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Theoretical determination of the law of motion of vibrating plate at surface compaction of polymer concrete

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To theoretically determine the law of motion of a vibrating plate with polymer concrete, the dynamic system "vibration plate - polymer concrete" was researched. The compacted polymer concrete in it is presented as a system with distributed parameters, which takes into account the action of elastic and dissipative resistance forces from polymer concrete at its surface compaction. In accordance with the accepted rheological model of polymer concrete, a partial derivative ratio between stress and deformation is proposed for conditions of a uniaxial stress state. A vibration wave equation describing the motion of the compacted polymer concrete was created. Its solution enables the determination of the law of propagation of elastic-viscous deformation waves in polymer concrete.

Key words: vibrating plate, polymer concrete, vibrations, deformation.

Теоретичне визначення закону руху вібраційної плити при поверхневому ущільненні полімерного бетону

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Для теоретичного визначення закону руху поверхневого вібраційного робочого органу з полімерним бетоном виконано дослідження динамічної системи «вібраційна плита – полімерний бетон». У даній динамічній системі ущільнюваний полімерний бетон уявлений у вигляді системи з розподіленими параметрами, яка враховує дію пружних і дисипативних сил опору, що діють з боку полімерного бетону при його деформуванні у формі на жорсткій основі. Відповідно до прийнятої реологічної моделі полімерного бетону для умов одноосного напруженого стану запропонована залежність у приватних похідних між напруженням і деформацією полімерного бетону, характер якої залежить від динамічного модуля пружної деформації, динамічного модуля пружної деформації Максвелла та коефіцієнта динамічної в'язкості. Складено хвильове рівняння коливань, яке описує поширення пружно-в'язких хвиль деформації у полімерному бетоні, що деформується поверхневим вібраційним робочим органом, розв'язання якого дозволило визначити: закономірність поширення пружно-в'язких хвиль деформації у полімерному бетоні, що ущільнюється, а також теоретичні вирази для чисельного визначення наведених коефіцієнтів жорсткості та дисипативного опору полімерного бетону, приєднаної маси; закон руху і амплітуду коливань вібраційної плити, а також закономірності руху поверхневого шару полімерного бетону. Отримані теоретичні залежності дозволяють обгрунтовано визначити раціональні параметри вібраційного робочого органу залежно від фізико-механічних властивостей полімерного бетону, що ущільнюється, а отримані результати можуть надалі використовуватися для проведення теоретичних досліджень для аналітичного визначення закону зміни напружень, що виникають в ущільнюваному шарі полімерного бетону при вібраційному ущільненні, а також при аналізі та синтезі отриманого віброударного режиму роботи вібраційної плити.

Ключові слова: вібраційна плита, полімерний бетон, коливання, деформація.

Introduction

At surface compaction of polymer concrete by a vibration method, the vibrating plate of the working body interacts with the compacted medium. At the same time, the physical and mechanical characteristics of the compacted polymer concrete have a significant impact on the behavior of the dynamic system of vibration equipment and the choice of its main operating parameters. Determination of the physical and mechanical characteristics of the compacted polymer concrete will make it possible to establish a rational law of motion of a vibrating plate interacting with polymer concrete, to assess the operating modes of a vibrating plate, to correctly select the technological parameters of vibration action, the use of which will ensure effective compaction of polymer concrete.

Review of the research sources and publications

At present, research has been carried out on the process of vibration compaction of polymer concrete on a vibrating plate with vertically directed vibrations [1-5]. In papers [1, 2], a mathematical model of a dynamic system of a vibrating plate interacting with polymer concrete was created. As a result of the research, analytical expressions were obtained to determine the dynamic moduli of elastic deformation and the coefficient of dynamic viscosity of polymer concrete [3, 4], the law of motion of the movable frame of the vibrating plate and polymer concrete, depending on its physical and mechanical characteristics, the amplitude and frequency of forced vibrations and the height of the compacted layers. In paper [5], the design scheme of the dynamic system "vibrating working body - polymer concrete" is substantiated.

