Conditions modelling of low-temperature cracks existence in the road upper layer

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Abstract. Cracks, including low-temperature cracks, reduce to the greatest extent road surfaces quality, increase the cost their repair. This problem is most relevant in the regions with seasonal soil freezing. The purpose of this study is to develop a model of interaction between the asphalt concrete layer and the underlying layer by means of friction and adhesion forces at a negative temperature, also the analyze the conditions low-temperature cracks formation of in the asphalt concrete layer, in order to reduce the risk of cracking. Methods: as a research tool used numerical methods of structural mechanics. Results: the study found that the distribution of tensile forces in the segment of an asphalt-concrete layer is approximated by a polynomial of the second order with a maximum in the middle of the length of the segment. Shear forces are unevenly distributed along the length of the segment; the intensity of the shear forces is equal to zero in the middle of the length of the segment. The greatest shear strains and stresses are localized near the transverse boundaries of the segment of the layer. A shear deformation can lead to an increase in the crack width. The validity of the numerical simulation results is confirmed by their consistency with the known analytical solution of the same problem.

1. Introduction
Cracks, including low-temperature cracks, reduce to the greatest extent road surfaces quality, increase the cost their repair. This problem is most relevant in the regions with seasonal soil freezing [1, 2]. The analysis of the literature showed that, despite numerous studies, reviews of which can be found in articles [3–9], the interdisciplinary problem of low-temperature cracking remains relevant and requires further research.

Why is it important for practice to prevent low-temperature cracks? In the vicinity of the crack, the heat exchange conditions change substantially [4]. In addition, if the cracks are left open, then during thawing, water penetrates into the underlying layer, creating additional conditions for the deterioration of the road structure. Dynamic influences are also increasing in the vicinity of the transverse crack during the movement of vehicles (in analogy with the rolling of a railway wheel through rails joint). As a result, the quality of the road structure is reduced, the speed of vehicle traffic in problem areas is reduced too, fuel consumption for cars is increased, and their wear is accelerated [3]. Thus, the problem includes technical, technological and environmental aspects, discussed in more detail in article [1].

To lessen the severity of this problem, one can reduce the effect of cyclic temperature changes on the degradation of the upper layer of the road, which requires a sufficiently clear understanding of the components interaction of the road structure and the causes of destruction. A methodologically important result of the research in this area is the classification of cracks. The authors of the article [4] distinguish five cracks types, of which we only low-temperature cracks the very will consider. The
reason for their appearance is associated with tensile deformations and stresses in the coating material due to a significant decrease in its temperature.

Low-temperature cracks appear, as a rule, a few years after completion of the road construction, which is explained by the gradual degradation of bitumen and a decrease in its adhesion to the mineral component, as well as the accumulation of microcracks [6, 10, 11]. It is important to note that low-temperature cracks are oriented across the road; the step of the cracks depends on many factors and can be, for example, in the range from 2 to 25 m [4, 6, 8, 9].

The analysis of modern ideas about the causes of cracks in the road surfaces is given in [1, 4, 6, 7, 10, 11]. The authors of the articles [4, 6] note that to date, a number of important results have been obtained, but there is no sufficiently effective solution to the complex problem of cracks in road structures. At the same time, it is stated that in order to increase the service life of road surfaces, it is advisable to consider the crack resistance of the road surface as one of the main criteria for the quality of the road [1, 4].

It is possible to allocate at least two ways to increase the fracture toughness, namely: the development and application of new asphalt mixes [1, 6, 11]; optimization of geometrical and physical layer parameters such as thickness, distance between the temperature seams (if any), the coefficients of friction and adhesion of layers [1, 12–14].

The choice of goals objectives and methods in our work is limited and focused on the challenges of the second of the areas denoted above. This area includes a large number of studies, and in time, the number of publications is growing, due to the urgency of the problem and its complexity.

