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

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INFLUENCE OF THE LOAD-CARRYING CAPACITY OF VEHICLES WHEN PERFORMING REPAIR WORKS OF ROAD PAVEMENTS BY MEANS OF THE JET-INJECTION METHOD

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Statement of the problem. Upon the completion of repair works to eliminate defects such as potholes on non-rigid surfacing, traffic flow starts with no consideration given to the properties of a bitumen-mineral mix and load-carrying capacity of a traffic flow, which leads to the failure of the material in a surfacing pothole when applying the jet-injection method.
Results. The results of experimental studies on the effect of load on the rheological characteristics of bitumen-mineral mixtures are presented. The regularities between the strength and rheological characteristics of the bitumen-mineral mix taking into account the thickness of the mixture layer are established. According to the results of the experiment, the dependence of the compaction coefficient of the bitumen mineral mixture on the layer deformation under the action of the transport load was established. There are some restrictions on the carrying capacity of vehicles on the repair areas of a surfacing during the formation of the structure of the pothole material.
Conclusions. It is proved that the use of the jet-injection method in pothole repairs of a non-rigid surfacing does not provide the required characteristics of the material after it has been laid. To improve the quality of repairs, an additional compaction of a laid mixture in a pothole using vibration plates or vehicles with axial load limitation during the formation of the material structure in a pothole is required taking into account the properties of the bituminous mineral mix.

Keywords: jet-injection method, bituminous mineral mix, characteristics of a mix, transport load.

Introduction. An annual increase in the number of vehicles causes a surge in traffic accompanied by larger axial loads on pavements, which contributes to defects on non-rigid coatings

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taking the form of potholes. In order to increase the service life of pavements and ensure traffic safety, timely maintenance of pavements is needed. Otherwise there might be deterioration of surfacing thus requiring costly work to be performed in order to restore it [1—5, 7].

Presently, the most common way to eliminate defects occurring in non-rigid pavements taking the form of potholes is use of the jet-injection method, which is cost-efficient in terms of the amount of preparation needed. This method is referred to as a high-speed (operational) repair one: it takes much less time for work to be performed as opposed to traditional methods for patching surfacing (by means of cast and hot mixes). It has been found that from an economic standpoint, application of this method is more profitable compared to other methods of repairing potholes of a non-rigid surfacing [9—11, 13—20].

This method used to eliminate defects on non-rigid surfacing taking the form of chipping particles of the mix off a surfacing, sealing cracks and potholes with the depth of 0.01—0.02 m provides the required strength characteristics of the material in relation to transport loads.

It is generally considered that the advantage of the jet-injection method is the absence of a compaction process following laying of the material into a pothole of a roadway surfacing. To prove that, there is a fact that the bitumen-mineral mix (with the size of fractions from 2.5 to 10 mm) is fed into the pothole at the speed of 30—32 m/s from the height from a surfacing of 0.6 m and due to the energy of the particles there is a uniform and dense distribution and compaction of the laid material in the pothole.

The practical application of this method for repairing potholes that are more than 0.03 m deep has shown that due to the properties of the bitumen-mineral mix, heavy deformations cause plastic deformations in the laid layer of the material, which causes a decrease in the quality of repairs [6, 8].

1. Effect of traffic flow on the strength characteristics of the material inside the pothole. In order to identify the effect of heavy traffic loads on the strength characteristics of the material inside the pothole of a surfacing, samples were taken from surfacing areas where potholes were repaired using the jet-injection method in 2014 and 2015. Visual inspection revealed no external damage on the surface of the repaired potholes. It was found that the compressive strength of the samples ranged from 1.12 to 1.56 MPa, which was below the minimum value as required by GOST (ГОСТ) 9128-2009. The tensile strength of the samples at the temperature of 20 ºC corresponded to the compressive strength from 2.1 to 2.3 MPa, which meets the requirements of the GOST under discussion. Based on the results, it can be concluded that compaction of the bitumen-mineral mix even under transport loads does not always ensure a required density.

