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Research paper

Investigation of Vibration Machine Interaction With Compacted Concrete Mixture

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Abstract

Dynamic system calculation scheme "Vibrating machine is compacting medium", where the latter is represented as a system with distributed parameters is compiled. As a result of the wave equation of oscillations solution, the law of compacting medium deformation over the entire thickness of the concrete layer is determined depending on the increasing density of the molded mixture, its physico-mechanical characteristics, the thickness of the concrete layer, the mass of the oscillating part of the vibrating machine, the frequency and amplitude of the disturbing force, elastic suspension stiffness and coefficient inelastic resistance. Changes in the compacting concrete medium resistance forces during the vibration compaction, depending on its consistency are determined.

Keywords: *Vibrating machine, Interaction, Compacting medium..*

1. Introduction

The physical and mechanical characteristics of the compacting medium largely determine the nature of vibrating machine dynamic system and significantly influence the determination of its basic parameters. A sufficiently accurate identification of the physico-mechanical properties of the compacting medium makes it possible to establish a rational law of motion and a stable mode of vibrating machine operation, to choose correctly the technological parameters of the vibrational effect on the medium to be treated, which usage ensures efficient compaction with low energy intensity.

In previous studies, the physico-mechanical characteristics of the deformable medium interacting with the vibrational working body were represented as discrete rheological models: the elastic Hooke model, the viscous body described by the Newton model, the viscoelastic body in the form of the Kelvin-Voigt or Maxwell model, the Bingham model [1], [2], [3], [4], [5],[6].

Many researchers have tried to present the physical and mechanical characteristics of a deformed medium by various mathematical curves in the form of exponentiation function or a combination of a exponentiation function with a straight line [7], [8], [9], [10], [11], 12].

Such a representation of the compacting medium does not enable us to accurately determine the rational parameters of the vibrating machine and the modes of vibration influence on the molded mixture, since it is not take into account the influence of the changing physical and mechanical characteristics of the compaction mixture during compaction, the frequency and amplitude of the vibration effect, the thickness of the compacting layer. The most accurate description gives an idea of the compacting medium as a system with distributed parameters, taking into account its elastic and viscous properties.

In work [15] the interaction of a vibrating working member with a compacting medium is analyzed with an average of the dynamic modulus of elastic deformation and the coefficient of dynamic viscosity of a concrete mixture. In the works [13, 14], the change in these physical and mechanical characteristics is shown as a function of the density of the mixture, continuously increasing during compaction. In these studies, it was accepted that the compacting concrete medium has a uniform structure and its vibrations under the action of a vibrational disturbance can be described by the corresponding wave equation [13, 14]. At the same time, the frictional forces arising inside the concrete mixture between its individual constituents during the reorientation of mineral particles and their convergence, deformation, redistribution of the binder were not taken into account. Therefore, in order to justify the rational parameters of the vibrating machine and determine the necessary mode of vibration action, it is necessary to accurately determine the change in the physico-mechanical characteristics of the compacting medium, take into account the effect of the emerging forces of resistance of the concrete mixture under influence vibrations of the vibrating machine [16], [17].

The aim of this work is to study the process of vibrating machine with a compacting medium interaction and to determine the regularities of its oscillations during different consistency concrete mixtures compacting

2 Deformations in the Compacting Waves Medium Distribution Investigation

To determine the resistance forces that arise in the compaction process, let us consider the design scheme of the dynamic system "Vibrating machine-compacting medium" (Fig. 1), including a vibrating table 1, installed by means of elastic shock absorbers 2 on the base plate 3 and vibro-exciters 4 and 5 mounted in the low-

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er part of the vibrating table. On the surface of the vibrating table is fixed form 6 with a concrete mixture 7. Under the influence of the vertically directed harmonic force $Q\sin\omega t$ generated by vibration exciters of vibrations 4 and 5, the concrete mixture is compacting. Here is Q – the amplitude of the disturbing force; ω – angular frequency of forced oscillations; t – time.

