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METHOD OF DEVELOPMENT OF TECHNOLOGY FOR THE DEVICE OF ROAD STRUCTURES USING ASPHALT GRANULATE

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Statement of the problem. The currently used waste (asphalt granulate) for milling non-rigid pavements differs in its characteristics from hot and cold asphalt concrete mixtures as well as crushed stone. The used fleet of machines for compacting the material layer is characterized by a wide range of roller weights and roller parameters, which affects the compaction effect. ensuring the quality of compaction depends on the compliance of the technological modes of the mechanized link of machines with the properties of the materials used. It is necessary to develop a technology for the device of layers using asphalt granulate and taking into account its properties, thickness, as well as the parameters of compaction machines.

Results. The method of development of technology for the device of road structures in the reconstruction and repairs of highways with the use of asphalt granulate is considered. Based on experimental studies the dependence between the load and the deformation of the layer of material, deformation and compaction factor and the values of the angles of contact of the roller with the surface layer of the compacted material is identified with regard to its granulometric composition and thickness of the stacked layer. The simulation results are presented of the interaction of the roller rink with the sealing material obtained analytical dependence for the calculation of stresses in the contact zone of the roller with the material allowing one to set the parameters of the rollers depending on the properties of asphalt granulate.

Conclusions. An analytical dependence is obtained for calculating the stresses in the contact zone of the roller with the asphalt granulate layer, which allows one to assign the parameters of the rollers depending on the properties of the material being laid. The suggested method for developing the technology of layer arrangement using asphalt granulate enables the required quality of compaction taking into account the properties of the material, the thickness of the layer to be laid and the parameters of compacted machines.

Keywords: asphalt granulate, compaction, stress, deformation, roller contact angle.

Introduction. For construction, reconstruction and repairs of highways a significant amount of road construction materials is required with their costs affecting the total ones of a particular project. In order to reduce the material costs, industrial waste is commonly used.

Presently, non-rigid pavements make up to 97 % of the total length of paved roadways. At the preparatory stage, during the overhaul and reconstruction of highways, the existing pavement layers are milled. It has been estimated that cold milling of an old asphalt concrete pavement with a lane width of 7.0 m and a milled layer thickness of 0.05 m produces 500—600 tons of waste from one kilometer of the road surface. The resulting material is called asphalt granulate. The waste material is sent for further use by local road organizations to reinforce curbs, construct access roads and temporary detours.

The world practice of using asphalt granulate has shown that overseas (USA, England, Germany and France) all the obtained material is recycled for road works following the waste processing. In the countries such as Japan, the Czech Republic and Slovakia, up to 80 % of asphalt scrap is recycled, in Hungary — 60 % and Poland — 50 %. According to experts, use of asphalt granulate can reduce the need for a binder of up to 3.8 million tons and more than 72 million tons in aggregate. The total savings are estimated to be over 2.1 billion US dollars.

The guideline documentation Design Standards for Industrial Roads (ОДН) 218.3.039-2003 “Reinforcing Curbs” and Construction Rules (СП) 78.13330.2012 “Highways” define the areas of application of asphalt granulate for highways. With appropriate processing of an asphalt granulate, it can be used in the base and in the lower layers of surfacing provided that it meets the requirements of GOST (ГОСТ) 8267 for the strength to crushed stone. The addition of a binder during recycling of asphalt granulate increases the ultimate strength of the layer from 0.5 to 2.0 MPa. An asphalt granulate without a binder is recommended for use in construction of IV category highways with a compressive strength of 0.7 MPa as well as for splitting the upper layer of crushed stone. While strengthening curbs of roadway surfacing, setting up industrial sites, crushed stone bases and surfacing by means of the wedge method, asphalt granulate is used, which is laid in layers of different thickness and granulometric composition. As depending on the particle size distribution and layer thickness, the strength characteristics of the material change affecting the compaction process and choice of the parameters of compaction machinery.

It has been proven that in order to achieve the required strength during compaction, it is essential to ensure that the parameters of the compaction machines correspond to the properties of compacted material [1—3, 15]. In compliance with Construction Rules (СП) 78.13330.2012, the achievement of the required density and strength of a layer of asphalt granulate is ensured by rollers on pneumatic tires weighing at least 16 tons at an air pressure in the tires of 0.6—0.8 MPa, trailed vibration masses of at least 6 tons, lattice masses not less than 15t, selfpropelled smooth roller mass of at least 10t and combined mass of more than 16t. The analysis of the recommended parameters of the rollers showed that they belong to the group of heavy rollers used at the final stage of material compaction. At the initial stage of the compaction of the layer, it is essential to use rollers with a lower mass depending on the characteristics of a compacted layer of a material [6, 7, 10, 16—20].

Use of asphalt granulate in this country has shown that the material obtained while milling road surfaces is consumed according to the residual principle, i.e. in a not entirely rational way. Therefore the objective of the study is to select the parameters of the rollers to ensure the quality of compaction of the asphalt granulate layer considering the influence of the granulometric composition and its thickness to improve the quality of work during laying and compaction of this material.

1. Influence of the properties of the compacted material on the strength characteristics of a surfacing. Whether the required strength of a road structure using asphalt granulate is achieved depends on the strength characteristics of a material being used, the technology of laying and compaction. Depending on the method of distribution for laying a material, the volumetric mass of an asphalt granulate ranges from 1.4 to 1.8 t/m^3. Asphalt granulate with a fraction of 5—20 mm is most commonly used in the construction of layers of pavement whose bulk density when laid is 1450 t/m^3, the maximum density is 2450 kg/m^3. When the material is being laid, partial compaction occurs which is characterized by the pre-compaction coefficient. The amount of pre-consolidation depends on the properties of the material and the mechanization tools used for a layer. The use of earthmoving machines ensures the coefficient of preliminary compaction of the asphalt granulate layer in the range of 0.76—0.87. During the operation of compaction machines, due to the deformation of the material, the density increases, which contributes to a greater strength of a compacted layer. Based on the results of experimental studies, the dependence of the density of the compacted material (ρ) on the layer deformation is identified:

$$\rho = 1.45 e^{0.017\lambda}, \text{ t/m}^3 \quad (1)$$

where λ is the deformation of a material layer, mm. The correlation coefficient of the equation is 0.97.