At the stage of the preparation of the bitumen-mineral mix, in order to ensure required characteristics of asphalt concrete in a surfacing pothole, the optimal granular and metric composition of crushed stone grains of the fraction of 2.5—10 mm was selected with a grade of at least 1200, wear grade I-1 and the content of dusty and clay particles not more than 1 %. As a cementitious material, a rapidly decaying cationic bitumen emulsion in a 60 % concentration (EBK-1), was employed. The optimum temperature of the bitumen emulsion was taken to be 71—80 °C.

In order to identify the effect of traffic intensity and axial vehicle load on the result of repairs to eliminate defects on non-rigid surfacing by means of the jet-injection method, a serial computer-controlled road machine Madrog Madpatcher was used (Fig. 1). The studies were carried out in during repairs of potholes on non-rigid pavements of the R-22 Caspian highway.

Fig. 1. Road machine Madrog Madpatcher

To ensure a specified layer thickness while laying the bitumen-mineral mix in the pothole of the pavement and to eliminate the influence of an uneven base of the pothole on the characteristics of the material during compaction caused by the movement of transport, the place of laying the mix was milled with a cold mill. Following the milling, the surface of the pothole was cleaned with an air stream under pressure and then the mix was laid by means of the jetinjection method (Fig. 2).

Fig. 2. Preparation of the area for the pothole repairs and filling it with the mix

The thickness of the mix layer in the pothole was taken to be 0.05 m. The compaction coefficient of the material in the surfacing pothole following laying of the mix and during the movement of vehicles was identified by means of the non-destructive method using the PAB-1 densitometer, which makes it possible for the material density and compaction coefficient to be determined following the loading.

The movement of transport in the repairs site was recorded automatically as shown in Fig. 3.

Fig. 3. Transport flow in the surfacing repairs site

It was found that following the laying of the mix in the pothole of the surfacing by means of the jet-injection method, the compaction coefficient is 0.81—0.83. When the vehicle is in motion, the compaction coefficient has different values depending on the axial load. After a number of cars (up to 6m) have passed, small trucks (6—9 m), and trucks (9—13 m), the value of the coefficient increases to unity, and after heavy vehicles have passed, it decreases. 10 hours following the repairs, the compaction coefficient of the material in the pothole was 0.85. The tests of the material samples taken from the repairs 60 days later showed a compaction coefficient of 0.96 and water saturation in percentage by volume of 9.3, which does not meet the requirements of the GOST (ГОСТ) 9128-2013.

The traffic flow from 9 am to 7 pm ranged from 680 to 800 cars per hour. The analysis of the traffic flow according to the load-carrying capacity showed that the share of heavy vehicles was 30—40 % of the total number of the vehicles.

2. Determining the rheological characteristics of the bitumen-mineral mix. Unlike the hot asphalt mix, the structure of the bitumen-mineral mix laid in the pavement pothole takes a relatively long time to form [10]. When a vehicle is moving under the influence of stresses in the contact zone of the tire with the compacted surface of the material, the stress is transferred from the tire to the surface of the laid mixture in the surfacing pothole. Depending on the contact stress and the properties of the material being compacted, both an increase in the coefficient of compaction of the material and its decrease will take place. The ability of a material to absorb an external load without destroying the layer is characterized by means of the elastic modulus E_y. When compaction of the material associated with the development of irreversible deformation and the formation of a strong structure, the properties of the material are characterized by means of the deformation modulus $E_д$ and the elastic coefficient $K_{жс}$.

In order to establish the rheological characteristics of the bitumen-mineral mix, studies were carried out. As a result, the numerical values were obtained of the stiffness coefficient $K_{жс}$, N/mm, and the coefficient of viscous resistance $K_в$, Ns/mm, from the load at different layer thicknesses.

It has been experimentally proved that in the zone of contact of the tire with the surfacing due to the stresses under the car tire, material deformation takes place. Depending on the contact stress and the properties of the material, both elastic deformation and plastic deformation can occur, which characterizes fracture process. Exceeding contact stresses in relation to the tensile strength of the material causes a decrease in the strength of the mix layer and a decrease in the stiffness coefficient of the mixture. Fig. 4 shows the change in the coefficient of rigidity of a bitumen-mineral mix from deformation obtained experimentally when loading a layer of a mixture with the thickness of 0.07 m^2.