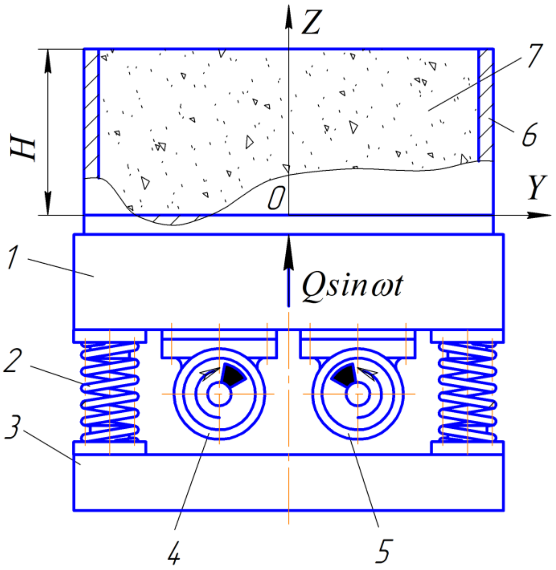

Fig. 1: Dynamic system "Vibrating machine is compacting medium" calculation scheme

Let us study the uniaxial stress state of a compacting concrete mix. In this case, the relationship between stress and deformation in a compacting medium is represented in the first approximation by the following equation:

$$\sigma(z,t) = E\frac{\partial u(z,t)}{\partial z} + \eta\frac{\partial u(z,t)}{\partial t}, \quad (1)$$

Where σ – the stresses occurring in the compacting volume in the vertical direction; u and z – Euler and Lagrange coordinates; E – dynamic modulus of elastic deformation of the volume being compressed; η – the coefficient of inelastic resistance of the compacting volume, taking into account the internal friction of mineral particles in the mixture to be sealed, the cost of energy to destroy internal bonds, the displacement of air, the reorientation of particles and other phenomena in the condensed medium accompanying the vibration seal.

Based on the presented calculation scheme (Fig. 1), we represent the motion of the condensed mixture in the direction of the coordinate z in time t in the form of a known differential equation (Maslov and Salenko,

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

where ρ – is the density of the concrete mixture in the compaction volume.

Taking into account expression (1), the dependence (2) is transformed into the following wave equation:

$$E\frac{\partial^2 u(z,t)}{\partial z^2} + \eta\frac{\partial^2 u(z,t)}{\partial z\partial t} - \rho\frac{\partial^2 u(z,t)}{\partial t^2} = 0 \quad (3)$$

The solution of the wave equation of the oscillations (3) for the mathematical model is sought under the following boundary conditions:

– at interaction of a compacting layer concrete with a surface of the bottom of the form 5 at a coordinate $z=0$,

$$-m\frac{\partial^2 u(0,t)}{\partial t^2} - b\frac{\partial u(0,t)}{\partial t} - cu(0,t) + EF\frac{\partial u(0,t)}{\partial z} + \eta F\frac{\partial u(0,t)}{\partial t} = -Q\sin\omega t; \quad (4)$$

– for the free surface of the compacting layer of the concrete mixture at the coordinate $z=H$,

$$\sigma(H,t) = EF\frac{\partial u(H,t)}{\partial z} + \eta F\frac{\partial u(H,t)}{\partial t} = 0. \quad (5)$$

Here is m – the mass of the vibration table along with the shape; , c and b – coefficients of stiffness and inelastic resistance of amortizators in the vertical direction; F – the area of the bottom of the vibrating plate, which contacts the sealing layer; H – height of the compacting layer.

We represent the solution of (3) in the form of an imaginary part of the complex function (Maslov and Salenko, 2014a), ie,

$$u(z,t) = U(z)e^{i\omega t}, \quad (6)$$

where $U(z)$ – the complex amplitude of the oscillations determined by the boundary conditions (4) and (5).

