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Method for Determining Temperature Stresses in Asphalt Concrete Using the Finite Element Method

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Abstract: *A method for determining temperature stresses in asphalt concrete based on a finite element model is proposed. The possibility of rapid assessment of temperature stresses in asphalt concrete with the possibility of predicting low-temperature cracks is shown.*

Keywords: *asphalt concrete, bitumen, elastic modulus, relaxation modulus, finite element method, stress-strain state.*

Introduction. In asphalt concrete pavement, temperature stresses occur during cooling due to the friction of the asphalt concrete layer with the underlying base, which counteracts compression. If the temperature stresses reach the values of the tensile strength of asphalt concrete, cracks are formed perpendicular to the axis of the road, with approximately the same interval (4-100 m). These cracks serve as foci of migration of moisture and deicing reagents in the base with the formation of ice lenses and subsequently with the localization of destruction.

The formation of temperature cracks is one of the main types of destruction of the road surface, therefore, the prediction of crack formation, the correct calculation of pavement structures and the choice of materials according to the crack resistance criterion remains an urgent task.

Analysis of publications. Approaches related to the prediction of the formation of temperature cracks in asphalt concrete coatings can be divided into three groups: 1 - regression equations; 2 – mechanical models; 3 – laboratory tests. An example of the first group is the equation relating the distances between transverse temperature cracks with the properties of the material, the thickness of the asphalt concrete coating, and the minimum cooling temperature [1]. The second group includes mathematical models describing the mechanical behavior of asphalt concrete with a prehistory, for example [2, 3]. For the third group, out of the whole variety of devices and methods that determine the temperature stresses and the temperature of cracking of asphalt concrete, an example of a technique for determining the coefficient of thermal crack resistance of asphalt concrete can be presented [4].

Objective and statement of the task. The purpose of this work was to determine the stress-strain state inside the volume of asphalt concrete during its cooling on the basis of a two-composite volume model using the method of finite elements.

For an elastic material, temperature stresses are determined by unrealized deformation when the temperature changes ΔT

$$\sigma_x = E\alpha\Delta T \quad (1)$$

where α is the coefficient of linear temperature deformation.

The features of the solution for viscoelastic material are as follows. A change in temperature on dT in the time interval $d\tau$ leads to a change in deformation

$$d\varepsilon_x(\tau) = \alpha dT \quad (2)$$

Temperature deformation is not realized and therefore there is a stress

$$d\sigma_x(\tau) = E(\tau)d\varepsilon_x(\tau) \qquad (3)$$

where $E(\tau)$ is the relaxation modulus of a viscoelastic material.

To find the voltage in the rod at time *t*, sum up its increments for all previous moments of time [2]

$$\sigma_x = \int_{t_0}^{t} E(\tau)\alpha\left[\frac{d}{d\tau}T(\tau)\right]dt \qquad (4)$$

where $\tau = t_2 - t_1$ is the difference between the current and the previous time; $\frac{d}{d\tau}T(\tau)$ - the rate of temperature change v.

The coefficient α is taken as a constant value. In the case when the coefficient of linear temperature deformation is not a constant value when the temperature changes from T_0 to T, its average value can be taken by the formula

$$\alpha = \frac{\int_{T_0}^{T}\alpha(T)\,dT}{T - T_0} \qquad (5)$$

This approach is adopted based on the fact that when the temperature changes (from the initial to the final), the material can move from one physical state to another, each of which is characterized by certain physical indicators.

If the rate of temperature change is constant, then the stresses in the rod are determined by a simpler formula

$$\sigma_x = \alpha v \int_{t_0}^{t} E(\tau)dt \qquad (6)$$

where $\int_{t_0}^{t} E(\tau)dt$ – the sum of relaxation modules over time *t*.

There are formulas for determining the relaxation modulus of bitumen as a viscoelastic material, depending on its viscosity and the duration of the load [5].

Research methodology. A beam made of asphalt concrete as a composite material is considered. The composite consists of cubes of stone material and a binder bitumen. An axisymmetric problem is proposed (Fig. 1). The beam has restrictions of movement along the ends, the temperature is constant in thickness and varies over time. It is required to determine the average stress in the beam in time $\sigma_x(t)$, as well as stress concentrations in the material itself from the heterogeneity of the structure at a constant cooling rate *v*.

