the time of action and summed. Based on the accepted principle of superposition there is presented a generalized solution, which is used to determine stresses in the asphalt layer on cement concrete slab under the simultaneous action of temperature deformation and external load.

3. The criteria of strength of the asphalt layer on cement concrete slab on the adhesion strength of layers contact, shear-resistance and crack strength are determined.

4. It was established that in order to perform calculations of asphalt layers on a rigid base according to the criteria of strength it is necessary to determine the complete stress tensor caused not only by the action of the external load, but also take into account the horizontal and tangential thermal stresses in the asphalt layer.

References