After substituting the function (6) into expression (3), we obtain an equation for determining the complex amplitude of the oscillations:

$$E\frac{\partial^2 U(z)}{\partial z^2} + i\eta\omega\frac{\partial U(z)}{\partial z} + \rho\omega^2 U(z) = 0. \quad (7)$$

solution of equation (7) is presented in the following form:

$$U(z) = (M\sin kz + N\cos kz)e^{-i\delta z}, \quad (8)$$

where M and N – the integration constants (complex amplitudes) determined by the boundary conditions (4) and (5); k – the wave number,

$$k = \sqrt{\frac{\eta^2\omega^2}{4E^2} + \frac{\rho\omega^2}{E}}; \quad (9)$$

δ – the absorption coefficient characterizing the damping of the perturbation,

$$\delta = \frac{\eta\omega}{2E}. \quad (10)$$

Substituting expression (8) into dependence (6), we find the solution of equation (3) in the following general form:

$$u(z,t) = (M\sin kz + N\cos kz)e^{i(\omega t - \delta z)}. \quad (11)$$

Substituting the resulting solution (11) into the boundary condition (5), we establish the relation between the integration constants M and N:

$$M = N\frac{k\sin kH - i\delta\cos kH}{k\cos kH + i\delta\sin kH}. \quad (12)$$

On the basis of the obtained dependence (12) the expression (11), will take the following form:

$$u(z,t) = N\frac{k\cos k(H-z)+i\delta\sin k(H-z)}{k\cos kH + i\delta\sin kH}e^{i(\omega t-\delta z)}. \quad (13)$$

To determine the integration constant N, it is substituted the analytic dependence (13) in the boundary equation (4) and obtain:

$$N = \frac{Q}{c-(m+\mu)\omega^2 + i\omega(b+\lambda)}, \quad (14)$$

where μ – is the reduced mass of the concrete mixture,

$$\mu = 0{,}5EFk\frac{(k^2-\delta^2)\sin 2kH}{\omega^2(k^2\cos^2 kH+\delta^2\sin^2 kH)}; \quad (15)$$

λ – the reduced inelastic resistance coefficient of the concrete mixture,

$$\lambda = 0{,}5\eta F\frac{(k^2-\delta^2)\sin^2 kH}{(k^2\cos^2 kH+\delta^2\sin^2 kH)}. \quad (16)$$

Substituting the expression (14) into the dependence (13), we find in complex form the solution of the wave equation of oscillations (3), which satisfies the boundary conditions (4) and (5):

$$u(z,t) = \frac{Q[k\cos k(H-z)+i\delta\sin k(H-z)]}{(k\cos kH+i\delta\sin kH)[c+\theta-(m+\mu)\omega^2+i\omega(b+\lambda)]}\times$$
$$\times e^{i(\omega t-\delta z)}. \quad (17)$$

Multiplying the numerator and the denominator of expression (17) by the conjugate complex functions in the round and square brackets of the denominator, and picking out the imaginary part of the complex function from the resulting expression, we obtain after the transformations the desired solution of equation (3) satisfying The boundary conditions (4) and (5), in the following form:

$$u(z,t) = \frac{Q}{\sqrt{[c-(m+\mu)\omega^2]^2+\omega^2(b+\lambda)^2}}\times$$
$$\times\left[\frac{k\cos k(H-z)\sin(\omega t-\delta z-\varphi_1)}{\sqrt{k^2\cos^2 kH+\delta^2\sin^2 kH}}+\right.$$
$$\left.+\frac{\delta\sin k(H-z)\cos(\omega t-\delta z-\varphi_1)}{\sqrt{k^2\cos^2 kH+\delta^2\sin^2 kH}}\right], \quad (18)$$

where φ_1 – the phase angle between the displacement and the amplitude of the disturbing force,

$$\varphi_1 = \varphi + \xi; \quad (19)$$

$$\varphi = \arctan\frac{\omega(b+\lambda)}{c-(m+\mu)\omega^2}; \quad (20)$$

$$\xi = \arctan\frac{\delta\sin kH}{k\cos kH}. \quad (21)$$

The obtained solution (18) of the wave equation (3), satisfying the boundary conditions (4) and (5), describes the law of oscillations of the dynamical system "Vibrating machine - compacting medium". At $z=0$ the obtained dependence (18) describes the oscillations of the lower layer of the compacted medium and the bottom of the form of the vibrating mashine:

$$u(0,t) = A\sin(\omega t-\varphi), \quad (22)$$

where A – the vibration amplitude of the vibrating machine,

With $z=H$ the obtained dependence (18) describes the oscillations of the upper layer of the compacting medium, i.e.