Literature analysis showed that in the studies of low-temperature cracking of an asphalt layer, one-two- and three-dimensional models are used [13, 15–22]. As it has been noted, the tensile stress acting in the longitudinal direction of the road, leads to the appearance of the transverse cracks. The developers of the mathematical models of road surfaces take into account that if the cracks are parallel to each other, then from the point of view of mechanics it is possible to consider the deformable rod as a one-dimensional model of the segment of the asphalt concrete layer [8, 9, 15]. Analysis of the literature showed that from the point of view of methodology and taking into account the current state of computer technology, the known model [15] has certain prospects for development, if we use the rod approximation method in the problems of analysis of the stress-strain state of rod and continuum systems [16]. First of all, it is necessary to simplify the model, since nonlinear equations complicate the problem [15]. Methodologically, this means that one of the contradictions of mathematical modeling will be taken into account. Namely, on the one hand, it is necessary to ensure a sufficiently high accuracy of the numerical result; on the other hand, modeling methods should not be too complex. In this regard, it is necessary to pay attention to the insufficiently studied possibilities of application of methods of construction mechanics for modeling the condition of road surfaces. Our work is based on the assumption that the application of the above approximation [16], as well as numerical methods of structural mechanics, will simplify the modeling technique and make it more universal.

Thus, the purpose of this study is to develop a model of interaction between the asphalt concrete layer and the underlying layer by means of friction and adhesion forces at a negative temperature, also to analyze the conditions low-temperature cracks formation of in the asphalt concrete layer and to justify the possibility of reducing cracking.

Object of the research: a segment of an asphalt-concrete layer interacting with the underlying layer by means of frictional forces and adhesion at a negative temperature.

Subject of the research: patterns in the distribution of tensile forces and shear forces along the length of the segment.

2. Discrete model of interaction of asphalt-concrete layer with a base
Consider the part of an asphalt-concrete layer in width B and thickness H. The length of the segment is equal to the distance between the cracks \( L = 2l \) (Figure 1). Asphalt concrete is considered as an isotropic material for which the modulus of elasticity, the Poisson's ratio and the coefficient of thermal
expansion are, respectively, $E$, $v$ and $\alpha$. Numerical values of these parameters can be found in the literature [6, 8, 9–13, 21–25]. An asphalt concrete layer rests on a fixed base layer of thickness $H_0$.

Note that the models in the form of a rod system [16] are acceptable for the analysis of a sufficiently wide class of mechanical systems. However, without prejudice to the universality of the approach, this paper considers only the effect of temperature on the mechanical system in the form of a rod that elastically interacts with the base, while the forces of elastic interaction are oriented in a horizontal direction parallel to the axis of the rod. In this class of problems, from the point of view of practice, the greatest interest is the problem of the greatest distance between low-temperature cracks. Because by solving this problem, we will be able to determine the conditions under which the distance between the low-temperature cracks will be the maximum possible. This means that the number of such cracks will be minimal, which is important to ensure the quality and durability of the road surface [1, 3, 4, 6, 25, 26].

From the theoretical point of view, the choice of this problem is explained by the possibility of comparing the results and validating the numerical solution proposed in this article using the known analytical solution of the same problem [27, 28]. The numerical solution method in this case extends the set of tools for predicting the state and improving the design solutions of roads by minimizing the number of low-temperature cracks, as noted above. Continuing the analysis, we note the following.

With decreasing ambient temperature, an asphalt-concrete layer undergoes greater deformation than the underlying layer; while an asphalt-concrete layer is subjected to stretching, since the friction and adhesion forces with the underlying layer resist the reduction in its length.

As well known, two types of deformations arise at temperature impact on the rod: axial deformation and bending. Thermal analysis out in a linear formulation is carried usually and, in accordance with the superposition principle, the initial problem is decomposed into two subtasks: in one subtask only the axial deformation is taken into account (the temperature on thickness is constant and equal to the average temperature of the layer); in another subtask, only bending deformations are taken into account (when the temperature is zero at the points of the rod axis, but the temperature values at the upper and lower boundary of the layer are equal in modulus and opposite in sign).

