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Research paper

The Theory of Concrete Mixture Vibratory Compacting

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Abstract

Purpose. The creation of the compacting vibratory process theoretical basis enabling the assessment of the efficiency and the choice of rational modes of the vibration influence on the concrete mixture, based on the minimal energy input in the process of its compacting.
Methodology. The paper contains the description of the mechanism of compacting under the action of external vibration forces whereat a variable tensely deformed condition occurs in the concrete mixture. In this case the primary structural links break, the links between its separate elements weaken, the final movements of mineral particles result in the creation of a more compact packing. As the basic factor determining the character of the compacting process, the authors propose to use the product of voltage and the velocity of the vibratory action, which presents the power of the vibratory action on the compacted medium.
Results. The authors have obtained analytical expressions enabling the determination of the growth of the concrete mixture density in time function depending on the type of the vibratory load and the power of the applied vibratory action on the compacted medium. The paper contains the theoretical and experimental values of the specific work that provides compacting up to the values required by the technological norms depending on the consistence of the concrete mixture at vertical and horizontally directed vibrations.
Conclusions. The authors have specified the existing hypothesis and proposed a more general power hypothesis of the process of vibratory compacting of concrete mixtures, applicable to the description of the vibration process and concrete media treatment by various vibratory mechanisms, tools and machines. One can use the obtained results to set the rational modes and duration of the vibratory action on the compacted medium depending on the amount and type of the specific work of compacting and also to determine the basic parameters of vibration machines of various technological purpose.

Keywords: *theory of compacting, concrete mixture, density, power.*

1. Introduction

TOPICALITY OF THE PAPER. To create vibration machines it is necessary to determine with sufficient accuracy their basic parameters whereat one can provide the required low-power-consuming and efficient mode of vibratory action on the compacted medium depending on the physical and mechanical characteristics of the mixture, technological and dynamic processes taking place at the formation of the compacted medium structure, the configuration of the product, the type, direction and the zone of the vibratory action. The basic parameters of vibration machines include their mass, the mass of vibration tool and the area of its interaction with the compacted medium, frequency, amplitude or peak-to-peak value of forced vibrations of the vibration tool making harmonic, superharmonic or vibroimpulse vibrations, the frequency of vibrations of the vibration machine, geometric and kinematic parameters of the vibration machine, the velocity of movement of the vibration tool or the duration of the vibratory action on the compacted medium, protection of the maintaining staff and the environment against the harmful influence of noise and vibration at work. The determination of the mentioned parameters should take into account the physical and mathematical properties of the concrete mixture, its consistence, the size and configuration of the product, the place, direction and the area of application of vibratory disturbance (deep or surface vibration, external vibration by vertically or horizontally directed vibrating actions, volumetric vibration and vibration by single-frequency and poly-frequency vibrating actions), the required strength indicators of the final product, the quality of its surfaces and the required indices of its efficiency, power-consumption, duration of the vibratory action and the strength of the molded product .

2 Main Body

2.1. The Analysis of Recent Research Sources and Publications.

The determination of the qualitative and quantitative dependences between the said requirements and the determined parameters of the vibration machine is possible based on the theory of vibratory compacting of concrete mixtures, formulated in a clear and consistent form, expressed by mathematical dependences and confirmed by experiment.
The existing basic hypothesis of vibratory compacting relates to the notion of concrete mixture transition to the liquid (thixotropic) condition under the impact of vibration [1], [2], [3]. Thixotropy

results in considerable reduction of viscous resistance forces and appearance of the process of particles approaching, mainly under the influence of gravity though the action of the dynamic forces is also possible.

To assess the efficiency of the vibratory process of compacting a number authors proposed to use such parameters as product of vibration amplitude A and vibration angular frequency ω, as well as acceleration $A\omega^2$ or product of velocity and acceleration, i.e.. $A^2\omega^3$ [4], [5], [6] . These indices cannot provide a reliable assessment of the efficiency of concrete mixtures compacting as they do not take into account a number of important parameters: the direction and type of the vibratory action, the geometric dimensions of the formed product and physical and mechanical characteristics of the concrete mixture.

A specified theory, presented in papers [7], [8], [9], [10], [11], [12], [13], 14] in detail, describes the mechanism of propagation of resilient-plastic waves of deformation and breakage of structural links in a concrete medium, its plastic flow and displacement of air out of the mixture structure and formation of a dense structure under the impact of vibration. The authors substantiate the efficiency of formation of concrete products from harsh and plastic concrete mixtures based on the stresses occurring in the concrete medium, which break the structural links with a certain frequency of vibratory action. The papers contain grounded analytical dependences for the choice of the basic parameters of compacting vibration machines, mechanisms and tools.