$$u(H,t) = A\frac{k}{\sqrt{k^2\cos^2 kH+\delta^2\sin^2 kH}}\sin(\omega t-\delta H-\varphi_1). \quad (24)$$

Analysis of the laws of motion of the compacted medium (18), the vibrating machine (22), and the upper layer of the compacted mixture (24) shows that the oscillation amplitude of the vibrating machine (23) as the law of motion of the compacting layer (18) itself essentially depends on inertial and dissipative forces resistance of the compacting medium determined by the reduced mass (15) and the reduced inelastic resistance coefficient λ (16) of the concrete mixture, as well as the angular velocity of the forced oscillations. elationship between the physical and mechanical characteristics of the medium to be consolidated, the height of the compaction layer, and the parameters of the vibrating action.

The value of the elastic deformation dynamic modulus of the mixture volume to be compacted, depending on the consistency of the concrete mix and its relative density

$$\varepsilon = \frac{\rho-\rho_0}{\rho_k-\rho_0} \quad (25)$$

can be represented in the form of the following exponential function:

$$E = E_0\left[1+z_1\cdot\varepsilon^{z_2}\right], \quad (26)$$

where E_0 – the dynamic modulus of elastic deformation of a non-compacted mixture layer at a density ρ_0, the values for different consistencies of concrete mixtures are given in Table 1; ρ_k – density of the packed layer of the mixture; z_1 and z_2 – the indices assumed to be equal $z_1=4$ and $z_2=2$ for heavy concrete mixtures with a cone draft of 3.5 ... 4 cm (the equivalent rigidity of the mixture G_e = 5-7 s) and rigidity of G_e = 30 ... 120 s [7].

The values of the inelastic resistance coefficient η for the volume of the medium under consideration can be determined with a sufficient degree of accuracy from the following relationship:

$$\eta = K_1He^{f_1}\sqrt{E\rho}. \quad (27)$$

where K_1 – the proportionality coefficient, $K_1=0{,}05$; f_1 – the coefficient of internal friction of a concrete mixture under vibration,

$$f_1 = f_0\left[\frac{\rho_k-\rho}{\rho_k}+G_e^{z_4}\varepsilon^{z_3}\right]; \quad (28)$$

f_0 – the coefficient of internal friction of the concrete mixture at the beginning of the vibration process of compaction; z_3 and z_4 – indicators m, that take the following values: z_3 = 0,3; z_4 = 0,08.

Obtained theoretical dependencies enable to take accurately into account the physical and mechanical characteristics of the compacting medium and to determine the rational parameters of the vibrating machine and the modes of vibration action, under which the effective compaction of concrete mixtures is ensured. Expressions (15 – 16) and (26 – 28) enable to determine the physical-mechanical characteristics of the concrete mixture at its dynamic loading. The present values of the mass μ and the coefficient of inelastic resistance λ of the concrete mixture, obtained on the basis of the wave theory of oscillations, can also be used in the study of complex dynamical systems with spatial oscillations and in the compaction of hollow-core reinforced concrete products and products with complex configurations.

3 Results and Discussion

The obtained theoretical dependencies were verified on a laboratory vibration machine with the following main parameters: mass of the vibration table together with the form $m = 65$ kg; amplitude of disturbing force Q =2700 N at angular frequency of forced oscillations ω =293 rad/s; the rigidity of elastic supports is $c = 240$ kN/м.

Concrete mixtures with a water-cement ratio of 0.4 were compacted on the vibrating machine. The concrete mixture was compacted in a mold having a size in the plan of 350 350 mm^2. Molded concrete products with a thickness 200 mm.

In Fig. 2 shows the changes in the dynamic modulus of elastic deformation E of concrete mixtures of different consistency under vibratory action as a function of the relative density of the concrete mixture. Analysis of the presented dependences shows that for all consistencies of the mixture, the values of the dynamic modulus of elastic deformation E increase with increasing relative density ε .