When tensile stresses in the layer of asphalt concrete reach the limit of its strength, a fracture occurs and a crack appears. Resistance to shear is provided by forces $T$ that are distributed over the contact area of the layers and depend on the friction and adhesion of the layers (Figure 1.2). The interaction of the layers at their shear is modeled by set of vertical elastic rods of length $H_0$ and flexural stiffness $E_0I_0$, settled in increments of $\Delta x$ (Figure 1). The definition of flexural rigidity $E_0I_0$ is considered below (formulas (1) and (2)).

It is assumed that the thickness of the layer $H$ is small enough to neglect the uneven distribution of temperature, strains and stress along the thickness of this layer (Figure 1.3).

The model is more realistic if there are more discrete supports, i.e. the smaller $\Delta x$. The shear force $T$ (Figure 1.2) is equal to the transverse force $Q$ in the vertical rod when it is bent. The bending moment $M$ is related by the well-known relations of the mechanics of structures with displacement $u$. 

![Figure 1. Model of an asphalt-concrete layer of thickness $H$ on discrete supports.](image-url)
and transverse force $Q$. As it is known, the transverse force $Q$ is equal to the first derivative of the bending moment $M$ in the direction of the longitudinal axis of the beam (in this case along the axe $y$).

The bending stiffness of vertical rod (as springs) is $C = T / u$ (N/m). On the other hand, the bending stiffness $s = E_0 I_0$ of the same spring and the displacement $u = TH_0^2 / 3E_0 I_0$ are related by the well-known ratio of structural mechanics. Then

$$E_0 I_0 = CH_0^2 / 3.$$  \hfill (1)

In real construction, the spring leaf stiffness is distributed over the contact area of the asphalt-concrete layer with the underlying layer $a = \Delta x B$, where $B$ is the width of the asphalt-concrete layer (Figure 1.3). Let $c$ (N/m$^2$) be the stiffness distributed over the area $a$. Then $C = c \Delta x B$ and taking into account (1) we obtain:

$$E_0 I_0 = c \Delta x B H_0^2 / 3.$$  \hfill (2)

Note, that the numerical implementation of the proposed model does not require the knowledge of the separately taken elasticity modulus $E_0$ values of the vertical rod material (Figure 1.2) and the moment of the cross-section inertia $I_0$ of the same rod. We use the fact that for the calculations using the displacement method known in construction mechanics [16], it is sufficient to know only the product $E_0 I_0 = s$ (2). In this case, the values of $c, \Delta x, B, H_0$ used in the formula (2), along with other parameters of the model (Figure 1), should be indicated in the initial data, as shown in the following example.

Taking into account the above explanations, let us consider an example of numerical simulation. Let $L = 2l = 12$ m, $\Delta x = 2$ m. Using data known from scientific publications, we accept: the width of the road is $B = 10$ m, the thickness of an asphalt concrete layer is $H = 0.2$ m, the stiffness distributed over the area is $c = 416$ MN/m$^2$ [15]; $H_0 = 1$ m; the coefficient of asphaltic concrete thermal expansion is $\alpha = 2.2 \cdot 10^{-5}$ (1/°C). The stretching tensile strength of asphalt concrete at $t = -20$ °C was determined by the well-known formula [29], obtained as the result of theoretical and experimental studies:

$$\sigma_t = 4.015 \exp (-0.042t) = 4.015 \exp (-0.042(-20)) = 9.300 \text{ MPa}.$$  \hfill (3)

Asphaltic concrete elasticity modulus is $E = 12500$ MPa at $t = -20$ °C. In the case under consideration $\Delta x = 2$ m (Figure 1).

Cross-sectional area of an asphalt concrete layer is $A = BH$, tensile rigidity $EA = 12500 \cdot 10^6 \cdot 10 \cdot 0.2 = 25$ GPa. The flexural rigidity of leaf springs according to (2) is equal to $E_0 I_0 = 2773333333$ Nm$^2$ (Figure 1.2).