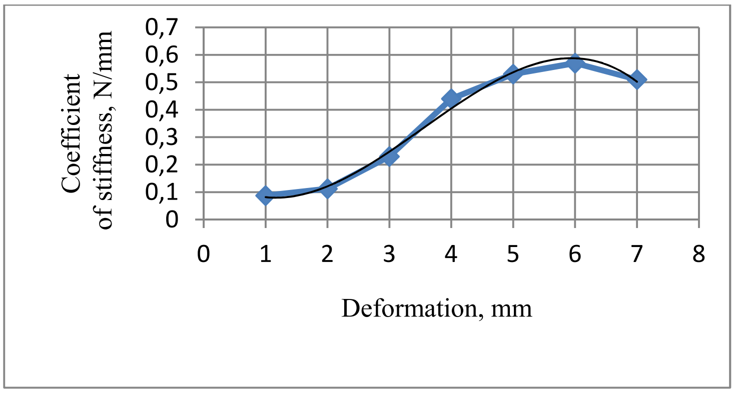


Fig. 4. Dependence of the stiffness coefficient on the deformation

The data in Fig. 4 shows that with as the strain of the mixture layer increases under the load, so does the stiffness coefficient of the mix layer. Moreover, the stiffness coefficient of the mix increases up to a certain value, then decreases. The process of the decrease in the stiffness coefficient is indicative of the development of plastic deformation, i.e., the start of fracture process. The numerical value of the stiffness coefficient of the mix from deformation of the material under the load can be given by the formula:

$$K_{жс} = -0.009\lambda^3 + 0.099\lambda^2 - 0.193\lambda + 0.18, \quad (1)$$

where λ is the deformation of a material layer, mm. The coefficient of the equation correlation is 0.99.

It was experimentally proved that there are some patterns in the characteristics of the material that are critical to its response to external loads $E_у$, $E_д$, $K_{жс}$ as shown in Fig. 5.

a) b)

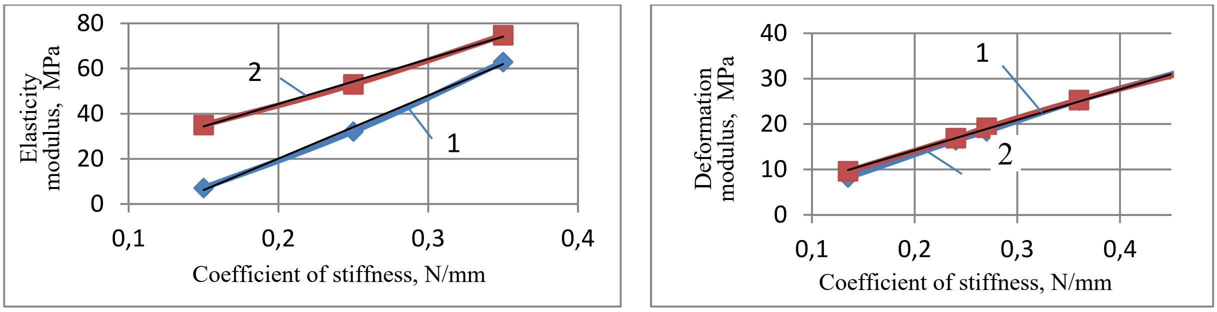


Fig. 5. Dependence of the elasticity modulus (a) and the deformation modulus (b) on the stiffness coefficient of the mix layer: 1 is the thickness of the layer of 0.05 m; 2 of 0.07 m

The analysis of the data presented in Fig. 5 enabled us to conclude that there are certain dependencies between the parameters $E_у$, $E_д$ and $K_{жс}$. If there is a slight change in the thickness of the layer, the deformation modulus of the material being compacted is less dependent on the stiffness coefficient of the mix in relation to the elastic modulus. In order to identify the general patterns of the characteristics of the mix ($E_у$ and $K_{жс}$), we take the elastic moduli at a material layer with the thickness of 0.05 m per unit and denote the obtained relative value using the coefficients of the influence of the layer thickness on the elasticity modulus and deformation modulus (Fig. 6).