For the effective operation of vibration compaction equipment, it is necessary to accurately determine its main parameters and modes of vibration action, depending on the physical and mechanical characteristics of the compacted medium, which can be represented by various types of rheological models [6-9]. In [1-5], the physical and mechanical characteristics of polymer concrete compacted by vibration load are presented by the Zener rheological model, which, along with reversible and irreversible deformation, describes reversible highly elastic deformation, which is most clearly manifested in media containing polymers [10-12]. At the same time, for the most accurate description, polymer concrete is presented in the form of a system with distributed parameters, taking into account its elastic and viscous properties.

Definition of unsolved aspects of the problem

All these results were obtained to determine the rational parameters of vibration areas and cannot be applied to surface vibration compactors of polymer concrete.

Therefore, carrying out further theoretical research aimed at accurately determining the law of motion of vibration equipment for surface compaction of polymer concrete, determining the modes of vibration impact depending on the physical and mechanical characteristics of the compacted material and the size of the products is a very topical task.

Problem statement

The purpose of this research is to theoretically determine the law of motion of the vibrating plate of the working body during surface compaction of polymer concrete.

Basic material and results

Determining theoretically the resistance forces acting during surface compaction in the vertical direction from the polymer concrete on the vibrating plate, let us consider the design scheme of the dynamic system "vibrating plate - polymer concrete", in which polymer concrete is presented in the form of a system with distributed parameters [4] (Fig. 1).

In the operating mode, the vibration plate 3 of the working body, which is suspended on elastic shock absorbers 2 to the support frame 1, is subjected to the disturbance in the form of a vertically directed harmonic force $Q\,\sin\omega t$. As a result, vibrating plate 3 vibrates in the vertical plane and vibrates the polymer concrete 5 in the mold 4. With this interaction, a stress state occurs in the deformable layer of polymer concrete 5.

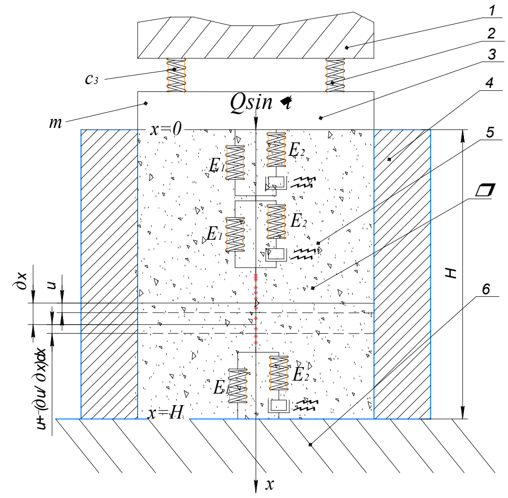

Figure 1 – Design diagram of the dynamic system "vibration plate - polymer concrete":
1 – support frame; 2 – elastic shock absorber;
3 – vibrating plate; 4 – mold;
5 – polymer concrete; 6 – base

In accordance with the proposed rheological model of polymer concrete [6], the relationship between stress and deformation in polymer concrete has the form [1]:

$$\sigma(x,t) = E_1\frac{\partial u(x,t)}{\partial x} + \eta\cdot\left(\frac{E_1+E_2}{E_2}\right)\frac{\partial^2 u(x,t)}{\partial x\partial t} - \left(\frac{\eta\cdot\rho}{E_2}\right)\frac{\partial^3 u(x,t)}{\partial t^3} \quad (1)$$

where $\sigma(x,t)$ – stresses arising in the compacted layer of polymer concrete;

u and x – Euler and Lagrangian coordinates;

E_1 and E_2 – dynamic modulus of elastic deformation of polymer concrete;

η – dynamic viscosity coefficient taking into account internal friction in polymer concrete;

ω – forced angular frequency; t – current time.