The data presented above is sufficient to find numerically the forces in the rods by the methods of structural mechanics, as well as to determine the movements of the nodes in the construction as shown in Figure 1. In this paper, the corresponding calculations are performed according to the POLE program [23], in which the displacement method is implemented. Let’s consider the results of the calculations.

The results of the calculations are presented in graphical form. The distribution of tensile forces $N$ that cause stretching of the asphalt-concrete layer is shown in Figure 2.

![Figure 2. Distribution of tensile forces $N$ (MN).](image-url)
For the asphalt-concrete layer, the forces $T$ are shear forces (Figure 1). On the other hand, they are equal to the transverse forces $Q$ in vertical rods when bent (Figure 1.2). The transverse forces $Q$ are connected by the equilibrium conditions of the nodes with tensile forces $N$ (Figure 2). To determine the transverse forces $Q$, we use the above program. The results of the calculations are presented in the graphical form (Figure 3).

![Figure 3. The distribution of shear forces $T$ (MN).](image)

Taking into account that the support rods are a discrete model of a continuous medium (Figure 1), for each segment $\Delta x$ it can be written $\Delta N = \Delta Q = \Delta T$, where $\Delta Q$ is the transverse force in a single support rod. Equality $\Delta N = \Delta Q$ is illustrated by the data in Figure 1 and Figure 3. Thus, the intensity of the shear forces is $q_T = \Delta Q / \Delta x = \Delta T / \Delta x = \Delta N / \Delta x$. With $\Delta x \to 0$ we get

$$ q_T = dN/dx. $$

(4)

Ratio (4) is an analog of the well-known Zhuravsky formula, which determines a differential relationship between the lateral force and the intensity of the lateral load on the beam.

In the example considered, the results of the calculations show a change in the tensile forces $N$ and shear force intensity $q_T$ for a 12 m asphalt-concrete layer (Figure 4). The distribution of tensile forces $N$ in the asphalt concrete layer is adequately modeled by a polynomial of the second degree. The intensity of the shear forces $q_T$ varies linearly.

![Figure 4. Tensile forces and intensity of shear forces $q_T$.](image)

It is important to emphasize that the numerical solution considered above is the first approximation. To get an idea of the accuracy of the solution, it is necessary to perform a second approximation. According to the recommendations known in the numerical analysis, the result is sufficiently accurate if the discrepancy between the new and previous approximations is small, to do this, we increase the number of discrete supports by half and, correspondingly, reduce $\Delta x$ twice and flexural stiffness (2). The new scheme for $\Delta x = 1$ m is shown in Figure 5. The results of the calculations for the above method are shown in Figure 6.
Figure 5. Scheme for the second approximation.

Figure 6. Tensile forces $N$ and intensity of shear forces $q_T$ (the second approximation).

The comparison of the data obtained (Figure 4 and Figure 6) shows that the results of the new approximation do not differ from the results of the previous one. Consequently, the solution obtained can be considered as sufficiently accurate for further analysis of the strength and deformations of an asphalt-concrete layer.

Note that the amount of calculations and the accuracy of the numerical simulation result usually depends on the fact how well the calculation scheme has been chosen from the physical point of view. For example, if the support rods in the construction of Figure 1 are set at points with the coordinates $x = 0; \Delta x; 2\Delta x; \ldots$, then with $\Delta x = 2\text{ m}, 1\text{ m}$ and $0.5\text{ m}$ we will get $N_{\text{max}} = 43.930, 38.438$ and $35.693\text{ MN}$. In this case, the discrepancy between the first and second, second and third approximations is 14 and 7\%, respectively. Slow convergence and inadequacy of such a computational scheme is due to the fact that in the support rods at $x = 0$ and $x = 2l$ with transverse forces appear. They are transformed into tensile forces acting on an asphalt-concrete layer. However, in a real asphalt-concrete layer with $x = 0$ and $x = 2l$ there are no tensile forces. Thus, the 2 model according to the Figure 1 with support rods at the coordinate’s points $x = 0.5\Delta x; 1.5\Delta x; 2.5\Delta x; \ldots$ is adequate from the physical point of view. It is confirmed by the accuracy of the results obtained with relatively low computational resources costs (Figure 6).