The deformation in the layer of material takes place under the action of stresses emerging in the contact zone of the operating body of the machine with the sealed surface of the material. The stress-strain dependence is shown in Fig. 1.

The value of deformation caused by stress for an asphalt granulate layer of a fraction of 5—20 mm with a layer thickness of 0.22 m is given by the dependence:

$$\lambda = 6.18 ln\sigma + 19.34 \text{, mm} \quad (2)$$

where σ are contact stresses, MPa. The correlation coefficient of the equation is 0.98.

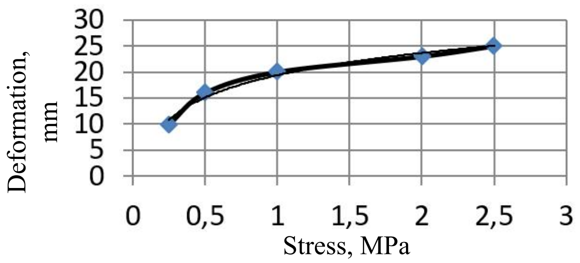


Fig. 1. Dependence of the deformation of a material on the stress under a roller drum

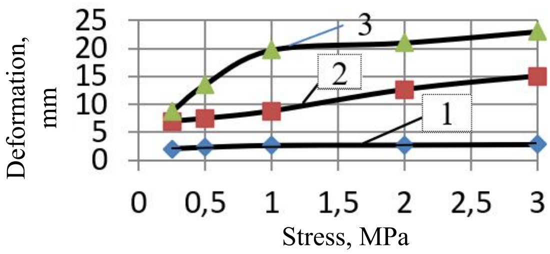


Fig. 2. Dependence of the deformation of a compacted layer on the stress at its varying thicknesses, m: 1—0.05; 2—0.10; 3—0.15

As the thickness of a layer changes, so does the amount of deformation. Figure 2 shows the dependence of the deformation of a layer of an asphalt granulate with a fraction of 5—20 mm at varying thicknesses.

Using the data presented in Fig. 2, we assume that the deformation value depends on the load and the layer thickness. As the stress goes above a certain value, plastic deformation takes place. The deformation of the material under a load from the roller drum is characterized by the angle of contact of the drum with the surface of a material layer, which depends on the load on the roller and its radius as well as the properties of a compacted material. The generalized characteristic of the deformability of a material under an external load according to GOST R (ГОСТ) 54477 is the deformation modulus ($E_д$) which characterizes the linear relationship between the pressure increment in the zone of contact of a stamp on the material and its deformation. The numerical value of the deformation modulus is given by the formula:

$$E_д = \sigma \, d_ш / \lambda_n \text{, MPa} \quad (3)$$

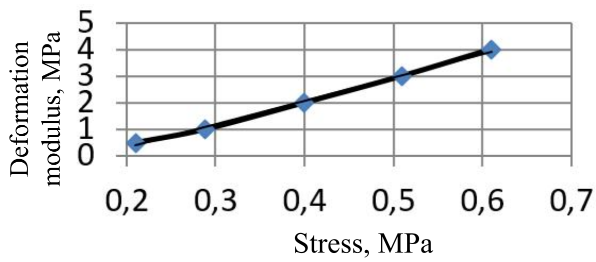


Fig. 3. Dependence of the deformation modulus of a compacted material on the stress

Where $d_ш$ is the diameter of a stamp, m; λ_n is complete deformation of a compacted layer, m.
The dependence of a deformation modulus of a compacted material on the stress in the contact zone of the roller with a material is shown in Fig. 3.
The amount of deformation of the material layer is known to be influenced by the time of action of the load which is determined by the number of load cycles (the number of roller runs). Figure 4 shows change in the angle of contact of the roller with the surface of acompacted layer depending on the number of runs and the deformation modulus of asphalt granulate.

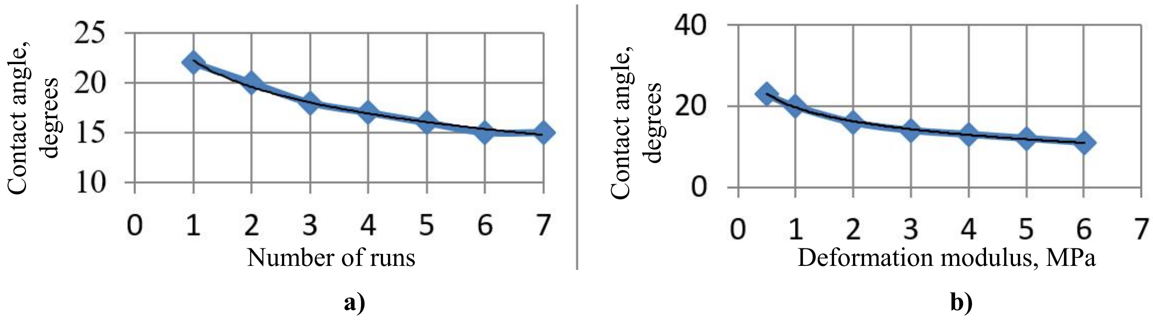


Fig 4. Dependence of the contact angle of the roller drum:
a) on the number of runs; b) deformation modulus of a material

Based on the data in Fig. 4, the angle of the arc of contact of the drum with a material depends on the number of roller runs and the properties of a compacted material which must be taken into account when simulating the process of compaction of a material.
According to the results of rheological studies, the dependences of the deformation modulus of asphalt granulate on the layer thickness during laying were identified which are given by linear dependences:

at a layer thickness of 0.05 m $E_д = 2.99\sigma + 1.03$, MPa

at a layer thickness of 0.10 m $E_д = 4.32\ \sigma + 2.58$, MPa

at a layer thickness of 0.15 m $E_д = 23.66\sigma + 3.21$, MPa (4)

The correlation coefficient of the equations is 0.99.
In order to identify the general regularity of the influence of a layer thickness on the deformation modulus, the obtained data is presented in relative values taking the deformation modulus of a layer to be 0.1m as a unit. Let us designate the adopted value by the coefficient of influence of a layer thickness of asphalt granulate ($К_н$) on the deformation modulus (Fig. 5).