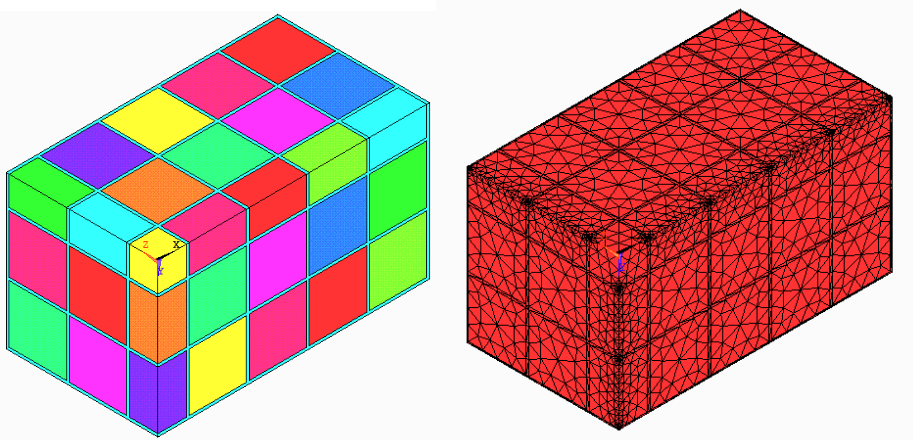

Fig. 1. Geometrical and technical model of asphalt concrete.

The initial is considered (at temperature T_0 at time t_0) and final states of asphalt concrete (at temperature T at time t) are considered.

The proposed model of asphalt concrete as a composite consisting of elastic stone (mineral) materials and viscoelastic bitumen binder is characterized by a different set of physical indicators. For stone materials, these are the modulus of elasticity E, the coefficient of transverse deformation μ and the coefficient of linear temperature deformation α. For bitumen, this is the average relaxation modulus E_a, determined by the formula (7), the coefficient of transverse deformation μ and the coefficient of linear temperature deformation α, determined by the formula (5). The average relaxation modulus of bitumen was calculated as

$$E_a = \frac{\nu \int_{t_0}^{t} E(\tau)dt}{\Delta T} \qquad (7)$$

then formula (6) took the form similar to formula (1) for an elastic material

$$\sigma_x = E_a \alpha \Delta T \qquad (8)$$

The physical parameters of the asphalt concrete components E, E_a, μ and α were entered as input data for calculation into the ANSYS software package. The calculation of temperature stresses in asphalt concrete was carried out both for structures where its elements had different material properties. The calculation results were internal stresses in the volume of the asphalt concrete sample.

Results. The results of the calculation of temperature stresses based on the following initial data are obtained. The geometric model (Fig.1) has dimensions: cubes with an edge of 5 mm, the distance between them is 0.25 mm. Volume fractions of a two–phase system: bitumen – C_1=0.157 and stone material – C_2=0.843.

Consider the properties of the materials used for the calculation. Bitumen grade 50/70 (according to EN standards, the middle of the penetration interval is 60 1/10 mm and the middle of the softening temperature interval is 50 ° C), the penetration index is minus 0.8. The coefficient of linear temperature deformation α for bitumen is $2{\cdot}10^{-4}$; for stone material – $1{\cdot}10^{-5}$; the coefficient of transverse deformation μ for bitumen – 0.45, for stone material – 0.15. The modulus of elasticity of the stone material is 50,000 MPa. The relaxation modulus of bitumen was determined by the formulas [5]. According to the TSRST method included in the standard [6], the temperature decreased at a constant rate of 10 degrees per hour.

Figure 2 shows the calculated average temperature stresses in asphalt concrete during cooling (curve 3) and stresses obtained by different authors during laboratory tests using the TSRST method (curve 1 and 2).

The analysis of the obtained data shows that the calculated values of the average stresses are less than the experimental ones obtained by different authors for bitumen of the same brand. The calculated and experimental curves do not coincide in temperature by an average of 5 °C. Perhaps this is due to the fact that part of the bitumen in asphalt concrete is in a structured state, with a much higher viscosity than in the free state, and this should be taken into account when entering the initial data.