3. Determination of the cracking temperature in an asphalt-concrete layer

Let us check whether the strength condition of an asphalt-concrete layer is met when stretching. The maximum tensile force occurs in the middle of the plot (Figure 4) $N_{\text{max}} = 32.947 \cdot 10^6\text{ N}$. As defined above, the cross-sectional area of an asphalt-concrete layer is $A = BH = 10 \cdot 0.2 = 2\text{ m}^2$. We will write taking into account (3):

$$y = -0.9167x^2 + 11.007x - 0.0834$$

$$R^2 = 1$$

$$y = -1.8304x + 10.982$$

$$R^2 = 1$$
This means that the strength condition is not met and a new crack appears in the asphalt-concrete layer with $x = 6$ m (Figure 1). Therefore, the next cycle of the calculations considered has to be repeated, reducing the segment length and flexural stiffness (2) by half. The corresponding results of the calculations are analyzed below in a separate section of this paper.

Let us determine the lowest temperature $t^*$ at which the strength condition is met and a crack does not appear. The above value $\sigma_{\text{max}} = 16.474$ MPa corresponds to the temperature $t = -20$ °C. The stress $\sigma_{\text{max}}$ in the model under consideration is directly proportional to the temperature change $t$: the temperature $t = t^* < 0$ corresponds to $\sigma_{\text{max}} = 16.474 t^*/(-20)$. However, according to formula (3), the strength of asphalt concrete $\sigma_t$ decreases exponentially with the increasing temperature. Taking into account ratio (3), we will write the strength condition $\sigma_{\text{max}} = \sigma_{\text{max}}^t \leq \sigma_t$ in the form of a non-strict inequality $16.474 t^*/(-20) \leq 4.015 \exp(-0.042 t^*)$. Solving this inequality $t^* \geq -6.37$ °C predicts the temperature at which a crack does not appear. Accordingly, when $t = t^* = -6.37$ °C we find $\sigma_{\text{max}} = 16.474t^*/(-20) = 5.247$ MPa, $N_{\text{max}} = 10.49$ MN. The right-hand side of the inequality, i.e. the strength of asphalt concrete at $t = -6.37$ °C in accordance with formula (3) is equal to $\sigma_t = 5.247$ MPa. The crack width at $t < -6.19$ °C is the greater, the lower the temperature is.

4. Special features of shear forces $T$ distribution in an asphalt-concrete layer

Beside the cracks, another important event in the simulated interaction of road structure layers can be the slip of one layer relative to another in the area of their contact where the greatest shear forces act [11]. As noted above, with a low-temperature action, slippage of one layer relative to another one causes an increase in the width of the crack.

It should be noted that the greatest shear forces $T$, and therefore the greatest shear stresses $\tau \approx T / (\Delta x \cdot B)$ occur at the beginning and at the end of the segment (Figure 5). The experimental data known from scientific literature [13] shows that as the effect on the asphalt-concrete layer increases, the shear stresses $\tau$ linearly increase to a certain value $\tau_0$ (the so-called stationary value). Then the shear stress $\tau$ remains at the level $\tau_0$ (Figure 5).