The numerical value of the coefficient of the effect of a layer thickness on the deformation modulus is given by the equation:

$$K_{и} = 0,02h^{-1,74}, \quad (5)$$

where h is the thickness of a layer, m. The correlation coefficient of the equation is 0.98.

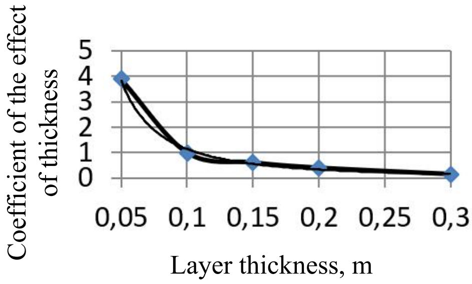


Fig. 5. Dependence of the coefficient of the effect of an asphalt granulate layer thickness on the deformation modulus

The deformation modulus of a compacted material at varying thicknesses of a layer is given by the formula:

$$E_{д} = K_{и}\left(4.32\,\sigma + 2.58\right), \text{ MPa}. \quad (6)$$

The efficiency of compaction machines was found to depend on the correspondence of stresses under the operating body of the machine to the tensile strength of a compacted material. The ultimate strength of an asphalt granulate layer depends on the particle size distribution of the material and a layer thickness during laying. It has been experimentally found that an increase in the layer thickness during laying causes a decrease in the ultimate compressive strength regardless of the particle size distribution (Fig. 6). The resulting pattern is confirmed by the studies of other authors [4–6].

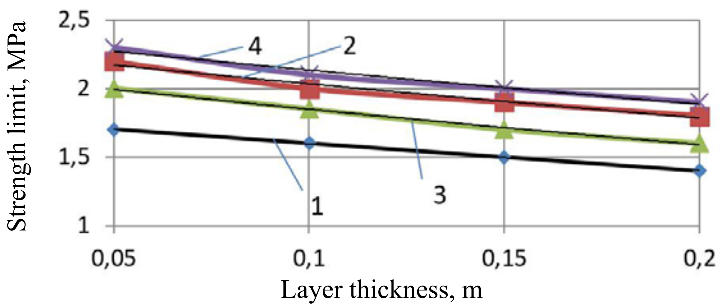
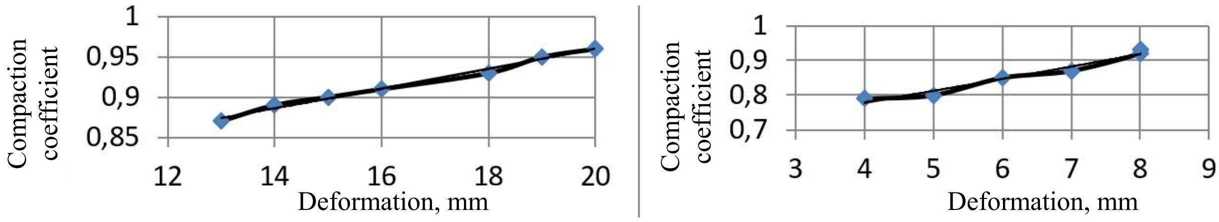


Fig.6. Dependence of the strength limit on a layer thickness at varying fractions of asphalt granulate: fraction 1 — 5—10 mm; 2 — 5—20 mm; 3 —10—20 mm; 4 — 20—40 mm

As the number of load applications to the surface of a compacted layer increases, so does its total deformation, which contributes to a rise in the density of the material and thus in the compaction coefficient.

It was found that the dependence of the compaction coefficient on deformation at a layer thickness of 0.05m does not depend on the fractional composition of asphalt granulate and is characterized by a linear relationship (Fig. 7). Similar results were obtained in [4—6].



a) **b)**

Fig. 7. Dependence of the coefficient $K_{упл}$ on the deformation at a layer thickness of 0.05 m and varying granular composition: a — fraction of 5—20 mm; b — fraction of 20—40 mm

The numerical value of the compaction coefficient on the deformation of a layer is given by the equations:

for fraction of 5—20 mm $K_y = 0.73\ e^{0.013\lambda}$,

for fraction 20—40 mm $K_y = 0.66\ e^{0.041\lambda}$, (7)

where λ is the deformation of a material layer, mm. The correlation coefficient of the equations is 0.97.

As a layer thickness rises by 0.1 m, the relationship between the compaction coefficient and deformation becomes exponential. The numerical value of the coefficient of compaction from deformation at a layer thickness of 0.1 m and more is given by the equations:

for fraction of 5—20 mm $K_y = 0.47\ e^{0.0363\lambda}$,

for fraction of 20—40 mm $K_y = 0.72\ e^{0.014\lambda}$. (8)

The correlation coefficient of the equations is 0.97.

Based on the above results, it can be concluded that the properties of the material employed and the design parameters of the layers affect the contact zone of the roller drum during compaction of layers using asphalt granulate.

2. Justification of the parameters of the contact of the roller drum with a compacted material. The process of compaction of the layer of material is performed by means of rollers with a rigid metal drum whose parameters are in a wide range both in terms of the mass of the roller and the geometric parameters of the rollers. The transfer of force to the compacted surface of the material layer takes place via its contact area of the roller which characterizes the stresses in the contact zone. The maximum effect during compaction was found to be provided under the condition when the value of contact stresses is similar to the ultimate strength of the material being sealed [4, 5, 7—9, 11, 12, 14]. Figure 8 shows a diagram of the interaction of the rigid roller drum with the compacted material.