2.2. The Selection of Previously Unsolved Parts of the General Problem.

The presented theory does not completely take into account the power aspect of the vibration process of concrete mixtures compacting, does not reveal the action of resilient, dissipative, inertial forces, the forces of non-resilient resistance and requires further specification.

2.3. The Main Material and Results.

A concrete mixture represents a complex multicomponent system consisting of filler (sand and crushed stone), astringent and water as well as new formations appearing under the impact of astringent with water and filler grains and involved air. In harsh mixture the volume of air goes up to 20 – 25%, in plastic mixtures to 10 -15%. Because of the interaction of the forces of surface tension between the liquid phase and the particles of the solid phase, this system acquires cohesion and can be considered as a single physical body.

Under the action of external vibration forces a variable tensely deformed condition occurs in the mixture, the primary structural links break, the links between its separate elements weaken, the final movements of mineral particles result in the creation of a more compact packing.

As stresses σ , occurring in the compacted layer under the vibratory action, are one of the main factors influencing the breakage of the structural links and the process of compacting and also the behavior of the dynamic system “concrete medium – vibration machine”, it is reasonable to suppose that the product of the stress and the velocity of the vibratory action can be used as the main factor determining the character of the compacting process, i.e.

$$P = \sigma V . \qquad (1)$$

where P – the power of the vibration machine tool vibratory action on the compacted medium; σ – normal stresses occurring in the compacted medium at the vibratory compacting; V – the amplitude of the velocity of the vibratory action.

At harmonic vibrations when the amplitude of the velocity of vibratory action equals $V = A\omega$, the power of the vibration machine tool vibratory action on the compacted medium is determined from the following expression:

$$P = \sigma A\omega , \qquad (2)$$

where A – the amplitude of the deformation of the compacted medium; ω – the angular frequency of vibrations.

In this case the specific work of the vibratory process of compacting is determined from the following expression:

$$W = \sigma A\omega t_v , \qquad (3)$$

where t_v – the duration of the vibratory compacting.

We can determine the growth of the concrete mixture density from its initial value ρ_0 to a certain value ρ , as a result of vibratory action, from the following empiric law:

$$\Delta\rho_i = \zeta W^n , \qquad (4)$$

where $\Delta\rho_i$ – the value of the growth of the concrete mixture density caused by plastic deformation; ζ and n – empiric coefficients characterizing resilient-plastic deformation at the dynamic loading in the form of vibratory action.

Based on expression (4), we will determine the current value of density ρ , resulting from the performed specific work of the compacting vibration process W , i.e.

$$\rho = \rho_0 + \Delta\rho_i = \rho_0 + \zeta W^n , \qquad (5)$$

where ρ_0 – the density of the concrete mixture subjected to vibratory compacting (initial density); ρ – the concrete mixture density achieved as a result of the applied vibratory compacting work.

In an analogous way we will determine the necessary, required by the technological norms, density of concrete compacted by vibration action:

$$\rho_k = \rho_0 + \Delta\rho = \rho_0 + \zeta W_k^n , \qquad (6)$$

where ρ_k – the concrete mixture density corresponding to 100% compacting required by the technological norms; $\Delta\rho$ – the value of the growth of the concrete mixture density from the initial ρ_0 to the final ρ_k values of density; W_k – specific work of the concrete mixture compacting from the initial ρ_0 to the final ρ_k values of density.

Based on expressions (5) and (6), we will get the following relation:

$$\frac{\rho - \rho_0}{\rho_k - \rho_0} = \left(\frac{W}{W_k} \right)^n , \qquad (7)$$

wherefrom, taking into account dependence (3), we will obtain the formula for the determination of the concrete density depending on the work consumed by the vibratory process of concrete mixture compacting, i.e.

$$\rho = \rho_0 + \chi \left(\frac{\sigma A\omega t_v}{W_k} \right)^n , \qquad (8)$$

where χ – the difference between the standard ρ_k and initial ρ_0 values of the density, adopted depending on the rigidity of the concrete mixture,

$$\chi = \rho_k - \rho_0 . \quad (9)$$

The value of coefficient n, used in expression (9), significantly depends on the concrete mixture rigidity and can be determined from the following dependence:

$$n = \Lambda G^{v} , \quad (10)$$

where Λ and v – empiric coefficients, Λ =0.046; v =0.25; G – the concrete mixture rigidity by Skramtaiev.