Functional values of dynamic modules E_1, E_2 and η based on the paper [4] can be found due to the following expressions:

$$E_1 = E_{01} \cdot \left[1 + \mu \cdot \left((\rho - \rho_0) / (\rho_k - \rho) \right)^z \right], \quad (2)$$

$$E_2 = E_{02} \cdot \left[1 + \mu \cdot \left((\rho - \rho_0) / (\rho_k - \rho) \right)^z \right], \quad (3)$$

$$\eta = H_1 \cdot \sqrt{(E_1 + E_2)\rho}, \quad (4)$$

where E_{01} and E_{02} – dynamic modulus of elastic deformation of uncompacted polymer concrete at an initial density ρ_0 (E_{01} =3.12 MPa, E_{02} = 4.28 MPa);
μ and z – experimental coefficients taken accordingly 3.5 and 3;
ρ – the current value of the polymer concrete density corresponding to the applied dynamic load P, kg/m^3;
ρ_0 – initial density of polymer concrete, kg/m^3;
ρ_k – density of polymer concrete mixture under load P_k = 40 MPa;
H_1 –reduced thickness of the compacted layer of polymer concrete, taken depending on the vibration direction and the ratio between the wavelength of the disturbance and the layer thickness [4].

Vibrations of polymer concrete layer in the direction of the coordinate x in time t will be of the form [1, 2]:

$$\frac{\partial \sigma(x,t)}{\partial x} = \rho \frac{\partial^2 u(x,t)}{\partial t^2}, \quad (5)$$

where ρ – polymer concrete density.

Substituting expression (1) into (5), we obtain the differential equation of motion of the compacted polymer concrete in the form [1]:

$$\frac{\partial^2 u(x,t)}{\partial x^2} + \eta \cdot \left(\frac{E_1 + E_2}{E_1 \cdot E_2} \right) \cdot \frac{\partial^3 u(x,t)}{\partial x^2 \partial t} - \left(\frac{\eta \cdot \rho}{E_1 \cdot E_2} \right) \cdot \frac{\partial^3 u(x,t)}{\partial t^3} = \left(\frac{\rho}{E_1} \right) \cdot \frac{\partial^2 u(x,t)}{\partial t^2}, \quad (6)$$

To solve the wave equation of vibrations (6), we use the following boundary conditions resulting from the design scheme in Fig. 1:
at $x = 0$:

$$-m \frac{\partial^2 u(0,t)}{\partial t^2} - c_3 u(0,t) + E_1 F \frac{\partial u(0,t)}{\partial x} + \left(\frac{E_1 + E_2}{E_2} \right) \times \eta F \frac{\partial^2 u(0,t)}{\partial x \partial t} - \left(\frac{\eta \rho F}{E_2} \right) \frac{\partial^3 u(0,t)}{\partial t^3} = -Q \sin(\omega t) \quad (7)$$

at $x = H$:

$$u(H,t) = 0, \quad (8)$$

where m – vibrating plate mass;
c_3 – coefficient of stiffness of elastic shock absorbers in the vertical direction in the vibrating plate suspension;
F – vibrating plate bearing surface area;
Q – disturbing force amplitude;
H – height of the compacted layer of polymer concrete.

Boundary condition (7) describes the interaction of the vibrating plate with the surface of the compacted polymer concrete. Boundary condition (8) indicates that the displacement of the compacted layer of polymer concrete at a distance H from the surface of the vibrating plate is zero.

We represent the solution to equation (6) in the form of the imaginary part of the complex number [1]:

$$u(x,t) = u(x) \cdot e^{i\omega \cdot t}, \quad (9)$$

where $u(x)$ – complex vibration amplitude meeting the boundary conditions for the design diagram shown in Fig. 1.

Using the technique described in [1], we find a solution to equation (6) in the complex form:

$$u(x,t) = \left[B \cdot e^{-(ik+\alpha)\cdot x} + D \cdot e^{(ik+\alpha)\cdot x} \right] \cdot e^{i\omega \cdot t}, \quad (10)$$

where B and D – integration constants (complex amplitudes) determined by boundary conditions (7) and (8).

The functional values of coefficients α and k are determined in [1].