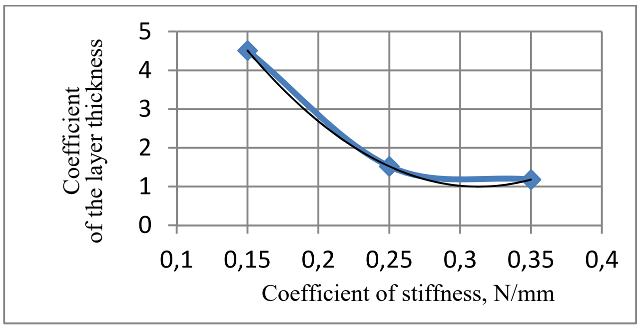


Fig. 6. Dependence of the coefficient $K_н$ on the stiffness of the surfacing layer for different thicknesses of the surfacing layer

The numerical value of $K_н$ is given by the formula:

$$K_н = 132.5H^2 - 82.9H + 13.96, \quad (2)$$

where H is the thickness of the compacted layer of the bitumen-mineral mix, m. The coefficient of the equation correlation is 1.0.

Fig. 6 suggests that as the stiffness coefficient of the mix increases above 0.25, the stiffness coefficient stabilizes and remains constant (1.0). The dependences for determining the elastic modulus and the deformation modulus of the material on the stiffness coefficient are as follows:

$$E_y = K_н \left(278.95 K_{жс} - 35.7\right),\ \text{MPa};\ \ E_д = 67.1\ K_{жс} + 0.8,\ \text{MPa}. \qquad (3)$$

The coefficient of the equation correlation is 0.99. Based on the experimental data obtained during the repairs by means of the jet-injection method, the dependence was found between the deformation of the surfacing pothole material and the coefficient of compaction (Fig. 7).

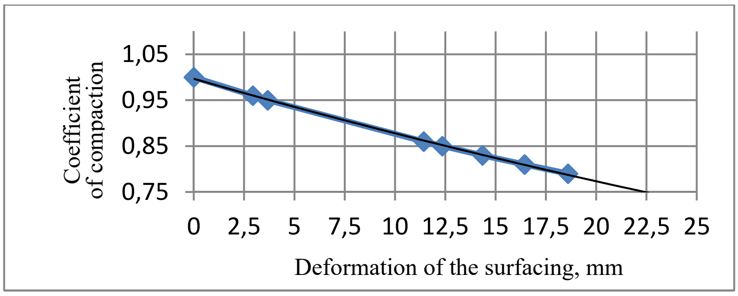


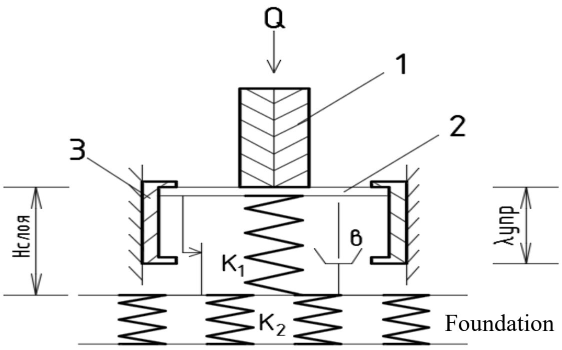
Fig. 7. Dependence of the coefficient of compaction on the deformation of the bitumen-mineral mix in the pothole

The numerical value of the coefficient of the compaction of the mix on the deformation of the mix during compaction can be given by the formula:

$$K_y = 0.996\, e^{-0.013\lambda}, \qquad (4)$$

where λ is the deformation of the surfacing pothole material, mm. The coefficient of the equation correlation is 0.999.

3. Modeling the process of interaction of the tire with the pothole surface. In order to determine the strain of the mixture under the load from the vehicle tire, a rheological model is considered as shown in Fig. 8.