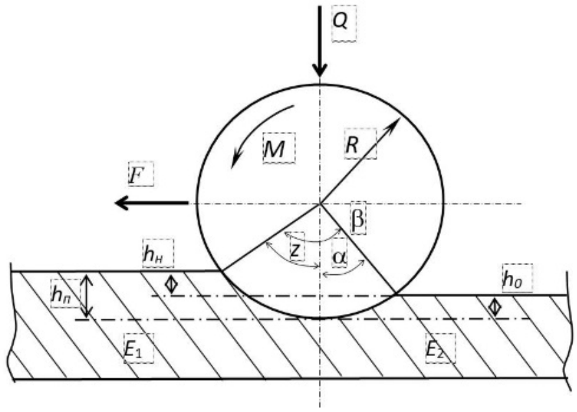


Fig. 8. Scheme of interaction of the rigid roller drum with a compacted material: Q is the force of gravity of the roller on the drum, kN; M is the torque applied to the driving drum of the roller, kN·m; R is the radius of the roller, m; E_1 and E_2 are the deformation moduli of the compacted material before and after the roller run, MPa; F is the force transmitted from the driving drum to the roller frame, kN; $h_п$, $h_н$, h_o are full, irreversible and elastic deformation of the material, m; β is the angle of contact of the roller drum with the material which characterizes irreversible deformation, degrees; α is the angle between the axis of motion of the drum and the point which characterizes the end of the contact of the drum with the material, characterizes elastic deformation, degrees; z is the angle between the point of contact of the roller with the compacted material and the axis of movement of the roller characterizing the total deformation of the material, m

According to the diagram, the contact area of the roller drum is characterized by the length of the arc of contact of the roller with the material surface which depends on the parameters of the roller and the properties of a compacted material. As the properties of the material change during its compaction, the length of the roller contact arc will be different, which affects the contact stresses under the roller. Therefore, in order to simulate the process of compaction of a material layer, it is essential to know the dependence of the drum contact angles on the parameters of the roller and the properties of a compacted material. Deformation of the material to be compacted is defined as the sum of irreversible and reversible deformations, i.e.

$$h_п = h_н + h_o \text{, m,} \tag{9}$$

where $h_п$, $h_н$, h_o are full, irreversible and residual deformation respectively.

At a constant roller width, the arc length of its surface is determined by the angles z, α and β which characterize the total, residual and elastic deformations of a compacted material, respectively. The numerical value of deformations considering the angles of contact of the roller with the material can be given by the formulas:

$$h_n = R(1-\cos z)\text{, m;} \qquad h_и = R(\cos\alpha - \cos z)\text{, m;} \qquad h_o = R(1-\cos\alpha)\text{, m.} \qquad (10)$$

The value of irreversible deformation during compaction with static rollers was found to be given by the formula [9]:

$$h_и = 20q / E\sqrt{R}\text{, m,} \qquad (11)$$

where E is the modulus of deformation of a compacted material, MPa; q is a linear pressure of the roller drum, kN/m; R is the radius of the roller, m; q is the linear pressure of the roller drum which is determined by the Q/B ratio where B is the drum width, kN/m.

Considering the dependence (9), the contact angle characterizing the complete deformation of the material under the roller drum is given by the formula:

$$\cos z = \cos\alpha - 20q / ER\sqrt{R}\text{ .} \qquad (12)$$

For the initial stage of compaction when the elastic properties of the material appear to be insignificant, it can be assumed that the angle α equals zero. In this case, the angle of contact of the roller with the material can be given by the formula:

$$\beta = \arccos(1 - 20q / ER\sqrt{R})\text{ .} \qquad (13)$$

Based on this dependence, the contact angle β depends on the parameters of the compaction machine (q, R) and the properties of the material characterized by the modulus of deformation of the compacted material ($E_д$). When the driving roller is in motion, the material deformation modulus changes under a load. As can be seen from this expression, as the material deformation modulus rises to an infinitely large value, a part of the equation turns into zero, which characterizes the contact of the roller drum with the material at a point. At the final stage of the roller operation, the material deformation modulus is stabilized and $E_1 = E_2$. Then the contact angle of the roller of the roller with the compacted material equals $\beta = 2\alpha$, which characterizes the end of the compaction process.

An analysis of the technical characteristics of the rollers used for compacting road pavements showed that the diameter of the rollers ranges from 0.4—2.1 m, which under the same load affects the angle of contact of the roller with the material. In order to identify the influence of the roller radius on the contact angle with a compacted material at a constant deformation modulus, stamps with the curvature radii from 0.2 to 0.8 m were used. The results are shown in Fig. 9.

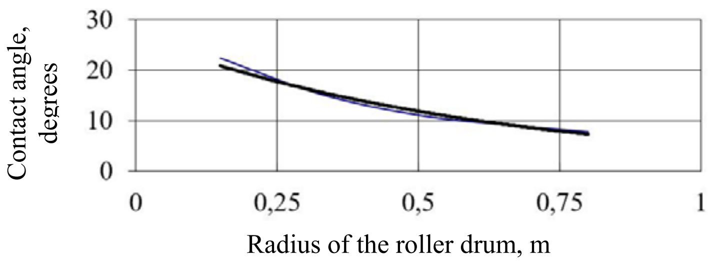


Fig. 9. Dependence of the contact angle of the roller drum on the radius

Based on the dependence, the diameter of the roller rises due to an increase in the contact arc, the angle β which characterizes the residual deformation of the material changes. The dependence of the roller contact angle (β) on its radius can be given by the formula:

$$\beta = 26.63\, e^{-1.61\, R}. \quad (14)$$

The correlation coefficient of the equation is 0.97.

The contact angle of the roller with the material to be compacted also depends on the load transmitted to the surface. Figure 8 shows the dependence of the change in the contact angle on the linear pressure of the roller drum at its constant radius on the material.

As the linear pressure of the roller increases, so does the load on the material in the contact zone, which leads to a rise in the deformation of the material and thus in the contact angle. The dependence of the roller contact angle on the linear pressure is the following:

$$\beta = 7.1 ln(q) - 10.1, \text{ degrees.} \quad (15)$$

The correlation coefficient of the equation is 0.96.

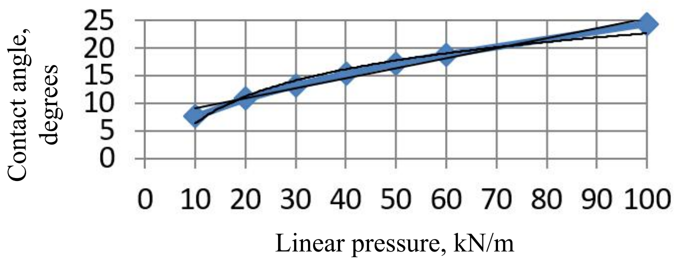


Fig. 10. Dependence of the contact angle of the roller drum on the linear pressure of the roller drum

Based on the diagram of the interaction of the roller with a compacted material in Fig. 10, the angle β characterizes the residual deformation of the material after a roller run. A change in the contact angles of a drum with a diameter of 560 mm and a linear pressure of 70 N/m at different roller runs is shown in Fig. 11.