To determine integration constants B and D we substitute expression (10) into the boundary condition (8) and, after transforming, we find the relation between the complex amplitudes in the form:

$$B = -D \cdot \frac{e^{(ik+\alpha)\cdot H}}{e^{-(ik+\alpha)\cdot H}}. \quad (11)$$

Substituting the found value B from relation (11) into expression (10), we find a solution to equation (6) in the form:

$$u(x,t) = D \left[\frac{-e^{(ik+\alpha)\cdot(H-x)} + e^{-(ik+\alpha)\cdot(H-x)}}{e^{-(ik+\alpha)\cdot H}} \right] e^{i\omega \cdot t}. \quad (12)$$

Substitute expression (12) into the boundary condition (7). Based on (9) expression $Q \sin \omega t$ in boundary condition (7) can be represented as the imaginary part of a complex function, namely $Q \sin \omega t = Q e^{i\omega t}$. After the transformations, we get the following expression:

$$2D \cdot \left\{ sh[(ik+\alpha)H] \cdot \left(c_3 - m\omega^2 - \frac{i\omega^3 \rho F}{E^2} \right) - ch[(ik+\alpha)H](ik+\alpha)F \left(E_1 + i\omega\eta \left(\frac{E_1 + E_2}{E_2} \right) \right) \right\} = Q \cdot e^{-(ik+\alpha)H} \quad (13)$$

Transforming expression (13), we determine the integration constant D in the following form:

$$D = \frac{Q \cdot e^{-(ik+\alpha)H}}{2sh[(ik+\alpha)H](c_3 + c_n - (m + m_n)\omega^2 + i\omega b_n)} \quad (14)$$

where c_n – reduced coefficient of compacted polymer concrete stiffness;
m_n – the reduced mass of compacted polymer concrete;
b_n – reduced coefficient of dissipative resistance of compacted polymer concrete:

$$c_n = F\left[(E_1\alpha)sh(2\alpha H) + \left(E_1 k + \eta\omega\alpha\left(\frac{E_1 + E_2}{E_2}\right)\right)\sin(2kH)\right] / [ch(2\alpha H) - \cos(2kH)] \; ; \quad (15)$$

$$m_n = Fk\eta\left(\frac{E_1 + E_2}{E_2}\right)sh(2\alpha H) / \omega \cdot [ch(2\alpha H) - \cos(2kH)] \quad (16)$$

$$b_n = \frac{1}{\omega}\left(\frac{F[(E_1 k + \eta\omega\alpha((E_1 + E_2)/E_2))sh(2\alpha H) - (E_1\alpha - \omega\eta k((E_1 + E_2)/E_2))\sin(2kH)]}{[ch(2\alpha H) - \cos(2kH)]} - \frac{F\omega^3\rho}{E_2}\right). \quad (17)$$

It follows from expressions (15) – (17) that numerical values of coefficients c_n, b_n and m_n will depend on the area of the supporting surface F of the vibrating plate; dynamic modulus of elastic deformation of polymer concrete E_1 and E_2; dynamic viscosity coefficient η; angular frequency of forced vibrations ω; the height of the compacted layer of polymer concrete H, vibration absorption coefficient α and wave number k. Substituting the value of integration constant D from (14) into expression (11), we determine integration constant B:

$$B = -\frac{Qe^{(ik+\alpha)H}}{2sh[(ik+\alpha)H]} \times \frac{Qe^{(ik+\alpha)H}}{(c_3 + c_n - (m + m_n)\omega^2 + i\omega b_n)} . \quad (18)$$

Substituting the found integration constants (14) and (18) into dependence (10), we find in the complex form the solution to the wave equation of vibrations (6), meeting the boundary conditions (7) and (8):

$$u(x,t) = \frac{Qsh[(ik+\alpha)(H-x)]e^{i\omega\cdot t}}{sh[(ik+\alpha)H]} \times \frac{Qsh[(ik+\alpha)(H-x)]e^{i\omega\cdot t}}{(c_3 + c_n - (m + m_n)\omega^2 + i\omega b_n)} \quad (19)$$