Values known from scientific literature $\tau_0$ and $u_0$ are very variable, and, for example, can have values, from the intervals [0.008, 0.106] MPa and [0.025, 1.400] mm respectively [12, p. 456]. The distribution of shear displacements in the model under consideration (Figure 1) is determined by the above program [23] and is shown in Figure 8, the greatest displacement being $u = 2.64$ mm. Therefore, if we take $u_0 = 1.40$ mm, then slippage will occur in the two intervals of the values $x = [0.00, 3.00]$ and $x = [9.00, 12.00]$ m.
Taking into account that in this case the displacement $u$ is directly proportional to the change in temperature, we determine the lowest temperature at which there will be no slipping:

$$t \geq \left( \frac{1.40}{2.64} \right) \cdot (-20) = -10.61 \, ^\circ C.$$  However, if the temperature decreases from zero to $-10.61 \, ^\circ C$, then taking into account the analysis performed above, we get that when $(-10.61) < t < (-6.37) \, ^\circ C$ a low-temperature crack appears in the middle of the segment shown in Figure 1. The width of the crack will increase in proportion to the decrease in temperature. If the temperature is lower than $-10.61 \, ^\circ C$, then, according to Figure 6, shear forces $T$ will not increase with a further increase in displacement $u$ (i.e., with a further decrease in temperature). Consequently, resistance to low-temperature deformations of the asphalt-concrete layer in the intervals $x = [0.00, 3.00]$ and $x = [9.00, 12.00]$ m indicated above will not grow, and that will slow the growth of tensile forces $N$ in the asphalt-concrete layer with a further decrease in temperature.

5. Model with a new (secondary) low-temperature crack

With a new low-temperature crack, the construction shown in Figure 5 breaks up into two substructures (Figure 9). The distribution of tensile forces $N$ and the intensity of shear forces $T$ in one of the substructures are shown in Figure 10.

By analogy with the method described above, we find $N_{\text{max}} = 8.237 \, \text{MN}$ (Figure 10). Note that reducing the segment length by half resulted in a fourfold decrease in the tensile forces $N$ compared to $32.947 \, \text{MN}$ (Figure 6). Thus, at $t = -20 \, ^\circ C$ we obtain, with the allowance for (3):

$$\sigma_{\text{max}} = \frac{N_{\text{max}}}{A} = 8.237 \cdot 10^6 / 2 = 4.118 \, \text{MPa} < \sigma_t = 9.300 \, \text{MPa}.$$  

Hence is a new crack will not appear at this temperature. The shear deformation $u$ of each substructure in the neighborhood of a new crack (Figure 9) will be 1.32 mm. And that is less than the...
above limitation \( u_0 = 1.4 \) mm (Figure 5). Thus, the width of the new crack will be equal to 2.64 mm. This value corresponds to \( t = -20 \) °C. Accordingly, if \( t = -40 \) °C, the crack width increases to \( 5.28 \approx 5.00 \) mm.

The calculations presented above show that the application of the developed model allows finding the largest segment length without cracks \( L_0 \) for a given negative temperature. So, if expansion joints with a step equal to \( L_0 \) are performed on the road surface, then theoretically new cracks in each of the segments does not appear. This means that the distance \( L_0 \) determines the optimal step of expansion joints. Indeed, if the step of the expansion joints is increased, a crack appears in the middle of the segment length at a sufficiently low temperature (the number of seams is insufficient). If the step of the expansion joints is reduced, a crack will not appear, but the number of expansion joints will increase and, accordingly, the cost of these joints will increase (the number of seams is excessive both from a technical and economic point of view).

![Graph](image)

**Figure 10.** Tensile forces \( N \) and intensity of shear forces \( T \) after the appearance of a new crack.

6. **Comparison with the results of other authors**

The above results of numerical simulation of a segment 12 m long and dividing it into two segments of 6 m in length each (Figure 9 and 10) are consistent with the scientific publication data. For example, at \( t = -40 \) °C «the spacing between these cracks ranges from 7 to 15 m. The crack opening displacement for the open cracks is around 5 mm» [9, p. 559].

There are also monitoring data for a number of asphalt concrete roads built in 2008. It was established in [6] that the average number of low-temperature cracks in asphalt-concrete coatings increases with increasing temperature drops to \( t = -18 \) °C and lower. In 2015, the average number of low-temperature cracks per 1 km was 76 in one road [6, p. 44]. Accordingly, the average distance between the cracks is 13.16 m, which does not contradict the results of numerical modeling given above by the proposed method.