Table 1. The values of specific work W_k depending on the consistence of the concrete mixture at a vertically directed vibratory action

Concrete mixture consistence, s	5…7	30	60	90	120
Value of specific work W_k, Pa·m	56	111.5	180.5	254	321.3

Then, based on expression (10), dependence (8) for the determination of the current value of the concrete mixture density depending on the specific consumed work transforms to the following form:

$$\rho = \rho_0 + \chi \left(\frac{\sigma A \omega t_v}{W_k} \right)^{\Lambda G^{v}} . \quad (11)$$

Table 1 contains the values of specific work W_k, necessary for the achievement of 100% concrete mixture density, required by the technological norms, depending on the mixture consistence at the vertically directed vibratory action. We got the data for the standard concrete mixture with the water-cement relation W/C=0.41 – 0.51 with the following content of mineral components and water (kg per 1 m^3 of concrete): crushed granite of the fraction of 5…20 mm – 1200; sand with the fineness modulus of M_{kp} =1.7…2 mm – 635; Portland cement M400 – 400; water – 165…205 l. In this case the consistence of the concrete mixture changed by means of batching a certain amount of water according to Table 2. With the growth of the concrete mixture rigidity the specific work W_k, required for complete compacting, grows rather significantly. Also, depending on the consistence, the initial ρ_0 and the final ρ_k densities of the concrete mixture change [9].

When vibration load acts on the concrete mixture in a horizontal plane, the values of specific work W_k (Table 3) decrease in comparison with the values of specific work W_k at vertically directed vibrations, but they also essentially depend on the concrete mixture consistence.

At the simultaneous impact on the concrete mixture by normal stresses σ_n (e.g. in the vertical direction) and by tangential stresses τ (in the horizontal plane) and, taking into account the ambiguity of their action influence on the efficiency of the compacting process and the breakage of the structural links in the concrete mixture, the equivalent value of the vibration impact power is determined taking into account the hypothesis of the energy of form variation,

$$P_{ekv} = \omega \sqrt{\sigma_n^2 A_n^2 + 3\tau^2 A_t^2} , \quad (12)$$

then we substitute it into formula (11), i.e.

Table 2. Water consumption and the values of the initial ρ_0 and final ρ_k density depending on the consistence (rigidity) of the concrete mixture

Concrete mixture consistence, s	110 – 120	80 – 90	50 – 60	25 – 30	5 – 7
Water consumption, l/m^3	165	172	180	187	205
Initial density of the mixture ρ_0, g/cm^3	1.85	1.89	1.95	2.02	2.09
Final density of the mixture ρ_k, g/cm^3	2.42	2.42	2.41	2.41	2.4

Table 3. The values of specific work W_k depending on the consistence of the concrete mixture at horizontally directed vibrations

Concrete mixture consistence, s	5…7	30	60	90	120
Value of specific work W_k, Pa·m	31.4	64.4	103.1	147.6	186.8

$$\rho = \rho_0 + \chi \left(\frac{P_{ekv} t_v}{W_k} \right)^{\Lambda G^{v}} , \quad (13)$$

where P_{ekv} – equivalent value of the vibration impact power; A_n – the amplitude of the deformation of the compacted medium in the normal direction; A_t – the amplitude of the deformation of the compacted medium in the tangential direction.

In the case of a poly-frequency action on the compacted medium the equivalent value of the power of the vibration impact is determined from the following expression:

$$P_{ekv} = \sqrt{P_{nsm}^2 + 3P_{tsm}^2} , \quad (14)$$

where P_{nsm} – the equivalent value of the power of the vibration impact in the normal direction,

$$P_{vsm} = \sum_{i=1}^{n} \sigma_i A_{ni} \omega_{ni} ; \quad (15)$$

P_{tsm} – the equivalent value of the power of the vibration impact in the tangential direction,

$$P_{tsm} = \sum_{i=1}^{n} \tau_i A_{ti} \omega_{ti} ; \quad (16)$$

σ_i, τ_i – normal and tangential stresses respectively at the angular velocities of the forced vibrations ω_{ni} and ω_{ti}; A_{ni}, A_{ti} – the amplitudes of the forced vibrations of the vibratory actions respectively at the angular velocities of the forced vibrations ω_{ni} and ω_{ti}.