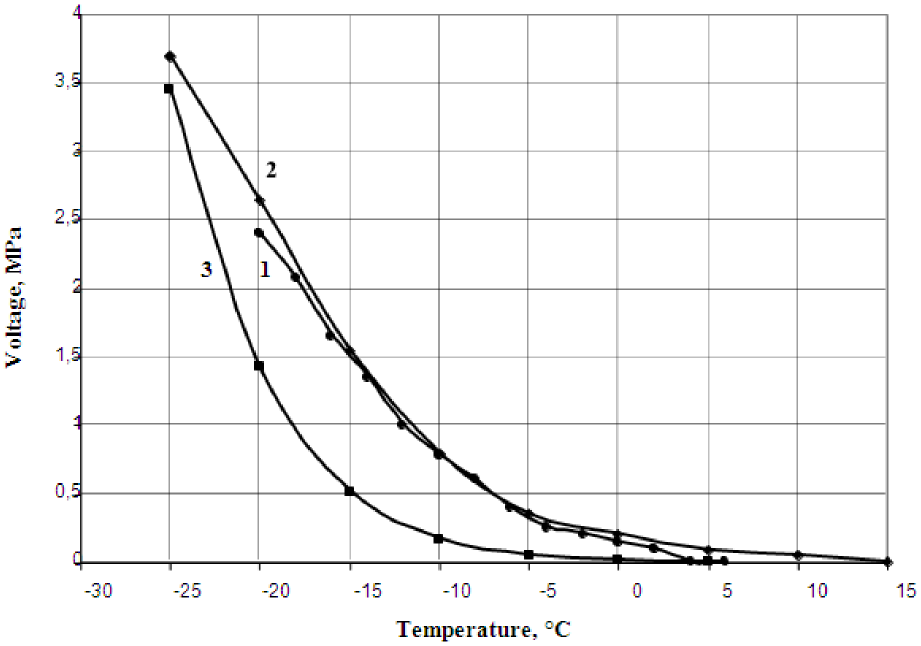

Fig. 2. Average temperature stresses in asphalt concrete on bitumen 50/70 when cooled by the TSRST method: 1 – according to [7]; 2 – according to the bitumen content is 5.6%; 3 – even values.

The distribution of tensile temperature stresses within the volume of the asphalt concrete model is shown in Fig. 3.

For the accepted geometry of stone materials, the stress concentration coefficient in the zones of sharp changes in the shape of inclusions reaches a value of 2.

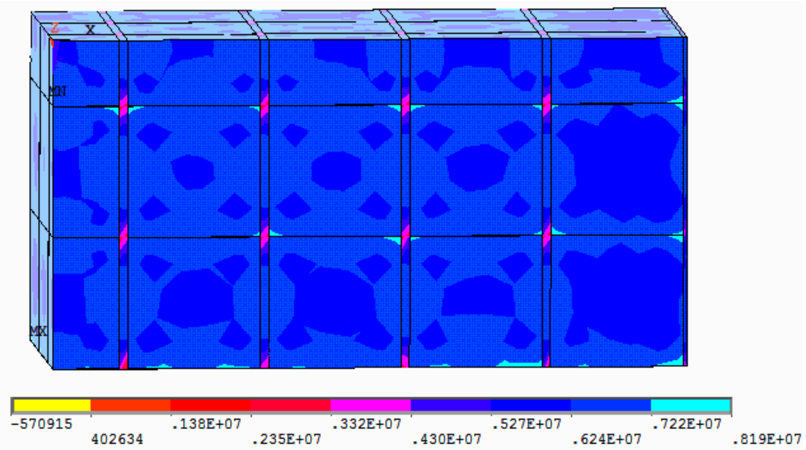

Fig. 3. Distribution of tensile stresses along the beam.

Conclusions. A method for determining temperature stresses in asphalt concrete, taking into account the background, is proposed for its implementation in the ANSYS software package with the possibility of determining temperature stresses within the volume of asphalt concrete.

The discrepancy between the calculated and experimental data is shown, which may be due to the lack of taking into account the increase in the viscosity of a part of bitumen in a structured state in asphalt. Such accounting can be implemented on the basis of new experiments to determine the viscosity of structured bitumen.

Based on the finite element analysis of the stress-deformed state of asphalt concrete using the proposed method, it is possible to determine stress concentrations inside the viscoelastic material during cooling. So, for the accepted geometric model of asphalt concrete, stress concentrations reached a value of 2.

The proposed method can be considered as a simple tool for rapid assessment of temperature stresses and can be used as a prediction of low-temperature cracks in the asphalt concrete pavement of highways.

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