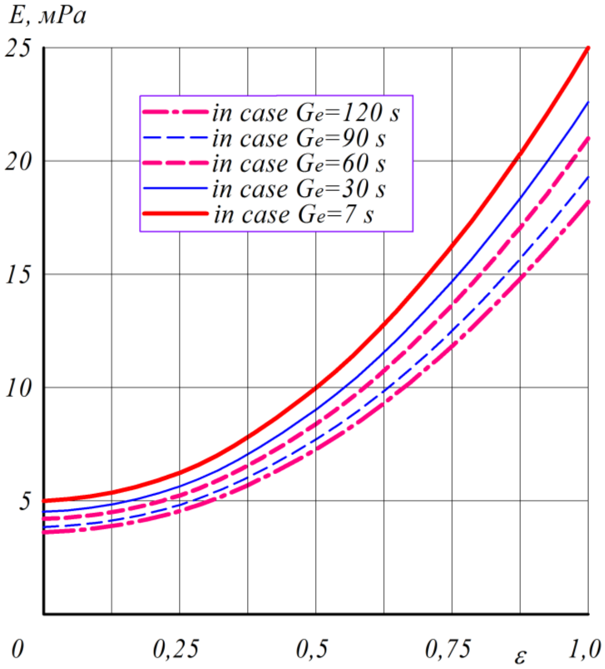

Fig. 2: Different consistency concrete mixtures dynamic modulus f elastic deformation modification (at a rigidities of Ge = 7-120 s) as a function of the mixture relative density

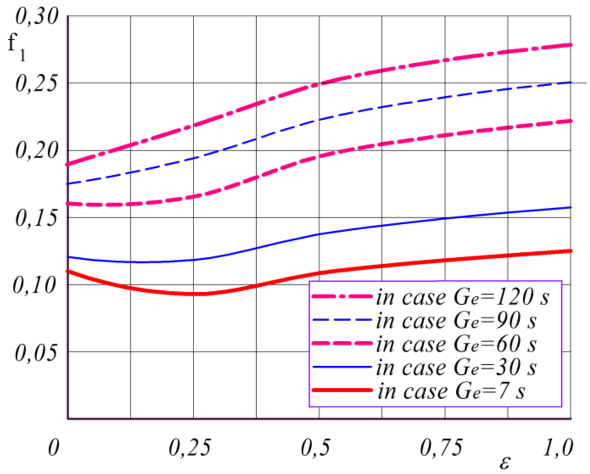

Fig. 3: The change in the coefficient of internal friction of concrete mixtures of different consistency (at a rigidities of 7 - 120 s) during the vibration compaction, depending on the relative density of the mixture

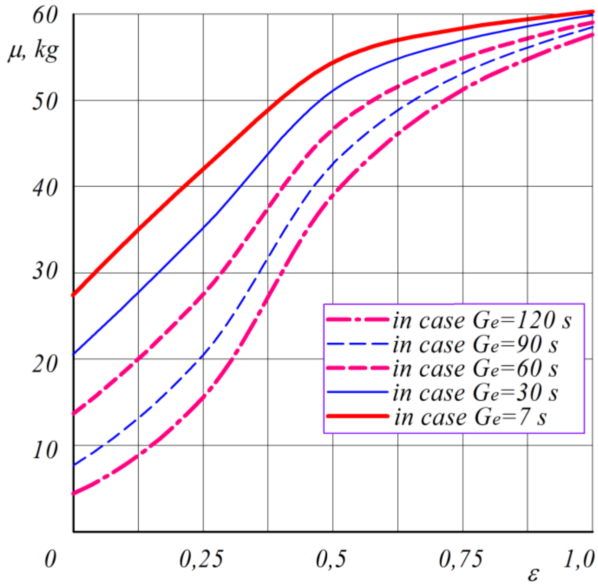

Fig. 4: The change in the reduced mass of the concrete mixture during the vibration compacting, depending on the mixture different rigidity relative density.