In the case of vibration action on the compacted medium simultaneously in the normal and horizontal directions and by tangential actions in the vertical plane one uses the same equations to determine the equivalent power.

The values of specific work W_k depending on the consistence of the concrete mixture can be determined from the following one-type dependences respectively at vertically directed and horizontal vibrations:

– at vertically directed vibrations,

$$W_k = W_{0v}(1+K_v G);\qquad (17)$$

– at horizontally directed vibrations,

$$W_k = W_{0g}(1+K_g G).\qquad (18)$$

Here W_{0v}, W_{0g} – the values of specific work at the conventional value of the concrete mixture rigidity equal to W_{0v} =37.8 KPa·m; W_{0g} =23.2 KPa·m; K_v, K_g – coefficients of proportionality, K_v = 0.0624; K_g =0.0588.

Fig. 1 contains comparison of the theoretical and experimental data of the values of specific work W_k, obtained at different values of consistence (rigidity) of the concrete mixture at horizontally directed and vertical vibrations.

Using expressions (11) and (13), we will determine compacting coefficient k_y of the concrete mixture depending on the specific work consumed by compacting:

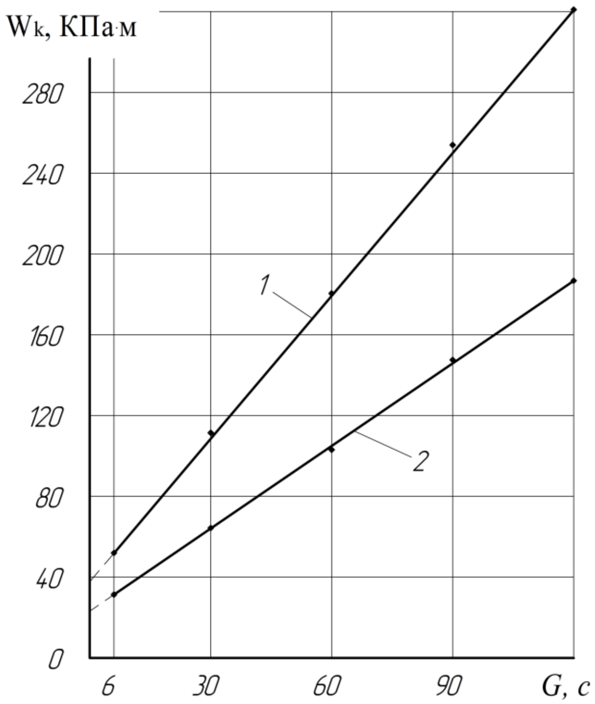

Fig. 1. Variation of the values of specific work W_k depending on the consistence of the concrete mixture at the vertical (1) and horizontal (2) vibration impact on the compacted concrete medium: 1, 2 – theoretical dependences; · – experimental data.

$$k_y = \frac{\rho_0}{\rho_k} + \frac{\chi}{\rho_k}\left(\frac{\sigma A \omega t_v}{W_k}\right)^{\Lambda G^v};\qquad (19)$$

$$k_y = \frac{\rho_0}{\rho_k} + \frac{\chi}{\rho_k}\left(\frac{P_{ekv} t_v}{W_k}\right)^{\Lambda G^v}.\qquad (20)$$

Based on expressions (19) and (20) we determine time t_v, required for the achievement of the definite coefficient of compacting the concrete mixture depending on the consumed compacting specific work and the physical and mathematical characteristics of the mixture:

$$t_v = \frac{W_k}{\sigma A \omega}\left(\frac{k_y \rho_k - \rho_0}{\chi}\right)^{\frac{1}{\Lambda G^v}};\qquad (21)$$

$$t_v = \frac{W_k}{P_{ekv}}\left(\frac{k_y \rho_k - \rho_0}{\chi}\right)^{\frac{1}{\Lambda G^v}}.\qquad (22)$$

The time required for the achievement of the standard values of the concrete density ρ_k is determined from the following expressions:

$$t_v = \frac{W_k}{\sigma A \omega};\qquad (23)$$

$$t_v = \frac{W_k}{P_{ekv}}.\qquad (24)$$

Using expressions (21) and (22), we determine the surface compactor movement necessary velocity V in relation to the compacted surface depending on the compacting specific work consumed to achieve the definite value of compacting coefficient k_y of the concrete mixture, physical and mathematical characteristics of the compacted medium and the vibratory plate length l_0:

$$V = \frac{\sigma A \omega l_0}{W_k}\left(\frac{k_y \rho_k - \rho_0}{\chi}\right)^{-\frac{1}{\Lambda G^v}};\qquad (25)$$

$$V = \frac{P_{ekv} l_0}{W_k}\left(\frac{k_y \rho_k - \rho_0}{\chi}\right)^{-\frac{1}{\Lambda G^v}}.\qquad (26)$$