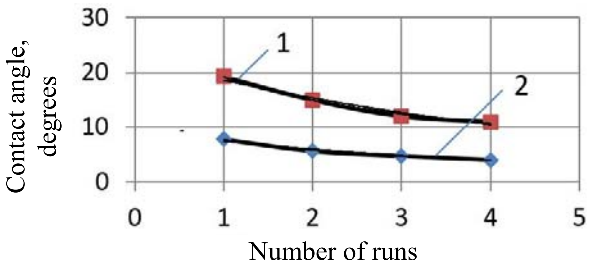


Fig. 11. Dependence of the contact angle of the roller drum with a compacted material on the number of roller runs: 1 is a contact angle β; 2 is a rear angle — α

Based on the data, a change in the contact angles of the drum (β and α) during compaction of asphalt granulate depending on the number of roller runs is governed by a logarithmic dependence and the numerical values are given by the formulas:

$$\beta = -6.17 ln(n) + 19.23 \text{, degrees,}$$

$$\alpha = -2.73 ln(n) + 7.7 \text{, degrees.} \quad (16)$$

where n is an ordinal number of a roller run. The correlation coefficient of the equation is 0.98.

As the roller makes more runs along the track, due to an increase in the deformability of the material, it is not only the roller contact angle β that changes but the α angle also does (Fig. 12).

The analysis of the experimental data as well as processing the results of other studies allows us to conclude that there is a general pattern between the contact angles β and α, which is shown in Fig. 12.

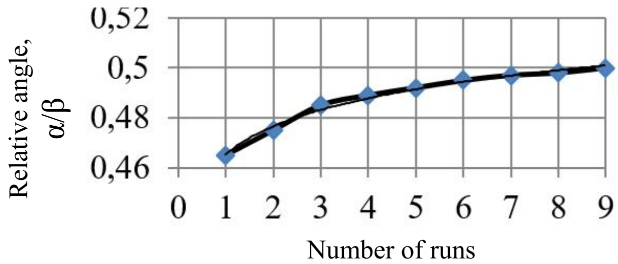


Fig. 12. Dependence of a relative contact angle of the roller drum depending on the number of roller runs

The numerical value of the relative angle of contact of the roller with the surface of the asphalt granulate layer is given by the formula:

$$\alpha / \beta = 0.016 ln(n) + 0.465 . \tag{17}$$

The correlation coefficient of the equation is 0.99. The identified regularities of changes in the angle of contact of the drum with the layer surface make it possible to justify the contact parameters while simulating the compaction process with a roller depending on the properties of the material, parameters of the roller and structural layers.

3. Development of a mathematical model of the interaction of the roller drum with the compacted material. The diagram suggests the interaction of the roller with a compacted material that under forces applied to the roller, normal (σ) tangential (τ) stresses arise in the contact zone with the surface of a material layer. The system of equations characterizing the stress distribution along the arc of contact of the roller with the material to be compacted takes the following form:

$$\sum x = 0; -\int_0^z \sigma \sin(z-\varphi) rBd\varphi + \int_0^z \tau_1 \cos(z-\varphi) rBd\varphi + \int_0^z \tau_2 \cos(z-\varphi) rBd\varphi + \int_z^\beta \sigma \sin(\varphi - z) rBd\varphi +$$

$$+\int_z^\beta \tau_1 \cos(\varphi - z) rBd\varphi + \int_z^\beta \tau_2 \cos(\varphi - z) rBd\varphi + T - SX = 0;$$

$$\sum y = 0; \int_0^z \sigma \cos(z-\varphi) rBd\varphi + \int_0^z \tau_1 \sin(z-\varphi) rBd\varphi + \int_0^z \tau_2 \sin(z-\varphi) rBd\varphi + \int_z^\beta \sigma \cos(\varphi - z) rBd\varphi -$$

$$-\int_z^\beta \tau_1 \sin(\varphi - z) rBd\varphi + \int_z^\beta \tau_2 \sin(\varphi - z) rBd\varphi - Q + SY = 0;$$

$$\sum M = 0; -\int_0^z Br^2 \tau_s d\varphi = M \tag{17}$$

The initial conditions are as follows:

$$\text{at } \varphi = 0 \to \sigma_{QY} = \tau_{QX} = \tau_{FX} = \tau_{FY} = \tau_{SY} = \tau_{SX} = 0$$

$$\text{at } \varphi = \beta \to \sigma_{QY} = \tau_{QX} = \tau_{FX} = \tau_{FY} = \tau_{SY} = \tau_{SX} = 0 \tag{18}$$

The boundary conditions can be presented as follows:

$$\varphi = z d\sigma_{QY} / d\varphi = 0; d\tau_{FX} / d\varphi = 0; d\tau_{SX} / d\varphi = 0;\ \sigma_{0X} = \tau_{FY} = \tau_{SY} = 0 . \tag{19}$$

In the system of equations the following designations are adopted: σ_{Qy} are the stresses caused by the force Q; τ_τ and τ_S are the shear stresses in the material caused by the forces T and S; S_x and S_y are the projections of the force S on the x and y axes. The force S occurs due to the torque M applied to the drum axis and is a constant value along the arc of the drum contact. The numerical value is given by the expression:

$$S = \int_0^{\beta} \tau_S d\varphi B r = M / r . \qquad (20)$$

In the final form, the solution to the system of equations characterizing the distribution of contact stresses under the roller drum takes the following form:

$$\sigma = (A_{11} + B_{11} + D_{11} + \Phi_{11} + S_{11} + O_{11})\,\varphi\ /\Delta + (A_{21} + B_{21} + D_{21} + \Phi_{21} + S_{21} + O_{21})\varphi^2/\Delta\ +$$
$$+(A_{31} + B_{31} + D_{31} + \Phi_{31} + S_{31} + O_{31})\varphi^3/\Delta + (A_{41} + B_{41} + D_{41} + \Phi_{41} + S_{41} + O_{41})\varphi^4/\Delta, \qquad (21)$$

where A_{i1}, B_{i1}, Φ_{i1}, D_{i1}, S_{i1}, O_{i1} are the coefficients of the system of equations depending on the angles of contact of the roller drum with a compacted material. The numerical value of the coefficients is given by the expressions:

$$A_{11} = R\beta^2[\beta y_2(C - \beta N) + y_3(\beta^2 M - C) + y_4(N - \beta M)]; A_{21} = R\beta[\beta^2 y_1(\beta N - C) + y_3(C - \beta^3 K) + y_4(\beta^2 K - N)];$$
$$B_{11} = R\beta^2\mu[\beta y_2(E - \beta W) + y_3(\beta^2 V - E) + y_4(W - \beta V)]; B_{21} = R\beta\mu[\beta^2 y_1(\beta W - E) + y_3(E - \beta^3 U) + y_4(\beta^2 U - W)];$$
$$O_{11} = R\beta^2\mu_1[\beta y_2(\beta W - E) + y_3(E - \beta^2 V) + y_4(\beta V - W)]; O_{21} = R\beta\mu_1[\beta^2 y_1(E - \beta W) + y_3(\beta^3 U - E) + y_4(W - \beta^2 U)];$$
$$D_{11} = F\beta^2[\beta y_2(\beta W - E) + y_3(E - \beta^2 V) + y_4(\beta V - W)]; D_{21} = F\beta[\beta^2 y_1(E - \beta W) + y_3(\beta^3 U - E) + y_4(W - \beta^2 U)];$$
$$\Phi_{11} = F\beta^2\mu[\beta y_2(C - \beta N) + y_3(\beta^2 M - C) + y_4(N - \beta M)]; \Phi_{21} = F\beta\mu[\beta^2 y_1(\beta N - C) + y_3(C - \beta^3 K) + y_4(\beta^2 K - N)];$$
$$S_{11} = F\beta^2\mu_1[\beta y_2(\beta N - C) + y_3(C - \beta^2 M) + y_4(\beta M - N)]; S_{21} = F\beta\mu_1[\beta^2 y_1(C - \beta N) + y_3(\beta^3 K - C) + y_4(N - \beta^2 K)];$$
$$A_{31} = R\beta[\beta y_1\left(C - \beta^2 M\right) + y_2\left(\beta^3 K - C\right) + y_4\left(M - \beta K\right)]; A_{41} = R\beta[\beta y_1(\beta M - N) + y_2(N - \beta^2 K) + y_3\left(\beta K - M\right)];$$
$$B_{31} = R\beta\mu[\beta y_1(E - \beta^2 V) + y_2(\beta^3 U - E) + y_4(V - \beta U)]; B_{41} = R\beta\mu[\beta y_1(\beta V - W) + y_2(W - \beta^2 U) + y_3(\beta U - V)];$$
$$O_{31} = R\beta\mu_1[\beta y_1(\beta^2 V - E) + y_2\left(E - \beta^3 U\right) + y_4(\beta U - V)]; O_{41} = R\beta\mu_1\left[\beta y_1(W - \beta V) + y_2\left(\beta^2 U - W\right) + y_3(V - \beta U)\right];$$
$$D_{31} = F\beta[\beta y_1(\beta V - E) + y_2\left(E - \beta^3 U\right) + y_4\left(\beta U - V\right)]; D_{41} = F\beta\left[\beta y_1(W - \beta V) + y_2\left(\beta U - W\right) + y_3\left(V - \beta U\right)\right];$$
$$\Phi_{31} = F\beta\mu[\beta y_1(C - \beta M) + y_2(\beta^3 K - C) + y_4(M - \beta K)]; \Phi_{41} = F\beta\mu[\beta y_1(\beta M - N) + y_2(N - \beta K) + y_3(\beta K - M)];$$
$$S_{31} = F\beta\mu_1[\beta y_1(\beta^2 M - C) + y_2(C - \beta^3 K) + y_4(\beta K - M)]; S_{41} = F\beta\mu_1\left[\beta y_1(N - \beta M) + y_2(\beta K - N) + y_3(M - \beta K)\right],$$

where R and F are the forces acting on the driving roller and are given by the expressions: $R = R_1 + R_2; F = F_1 - F_2\ (F_1 = T; F_2 = S\cos(z - \varphi); R_1 = Q; R_2 = S\sin(z - \varphi))$; K, U, M, V, N, W, C, E are the coefficients depending on the properties of a material and are given by the formulas:

$$K = -\beta\cos(\beta - z) + \sin(\beta - z) + \sin z;\ U = \beta\sin(\beta - z) + \cos(\beta - z) - \cos z;$$
$$M = -\beta^2\cos(\beta - z) + 2U;$$
$$V = \beta^2\sin(\beta - z) - 2K;\ N = -\beta^3\cos(\beta - z) + 3V;\ W = \beta^3 sin(\beta - z) - 3M;$$
$$C = -\beta^4\cos\left(\beta - z\right) + 4W;\ E = \beta^4\sin\left(\beta - z\right) - 4N;$$

where Δ is the determiner of a system of equations which is given by the expression:

$$\Delta = \beta[y_2(l_3l_8 - l_4l_7) + y_3(l_1l_6 - l_2l_8) + y_4(l_2l_7 - l_3l_6)] - \beta^2[y_1(l_2l_8 - l_4l_6) + y_3(l_4l_5 - l_1l_8) + y_4(l_1l_6 - l_2l_5)] +$$
$$+\beta^3\left[y_1(l_2l_8 - l_4l_6) + y_2(l_4l_5 - l_1l_8) + y_4(l_1l_6 - l_2l_5)\right] + \beta^4\left[y_1(l_2l_7 - l_3l_6) + y_2(l_3l_5 - l_1l_7) + y_3(l_1l_6 - l_2l_5)\right],$$

где $l_1 = K + \mu U - \mu_1 U$; $l_2 = M + \mu V - \mu_1 V$; $l_3 = N + \mu W - \mu_1 W$; $l_4 = C + \mu E - \mu_1 E$;

$l_5 = U - \mu K + \mu_1 K$; $l_6 = V - \mu M + \mu_1 M$; $l_7 = W - \mu N + \mu_1 N$; $l_8 = E - \mu C + \mu_1 C$,

where μ and μ_1 are the coefficients of the resistance to movement and cohesion of the drum. The analysis of the equation shows that if there is no torque ($\mu_1 = 0$), the stresses in the contact zone of the drum are distributed as follows:

$$\sigma_к = (A_{11} + B_{11} + D_{11} + \Phi_{11})\varphi/\Delta + (A_{21} + B_{21} + D_{21} + \Phi_{21})\varphi^2/\Delta +$$
$$+(A_{31} + B_{31} + D_{31} + \Phi_{31})\varphi^3/\Delta + (A_{41} + B_{41} + D_{41} + \Phi_{41})\varphi^4/\Delta . \quad (22)$$