Multiply the numerator and denominator of expression (19) by a complex number $(c_3+c_n-(m+m_n)\omega^2-i\omega b_n)$, after performing the decomposition of expressions $sh[(ik+\alpha)(H\text{-}x)]$ in the numerator and $sh[(ik+\alpha)H]$ in the denominator, and, separating the imaginary part of the complex function from the obtained expression, we get a solution to the wave equation of oscillations (6) meeting the boundary conditions (7) and (8) in the following form:

$$u(x,t) = \frac{A}{\sqrt{(sh\alpha H\cos kH)^2 + (ch\alpha H\sin kH)^2}} \times [sh[\alpha(H-x)]\cos[k(H-x)]\sin(\omega t - \theta) + ch[\alpha(H-x)]\sin[k(H-x)]\cos(\omega t - \theta)] \quad (20)$$

where A – amplitude of forced vibrations of the vibrating plate and the upper layer of polymer concrete:

$$A = \frac{Q}{\sqrt{[c_3 + c_n - (m + m_n)\omega^2]^2 + \omega^2 b_n^2}} \; ; \quad (21)$$

$$\theta = \varphi_1 + \varphi_2 \; ; \quad (22)$$

$$\varphi_1 = arctg\left(\frac{\omega \cdot b_n}{c_3 + c_n - (m + m_n)\omega^2}\right) \; ; \quad (23)$$

$$\varphi_2 = arctg(cth(\alpha H) \cdot tg(kH)) . \quad (24)$$

Expression (20) describes the law of the polymer concrete motion compacted by a vibrating plate of the researched dynamic system "vibrating plate - polymer concrete" in the direction of the coordinate x depending on the angular frequency of forced vibrations ω, the amplitude of the disturbing force Q, the thickness of the compacted layer H and the current time value t.

At $x = 0$ expression (20) describes the law of the vibrating plate motion of the surface vibrating working body in the form:

$$u(0,t) = A \cdot \sin(\omega t - \varphi_1) \; . \quad (25)$$

Taking into account the physical and mechanical characteristics of the compacted polymer concrete makes it possible to quite accurately determine the law of motion of the vibrating plate and select the modes of vibration action, which ensure the most effective compaction of polymer concrete. The obtained expressions (15)-(17) enable the determination of the physical and mechanical characteristics of polymer concrete in its model representation, which can be used in the research of complex dynamic systems.

Specific reduced weight m_{ny}, as well as specific reduced coefficients of resistance b_{ny} and rigidity c_{ny} of polymer concrete at vibrations of the movable frame of the vibrating platform in the vertical direction is determined by dividing m_n, b_n and c_n by the area F of the base of the molded product:

$$m_{ny} = \frac{m_n}{F} ; \quad b_{ny} = \frac{b_n}{F} ; \quad c_{ny} = \frac{c_n}{F} . \quad (26)$$

The theoretical provisions were tested on a laboratory vibrating working body with the following main parameters: the mass of the vibrating plate $m = 75$ kg; disturbing force amplitude Q =4415 N; forced angular frequency $\omega = 293$ rad/s; stiffness of elastic shock absorbers c_3 = 470880 N/m; the amplitude of vibrations of the movable frame of the vibrating plate in idle mode $A_{xx} = 0.68$ mm.

This vibrating working body was used to compact polymer concrete in a mold being the size in plan 0.2×0.4 m^2, of the following structural composition [13]: crushed granite fraction 5-20 (50 % of the total volume of the mixture), river sand with a fineness module M_k = 1.8 (22-27 %); marshal with fraction 0.05 mm (10-15 %); polyester resin Filabond 2000 PA (5 %); hardener MEKP-HA-2 (0,5…1 %).

Height H of the compacted layer was taken equal to 50, 60, 80, 100, 120, and 150 mm.

Figs. 4 and 5 show the change in the coefficients of specific reduced stiffness c_{ny} and dissipative resistance b_{ny} of polymer concrete with vertical vibrations of a vibrating plate depending on the relative density ε and the height of the compacted layer H.