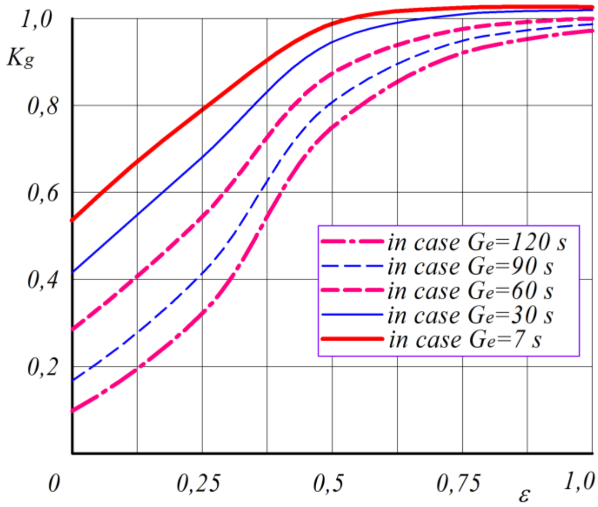

Fig. 5: Ratio change in the concrete mixture reduced mass during the vibration compacting, depending on mixture different rigidity relative density.

Internal friction coefficient (Fig. 3) of the concrete mixture at the beginning of the vibration process of compaction is f_0 = 0.11-0.9, then increases during compaction and at the final stage of compaction is f_1=0.125-0.28. Large values of the coefficient of internal friction are characteristic for concrete mixtures with lower mobility, i.e. at their greater rigidity. Also in Fig. 4 - 5, the reduced mass of the concrete mix μ and the coefficient of the reduced mass K_g ratio equal to the ratio of the reduced mass μ to the physical mass of the concrete mixture compacted volume are presented.

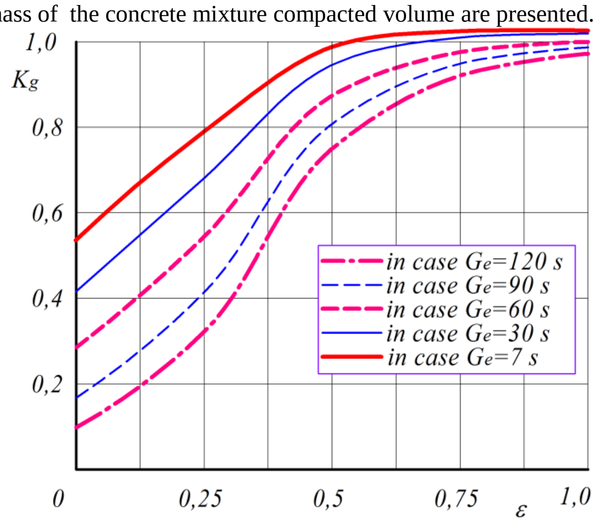

Fig. 6: Variation of the oscillation amplitude of the vibrating table vibrating machine in the process of different rigidity concrete mixtures vibrational compaction.

Consequently, at the end of the compaction, the reduced mass of the concrete mix approximates in magnitude to the physical mass of the molded volume of the concrete mixture. In this case, the inertial forces and the forces of inelastic resistance of the concrete mixture take approximately the same values at the final stage of the compaction process, regardless of the rigidity of the concrete mixture being formed. Therefore, the vibration amplitude of the vibrating machine at the end of the compaction becomes the same for concrete mixtures with a rigidities $Ge = 7$ - 120 s.

Thus, on the basis of the study of the propagation of deformation waves in a compacting medium, represented as a system with distributed parameters, dependences were obtained to determine the physical and mechanical characteristics of the medium to be compacting. These dependencies can be used with a sufficiently high degree of accuracy in complex discrete dynamical systems describing the vibrations of vibrating machines used for molding concrete products, both simple and complex shapes. When expression (12) is substituted into equation (1), one can find the stress-strain state of the compacting medium in the process of compaction and clarify the rational parameters of the vibrational action on the medium being compacting.

4 Conclusion

Based on the wave theory of oscillations, deformation waves in a compacting medium propagation process, represented as a system with distributed parameters, is studied and compacting medium regularity under vibration influence deformation is determined depending on the physical and mechanical characteristics of the compacting medium, the thickness of the packed bed, the mass vibrating machine, frequency and amplitude of the disturbing force, stiffness and inelastic resistance coefficient of the elastic suspension. The changes in the reduced mass and the reduced coefficient of inelastic resistance of the con create mixture enables a complex dynamic system with distributed parameters to be represented as a discrete dynamical system. The

determination of the stresses arising in the medium to be compacting will enable to substantiate the most rational modes of vibrational action on the medium to be compacting, while ensuring the ultimate destruction of its structural bonds and effective compaction.

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