Under this condition, the equation for the distribution of contact stresses along the contact arc of the driving roller corresponds to the equation for the driven roller. During compaction of a material with a small angle of internal friction, when we can conditionally assume μ = 0, the equation takes the following form:

$$\sigma_к = (A_{11} + D_{11})\varphi/\Delta + (A_{21} + D_{21})\varphi^2/\Delta + (A_{31} + D_{31})\varphi^3/\Delta + (A_{41} + D_{41})\varphi^4/\Delta) . \quad (23)$$

If there is no tractive effort, i.e., at $F = 0$ and $\mu_1 = \mu = 0$, the stresses under the drum are given by the expression:

$$\sigma_к = A_1 \cdot \varphi/\Delta + A21 \cdot \varphi^2/\Delta + A31 \cdot \varphi^3/\Delta + A41 \cdot \varphi^3/\Delta . \quad (24)$$

The components of the total stress in the contact zone of the driving roller of the drum are as follows:

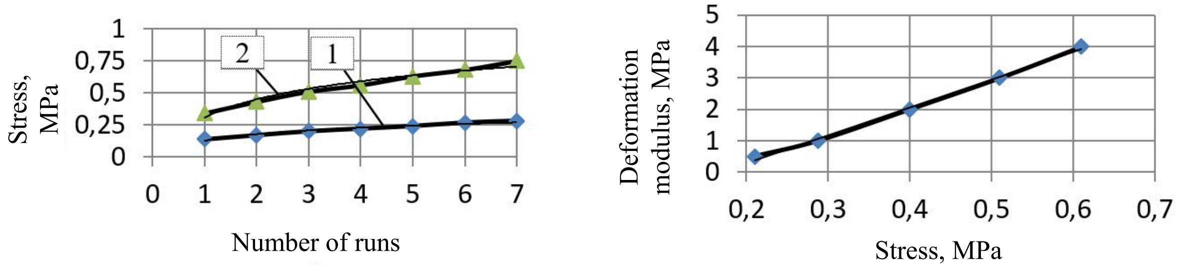
$$\sigma_{Qy} = (A_{11}\varphi + A_{21}\varphi^2 + A_{31}\varphi^3 + A_{41}\varphi^4)/\Delta; \tau_{Fy} = (D_{11}\varphi + D_{21}\varphi^2 + D_{31}\varphi^3 + D_{41}\varphi^4)/\Delta ,$$

$$\sigma_{Qx} = (B_{11}\varphi + B_{21}\varphi^2 + B_{31}\varphi^3 + B_{41}\varphi^4)\ /\Delta; \tau_{Fx} = (\Phi_{11}\varphi + \Phi_{21}\varphi^2 + \Phi_{31}\varphi^3 + \Phi_{41}\varphi^4)/\Delta ,$$

$$\tau_{sy} = S_{11}\varphi + S_{21}\varphi^2 + S_{31}\varphi^3 + S_{41}\varphi^4)/\Delta; \tau_{sx} = (O_{11}\varphi + O_{21}\varphi^2 + O_{31}\varphi^3 + O_{41}\varphi^4)/\Delta . \quad (25)$$

The resulting solution of the system of equations corresponds to the particular cases of contact of the driving roller of the drum with a compacted material in all modes of its operation. The above dependence makes it possible to identify the stresses in the contact zone of the roller of the drum with a compacted material depending on the power parameters of the roller and the properties of a compacted material.

4. Results of calculations of stresses in contact zone of the roller with a compacted material. In order to identify the stresses in the contact zone of the roller with a compacted material, a software program was developed [13] which makes it possible to establish the dependence of the stresses on the number of roller runs along one track and the properties of a compacted material. The results of calculating the stress under the roller drum (for a light roller with a weight of 1.5t and a heavy roller with a weight of 12.5t) and their effect on the deformation modulus of a compacted layer of asphalt granulate are in Fig. 13.



a) **b)**

Fig. 13. Dependence of the stresses on the number of roller (a) deformation modulus on the stress (b): 1 is a roller with a weight of 1.5t; 2 is a roller with a weight of 12.5t

Based on the data in Fig. 13, the value of the maximum stresses under the roller of the drum increases as does in the number of runs along one track, which is associated with a decrease in the contact angle of the roller. An increase in stress leads to that in the deformation modulus of a compacted material, which contributes to a decrease in the angle of contact of the roller with the surfacing (Fig. 14).

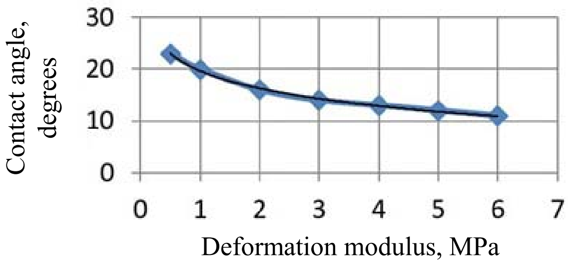


Fig. 14. Dependence of the contact angle of the roller drum on the deformation modulus of a compacted material

5. Results of the experimental studies of the influence of the parameters of the rollers on the quality of compaction of an asphalt granulate layer. In order to clarify the results obtained while modeling the process of compaction of an asphalt granulate layer and the influence of the parameters of the rollers on the quality of compaction in production conditions, experimental studies were performed. A link consisting of a 1.5t roller (DM-02-VD) and a vibrating smooth drum roller (Bomag BV213D4) with a weight of 12.3t in static operation was used as compaction machines. The thickness of a layer was 0.2m, the size of the fraction was 5—20 mm. In the process of compaction, the deformation of the material layer following each run of the roller, the angle of contact of the drum with the material, density and compaction coefficient were measured using the PAB-1 device. Figure 15 shows the results of measurements of deformation following each run of the roller.