The obtained data analysis reveals that the specific reduced stiffness coefficients significantly depend on the compacted layer height H and relative density ε of the polymer concrete. In this case, the specific reduced coefficient of dissipative resistance b_{ny} at surface compaction significantly depends on the relative density ε of polymer concrete and to a lesser extent depends on the height of the compacted layer H.

Fig. 6 shows the change in the vibration amplitude of the vibrating plate A depending on the relative density ε and the compacted layer height H.

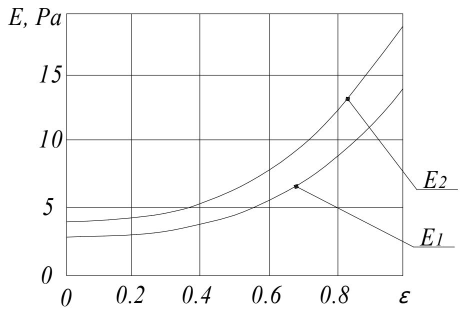

Figure 2 – Change in dynamic moduli of elastic deformation of polymer concrete E_1 and E_2 depending on the relative density ε

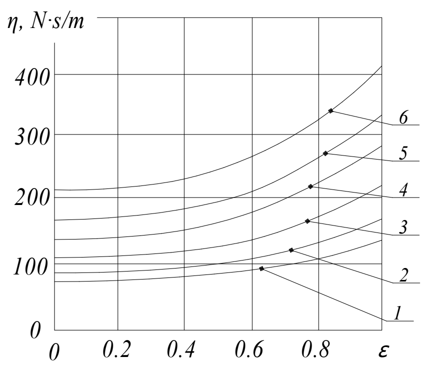

Figure 3 – Change in the coefficient of dynamic viscosity η depending on the relative density ε and the height of the compacted layer H:

1 – at H =50 mm; 2 – at H =60 mm;
3 – at H =80 mm; 4 – at H =100 mm;
5 – at H =120 mm; 6 – at H =150 mm

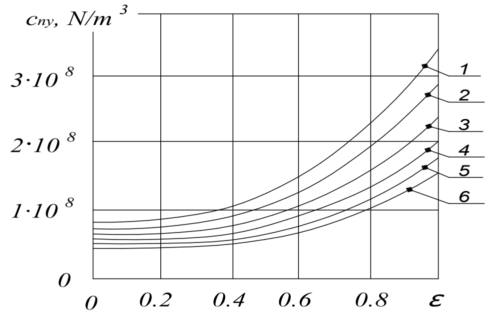

Figure 4 – Change in the specific reduced stiffness coefficient c_{ny} of polymer concrete depending on the relative density ε and the compacted layer height H:

1 – at H =50 mm; 2 – at H =60 mm;
3 – at H =80 mm; 4 – at H =100 mm;
5 – at H =120 mm; 6 – at H =150 mm

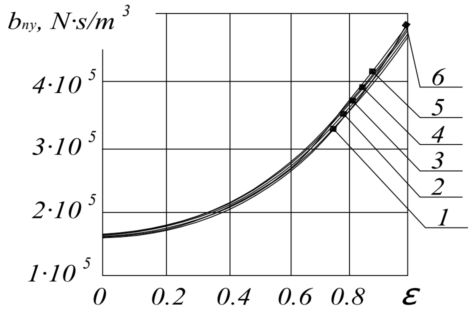

Figure 5 – Change in the specific reduced coefficient of dissipative resistance b_{ny} of polymer concrete depending on the relative density ε and of the compacted layer height H:

1 – at H =50 mm; 2 – at H =60 mm;
3 – at H =80 mm; 4 – at H =100 mm;
5 – at H =120 mm; 6 – at H =150 mm

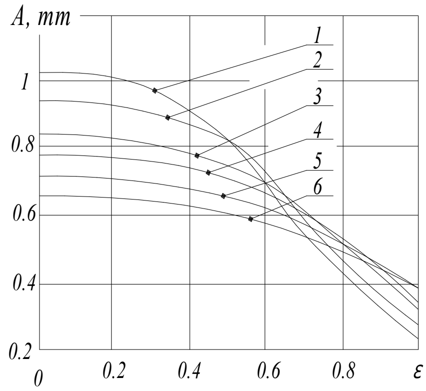

Figure 6 – Change in vibration amplitude A of a vibrating plate depending on the relative density ε and the compacted layer height H:

1 – at H =50 mm; 2 – at H =60 mm;
3 – at H =80 mm; 4 – at H =100 mm;
5 – at H =120 mm; 6 – at H =150 mm

Curves in Fig. 6 show that the physical and mechanical characteristics of polymer concrete and the compacted layer height H have a significant effect on the vibration amplitude A of the vibrating plate.

With an increase in the thickness of the compacted layer H from 50 to 150 mm and the relative density ε of polymer concrete, the vibration amplitude of the vibrating plate decreases.

At the very beginning of the vibration compaction process with the values of the layer heights H 50 and 60 mm and relative density ε from 0 to 0.5 there is a decrease in the vibration amplitude A of the vibrating plate, respectively, from 1.01 to 0.82 mm and from 0.93 to 0.82 mm. With a further increase in the relative density ε from 0.5 to 1 there is a significant decrease in the vibration amplitude A of the vibrating plate, respectively, to 0.23 and 0.27 mm.

During vibration compaction of polymer concrete of the specified composition with a layer thickness of 80, 100, 120, and 150 mm at a relative density ε from 0 to 0.5, a smoother decrease in the vibration amplitude of the vibration plate occurs. For the specified values ε the vibration amplitude changes from 0.83 to 0.76 mm at thickness $H = 80$ mm; from 0.77 to 0.71 mm – at $H = 100$ mm; from 0.72 to 0.67 mm at $H = 120$ mm and from 0.66 to 0.62 mm at $H = 150$ mm. With a further increase in the relative density ε from 0.5 to 1 there is a significant decrease in the vibration amplitude A of the vibrating plate to 0.39 ... 0.33 mm.

The obtained results make it possible to conclude that at the very beginning of the vibration compaction process at a relative density ε from 0 to 0.5 vibrating plate works in vibration mode. When this operating mode is implemented, the vibrating plate does not detach from the surface of the compacted layer of polymer concrete.

With a further increase in the relative density ε from 0.5 to 1 the dynamic system goes into the vibration-impact operation mode, in which the vibrating plate breaks off from the surface of the compacted layer of polymer concrete and moves in the air until the next impact. In this case, it is advisable to further research the discrete vibroimpact mode of operation of the vibrating plate interacting with the compacted plate, represented by the found physical and mechanical characteristics.

Thus, based on the study of the propagation of deformation waves in compacted polymer concrete, presented in the form of a system with distributed parameters, theoretical expressions were obtained to determine the physical and mechanical characteristics of the compacted medium (polymer concrete): stiffness and dissipative resistance coefficients. These coefficients make it possible to accurately determine the main parameters of the vibrating working body for surface compaction of polymer concrete, take them into account in the expression to establish the law of motion, and determine rational modes of vibration impact on polymer concrete, depending on the type of polymer concrete and its relative density, the height of the compacted layer, the vibration frequency and the amplitude of the disturbing force.

Conclusions

A physical and mechanical model has been developed as a result of theoretical research of the dynamic system "vibrating plate - polymer concrete". Polymer concrete is presented in it as a system with distributed parameters. The model enables rather accurate determination of elastic and dissipative forces acting from polymer concrete on a vertical vibrating plate moving in the vertical plane. The law of the vibrating plate motion of the working body is established depending on the found physical and mechanical characteristics of the compacted polymer concrete, the angular frequency of forced vibrations, and the thickness of the compacted layer.

The obtained theoretical expressions make it possible to reasonably choose the rational parameters of the working body for surface vibration compaction of polymer concrete.

The found results can be used in theoretical research on the analytical determination of the law of change in stresses arising in the compacted layer of polymer concrete, as well as in the analysis and synthesis of the obtained vibro-shock operation mode of the vibrating plate.

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