The above results do not contradict the well-known analysis of temperature in asphalt layer [10]. However, this estimate was obtained on the assumption that the friction coefficient between the asphalt layer and the granular layer is equal 2 [8, p. 749]. In our case, friction and adhesion are taken into account in the ratio (2) by the coefficient \( c \), which is assumed to be \( c = 416 \) MN/m\(^3\) in the examples (Figure 2–6).

Thus, the developed model for the formation of conditions for the appearance of low-temperature cracks in an asphalt-concrete layer of the road structure makes it possible to obtain sufficiently reliable data. However, it must be taken into account that the averaged characteristics of the asphalt and the
underlying layer were used as the initial data. Other factors, not taken into consideration in this work, also affect the low-temperature destruction. For example, according to the scientific publications, it is known that the coefficient of thermal expansion as a characteristic of frozen soils depends on the temperature essentially [14, 30, 32]. Slippage of the layers is affected not only by friction, but also by adhesion [22, 26]. To reduce cracking, the strength of asphalt concrete can be increased by the use of additives and modifiers [31, 33–39].

One of the main criticisms of modern methods for simulating low-temperature cracks in asphalt-concrete coatings is that the change in the properties of materials over time in the life cycle of roads is not fully taken into account [1, 6, 21, 25]. In this connection, it seems expedient to use step-by-step algorithms, in which the physical and mechanical characteristics of road construction materials are adjusted at each step, depending on temperature and time [34, 35], taking into account the results known from the scientific publications [18, 40, 41]. Actually, the article proposed a procedure for calculating one step for such an algorithm, but detailing requires further research.

Nevertheless, although simplified assumptions were used in the model developed, numerical modeling has improved the understanding the distribution of tensile  \( N \) and shear forces  \( T \) acting on the asphalt-concrete layer at its negative temperature. In particular, it is possible to quantify the distance between low-temperature open cracks. The model developed can be adapted to the analysis of low-temperature cracks in coatings of various types, which, however, also requires further research.

The prospects for the study of the topic may be related to the following factors: the use of new materials [34–36], temperature crack resistance of asphalt [37], and low temperature strength of asphalt binders [19, 26], viscoelastic properties of asphalt [2] and asphalt mixtures containing different recycled asphalt materials [38, 42-46].

7. Conclusions
A discrete mechanistic model of conditions for the formation of low-temperature cracks in an asphalt-concrete layer with account of its interaction with the underlying layer of the road structure is developed. The proposed model is a two-dimensional bar system, the analysis of which is performed by the methods of structural mechanics, and the results of the analysis are adapted to solving the problem of low-temperature cracks of formation. The results of the above numerical analysis are corresponding to the analytical solution [27, 28] of the problem.

It is established that the distribution of tensile forces  \( N \) in the segment of an asphalt-concrete layer is approximated by a polynomial of the second order with a maximum in the middle of the length of the segment. It is shown that if the temperature decreases and a new crack appear, the maximum of the tensile forces decreases fourfold.

Model calculations show that shear forces  \( T \) are unevenly distributed along the length of the segment; the intensity of the shear forces  \( T \) is equal to zero in the middle of the length of the segment and increases modulo while moving away from the middle of the segment.

The greatest shear strains are localized in the neighborhood of the transverse boundaries of the asphalt-concrete layer model segment. Shear deformations and slippage of the upper layer lead to an increase in the width of the crack.

The application of the model developed allows us to find the largest segment length without cracks  \( L_0 \) for a given negative temperature. The practical relevance of this result is as follows: if transverse expansion seam with a step equal to  \( L_0 \) are made on the road surface, then theoretically, new cracks in each of the segments do not appear. However, models, as well as real road-building materials, technologies and designs are not ideal therefore it is possible only to reduce probability of emergence of low-temperature cracks and thereby to increase durability of roads.

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