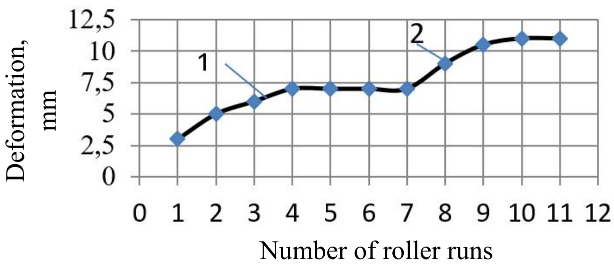
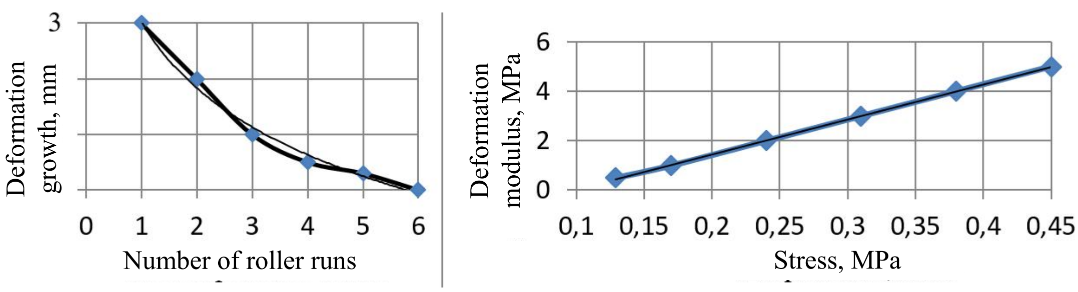


Fig. 15. Dependence of the deformation of an asphalt granulate layer on the number of roller runs: 1 is a roller DM-02-VD; 2 is Bomag BV213D4

According to the results, as the number of the roller runs along one track increases, so does the total deformation of the material layer to a certain value regardless of the parameters of the roller and then stabilizes. Thus depending on the power parameters (*q, R*), each roller has a specific field of application. At the same time, the residual deformation following each pass of the roller decreases accompanied by an increase in the material deformation modulus due to that in the stress in the contact zone of the roller with a compacted surface (Fig. 16).



a) **b)**

Fig. 16. Dependences of a deformation growth of a material following a roller run (a) and deformation modulus on the stress for a light roller (b)

Based on the data in Fig. 16, the compaction capacity of the roller depends on the force parameters (q/r) and the properties of the compacted material characterized by the deformation modulus. With constant power parameters of the roller and its run along one track, due to an increase in the material deformation modulus, the contact angle of the drum with the layer surface changes, which leads to a rise in contact stresses under the roller of the drum. E.g., Fig. 17 shows the dependence of the drum contact angle on the number of roller runs.

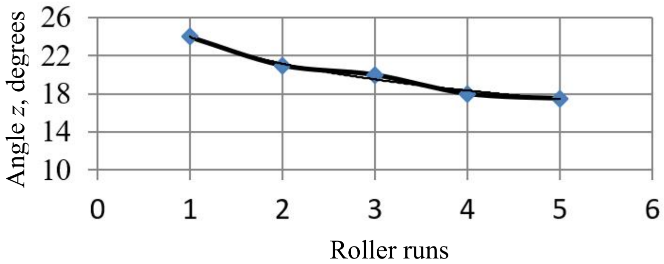


Fig. 17. Dependence of the contact angle of the drum on the number of roller runs

The analysis of the simulation results (Fig. 11) and the data of the experimental studies of changes in the angle of contact of the drum with a layer surface during roller runs showed that they are governed by the general laws. The maximum deformation of the compacted material is provided after 3—4 runs along one track. With subsequent runs of the roller, the increment of the layer deformation slows down due to an increase in the density of the material and at the final stage of compaction the deformation does not occur. The use of rollers at the initial stage of layer compaction whose strength characteristics exceed the ultimate strength of the material leads to the development of plastic deformations in a compacted material layer.

Change in the material density during compaction is characterized by the compaction coefficient whose value for an asphalt granulate with a fraction of 5—20 mm can be given by the formula:

$$K_y = 0.775e^{0.0083\lambda}, \tag{26}$$

where λ is the deformation, mm. The coefficient of the equation is 0.96.

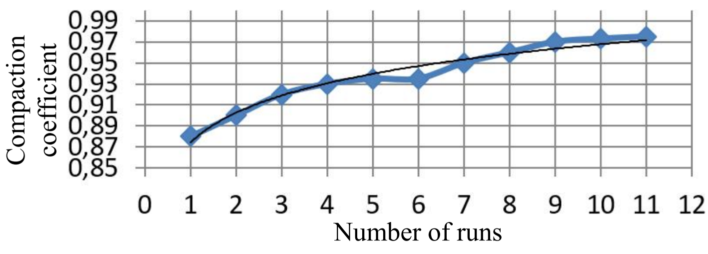


Fig. 18. Dependence of the compaction coefficient of an asphalt granulate layer on the number of roller runs

Considering the deformation of the material layer caused by stress (Fig. 15), Fig. 18 shows change in the compaction coefficient from the number of roller runs along one track.

Conclusions.

1. Ensuring the required quality of compaction of asphalt granulate depends on the compliance of the strength characteristics of a layer material with the load acting on it. Change in the thickness during the laying of a layer of asphalt granulate was found to affect the deformation and strength characteristics, which must be taken into consideration when assigning the parameters of compacting machines. An analytical dependence of the effect of the layer thickness on the ultimate strength and the deformation modulus of an asphalt granulate layer on the load has been obtained.
2. According to the results of the experimental studies, the regularities of the influence of the properties of the compacted material and the parameters of the roller on the arc of the roller contact during compaction are justified. The resulting analytical dependence for identifying the stresses in the contact zone of the drum with the material considering its deformability and the power parameters of the roller makes it possible to justify the parameters of the compaction machine depending on the properties of a material.
3. The relationships between the load and deformation of a material layer, the deformation and the coefficient of compaction under a compaction load considering the fractional composition of asphalt granulate have been experimentally established.
4. The suggested methodology for developing the technology of layers with the use of asphalt granulate enables one to ensure the required quality of compaction considering the properties of the material, the thickness of the layer to be laid and the parameters of compacting machines and can thus be employed in the development of technology for construction of road structure layers.

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