1 is a pneumatic tire;

2 is a compacted bitumen-mineral mix;

3 is a weightless seal modelling the residual deformation of the material

Fig. 8. Rheological model of compaction of the bitumen-mineral mix in the roadway surfacing pothole of the with a pneumatic tire: Q is the gravity transmitted from the vehicle to the tire, kN; K_1 is the coefficient (modulus) of material stiffness, N/mm; K_2 is the stiffness coefficient of the base, N/mm; $\lambda_{упр}$ is the deformation (movement of a weightless plug), characterizing the elastic deformation of the material, mm

When the vehicle is in motion, the force Q which characterizes the axial load that acts on the material in the surfacing pothole. Under the axial load in the contact zone of the tire with the surface of the material, stresses occur that contribute to the development of deformation of the material. The initial conditions for the motion of the surface and cork are as follows:

$$t = t_0\ ;\ x_1 = 0\ ;\ x_2 = 0. \quad (5)$$

As the deformation of the material layer progresses beyond the elastic deformation, a weightless seal moves which characterizes the complete deformation of the material under the load x_2. This condition takes the following form:

$$x_1 > \lambda_{упр},\ \text{mm}. \quad (6)$$

When removing the load, the surface of the material layer due to elastic deformation moves up till it reaches the upper stopper of the tube. The lifting speed of the surface depends on the speed of unloading of the material and is determined by the speed of the vehicle. The proposed rheological model allows us to represent it as a mathematical model described by an equation relating stresses and strains that take place simultaneously due to the load application:

$$\sigma = K_{жс}\lambda + \eta\lambda, \quad (7)$$

where $K_{жс}$ is the coefficient of stiffness, N/mm; λ is the deformation, mm; η is the viscosity, Ns/mm.

This dependence taking into account the deformation of the material and the rheological characteristics of the mix can be as follows:

$$\lambda = \sigma / K_{жс} + \sigma / \eta,\ \text{mm}. \quad (8)$$

According to this dependence, the $\sigma/K_{жс}$ ratio characterizes the elastic deformation of the material and σ/η the residual deformation. As the load is applied again and again, the residual deformation is given by the dependence [11]:

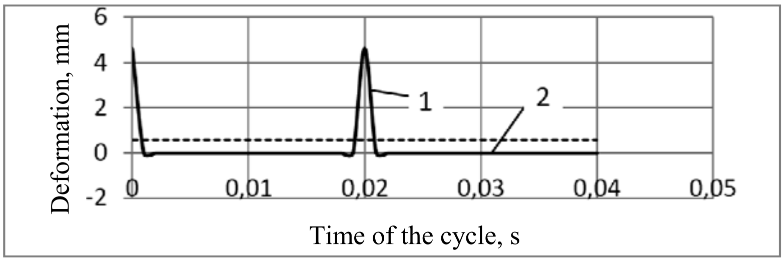
$$\lambda_{ост} = n\sigma t_н / \eta, \quad (9)$$

$t_н$ is the total load effect on the material, s; n is the number of the loading cycles.

In order to calculate the deformations of the bitumen-mineral mix in the roadway surfacing pothole under the contact axial stresses from vehicles, a software package was developed [12]. The calculation of the mix deformation under the load of 0.6 MPa and the stiffness coefficient of 0.13 is presented in Fig. 9.

Fig. 10 shows the results of modeling the deformation of the bitumen-mineral mix in the roadway surfacing pothole on the stiffness coefficient of the mix depending on the axial load of vehicles (according to GOST R (ГОСТ Р) 52899-2007).

According to the data in Fig.10, as the stresses in the contact zone of the tire with the surface increase, so does the deformation of the laid material, which is the reason for a decrease in the compaction coefficient.

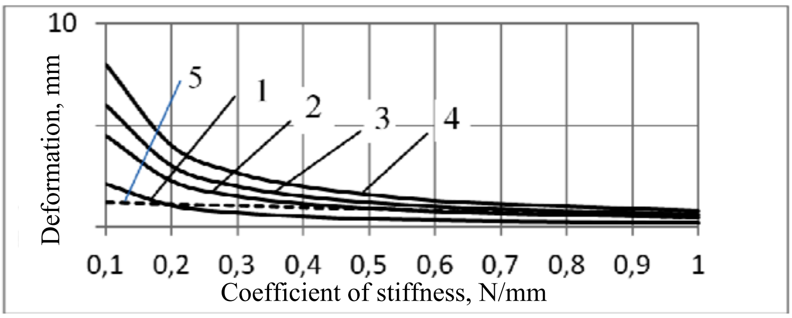


1 is the total deformation;

2 is the elastic deformation

Fig. 9. Deformations of the mix in the surfacing pothole under the tire load

As the machine with a reduced load passes again and again, the mix is compacted, which enhances its ability to resist external load, i.e., to increase the stiffness coefficient of the mix. An increase in the stiffness of the mix is characterized by an increase in the density, compaction coefficient, deformation modulus and elastic modulus of pavement.



1 is 0,21 MPa;

2 is 0,45;

3 is 0,6;

4 is 0,8;

5 is the elastic deformation

Fig. 10. Dependence of the deformation on the stiffness coefficient of the mix under varying stresses in the contact zone with the surfacing

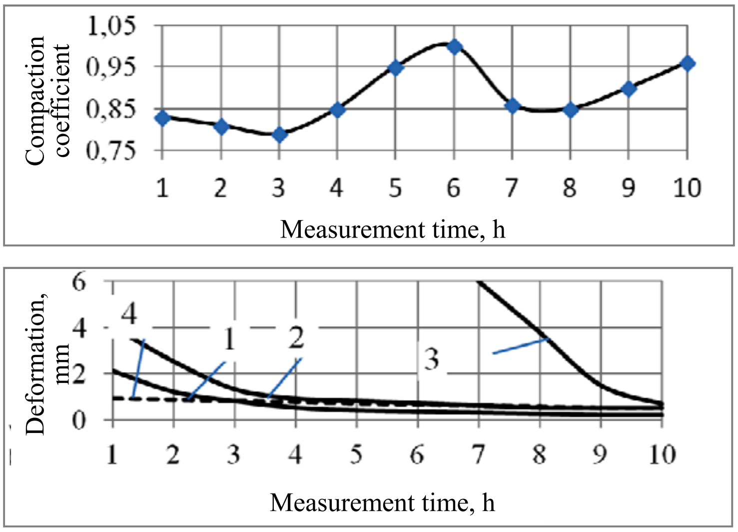
Fig. 11 shows combined graphs of changes in the coefficient of compaction of the roadway surfacing material and the deformation of the layer of the mix with different axial loads when vehicles move in time.

Fig. 11 shows that as the stress in the contact zone of the tire with the surface of the pothole increases, so does the deformation in the mix layer. When vehicles with an axial load exceeding the permissible limit in the tire contact zone with the pothole surface in the traffic stream, stresses occur that exceed the tensile strength of the material and thus decomposition of the laid material occurs, which causes the compaction coefficient to decrease.

The softening of the structure of the material (destruction) will take place under the following condition:

$$\sigma_{\kappa} \geq [\sigma], \tag{10}$$

where σ_{κ} are the contact stresses under a pneumatic tire, MPa; $[\sigma]$ is the strength limit of the compacted material, MPa.



1 is 0,21 MPa;

2 is 0,45 MPa;

3 is 0,6 MPa;

4 is the elastic deformation, mm

Fig. 11. Deformation of the mix layer under the axial load as vehicles move

When traffic flows with different axial loads move, given the formation of the structure of the bitumen-mineral mix, the deformation of the layer of the mix will depend on the load on the top layer of the pothole, which affects the value of the compression coefficient. The change in the coefficient of compaction of the layer of the mix will occur until the structure of asphalt is finally formed that is caused by complete removal of moisture from the layer of the mix.

Depending on the properties of the material in the surfacing pothole laid by means of the jet-injection method and the transmitted load from vehicles, the development of elastic, plastic or elastic-visco-plastic deformations is possible, which characterizes the process of compaction of the laid material or its decompression. The condition for the development of deformations under the load from vehicles on the laid material in the surfacing pothole can be represented in the form of the following dependencies:

— $\sigma_y + \tau_y \geq \sigma_{конт}$ is the elastic deformation,

— $\sigma_{конт} \geq \sigma_y + \tau_y$ is the plastic deformation,

— $\sigma_y + \tau_y = (0,9-1,0)[\sigma]_{пр}$ is the compaction, (11)

— $\sigma_x + \tau_x \geq [\tau_{сд}]$ is the shift of the particles in relation to each other, where [$\tau_{сд}$] is the shear strength limit of the material, MPa; [σ] $_{пр}$ is the compressive strength of the material, MPa; $\sigma_{конт}$ are the stresses in the contact zone of the tire and the material particle, MPa; σ_y and τ_y are the stresses in the material layer under the transport load.

Looking into the process of the contact of the particles of the mix with each other as they are being laid into the surfacing pothole under the transport load, we obtain analytical dependences that enable us to determine the stresses in the zone of contact of the particles [4, 5, 7]. The table shows the numerical values of the stresses in the zone of contact of the particles under the load from the vehicle tire considering the particle diameter of the mineral component of the bitumen-mineral mix.

Table

Stresses in the zone of contact of the particles under the load of the vehicle tire

Diameter of the particle, mm	Stresses under the vehicle tire, MPa									
	0.21		0.45		0.6		0.8		1.0	
	σ_x	σ_y	σ_x	σ_y	σ_x	σ_y	σ_x	σ_y	σ_x	σ_y
2.5	−0.02	0.6	−0.05	1.2	−0.06	1.6	−0.09	2.7	−0.11	2.7
5.0	−0.04	0.8	−0.08	1.6	−0.10	2.2	−0.15	2.9	−0.18	3.7
10.0	−0.05	1.1	−0.11	2.3	−0.15	3.1	−0.20	4.2	−0.25	5.2
15.0	−0.12	1.3	−0.26	2.8	−0.35	3.7	−0.46	4.9	−0.58	6.2
20.0	−0.11	1.5	−0.25	3.2	−0.33	4.3	−0.45	5.8	−0.56	7.2

According to the data presented in the table, as the load on the pavement increases, so do the stresses in the contact zone of the layer particles, which is in agreement with the results of modeling and experimental studies.

Conclusions

1. The results of the study are contrary to the current view that the use of the jet-injection method does not require additional compaction for laying material into a pothole.

2. The density and coefficient of compaction of the mix in the jet-injection method is ensured by the vertical deformation of the particles of the layer as the shear stresses do not ensure the movement of particles in the horizontal plane ($\tau < [\tau sd]$). The compaction coefficients and water saturation of the samples do not meet the requirements of the regulatory guidelines (K_y = 0.81—0.82; water saturation of more than 10 %), which is confirmed by simulation results and experimental studies.

3. When vehicles are moving with a pavement load of up to 0.5 MPa, the process of compaction of the bitumen-mineral mix of the 5—10 mm fraction in the surfacing pothole following the laying by means of the jet-injection method is ensured.

4. The movement of vehicles with a load on pavement of more than 0.5 MPa results in the development of plastic deformations in the mix layer of the surfacing pothole that affects the compaction coefficient. Plastic deformation of the material in the pothole occurs due to compressive and shear stresses, they are sufficient to overcome the adhesion forces between the particles.
5. When laying bitumen-mineral mixes with 5—15 and 5—20 mm fractions, an increase in the density occurs during traffic with a load on pavement up to 0.35 MPa. With a further increase in the load on the surface of the pothole, plastic deformations occur in the mix layer, as the contact stresses between the particles are beyond the tensile strength of the material ($\sigma_{к} > [\sigma_{пр}]$ and $\tau > \tau_{сд}$).
6. To ensure the required quality of repairs by means of the jet-injection method following the laying of the mix, it is necessary to limit the axial load of vehicles on the mix layer in the surfacing pothole while the material structure is being formed.

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