The power intensity of the concrete mixture compacting process is one of the basic parameters influencing the choice of the production technology, design and the basic parameters of the vibration machine, the mode of the vibration impact on the compacted medium during the manufacture of concrete products. Power intensity is determined as a ratio of the amount of the consumed energy to the amount of the manufactured product.

One of the main indicators of the concrete mixture compacting process consists in the efficiency, determined as the relation of the energy supplied to the compacted layer and directly spent on its formation up to the final rigidity, to the full energy spent by the vibration machine drive during a complete cycle of compacting one unit of the product. We determine the vibration machine efficiency in the following way:

$$\eta_{vm} = \frac{W_k F}{W_{vm}},\qquad (27)$$

where η_{vm} – the efficiency of the vibration machine; W_k – the values of specific work determined depending on the concrete mixture consistence and the direction of the vibratory impact by Tables 1 and 3, or from expressions (17) and (18); F –the area of the compacted surface; W_{vm} – the energy consumed by the vibration machine drive during a complete cycle of compacting a unit of product.

The energy consumed by the vibration machine to attain the technological density of the concrete mixture during the full cycle of compacting a unit of product, consists of the work spent on the support of the vibrations of all the vibrating parts of the vibration machine, on friction in the rolling bearings of the vibration exciters, on the absorption of energy in shock absorbers, on the friction of the separate parts of the vibration machine against the compacted mixture, on the motion of the vibration machine, as well as on the work spend directly on the concrete mixture compacting:

– for the moving surface vibro-compacting machines,

$$W_{vm} = (W_1 + W_2 + W_3 + W_4 + W_5 + W_k F)/\eta_{pr} ; \quad (28)$$

– for cycling vibration machines (table vibrators and deep vibro-compacting machines),

$$W_{vm} = (W_1 + W_2 + W_3 + W_k F)/\eta_{pr} . \quad (29)$$

Here W_1 – the energy spent on the support of the vibrations of all the vibrating active and reactive parts of the vibration machine,

$$W_1 = \frac{2gt_v}{\pi} \sum_{i=1}^{n_1} A_i m_i \omega_i , \quad (30)$$

where m_i – active or reactive mass vibrating with the angular frequency ω_i and vibration amplitude A_i, $i = 1 \ldots n_1$; n_1 – the amount of vibrating masses, $n_1 = 1, 2...$; t_v – the duration of the vibratory compacting of a unit of product, determined by dependences (21 – 24);

W_2 – the energy spent on friction in the rolling bearings of vibration exciters,

$$W_2 = \frac{f_{tp} t_v}{2} \sum_{j=1}^{n_2} Q_j \omega_j d_j , \quad (31)$$

where Q_j – the amplitude of the disturbing force of the j-th vibration exciter, $j = 1, 2 \ldots n_2$; ω_j – the angular frequency of the disturbing force of the j- th vibration exciter; d_j – the internal diameter of the bearings of the j-th vibration exciter; f_{tp} – the coefficient of friction of the bearings of the j-th vibration exciter; n_2 – the number of the vibration exciters;

W_3 – energy absorption and dispersion in the shock absorbers,

$$W_3 = m_p g f_{ta} t_v \sum_{j=1}^{n_2} A_j \omega_j , \quad (32)$$

where m_p – the sprung mass of the vibration machine; f_{ta} – the coefficient of the internal friction of the shock absorbers; A_j – the amplitude of the vibrations of the sprung mass;

W_4 – the energy spent on the tool friction on the compacted medium during the motion of the tool ,

$$W_4 = mgf_{tr} V_r t_v , \quad (33)$$

where m – the mass of the vibration tool; f_{tr} – the coefficient of friction of the tool against the compacted medium; V_r – the velocity of the tool movement;

W_5 – the energy spent on the movement of the vibration machine,

$$W_5 = m_{vm} g f_{tm} V_m t_v , \quad (34)$$

where m_{vm} – the mass of the vibration machine; f_{tm} – the coefficient of resistance at the movement of the vibration machine; V_m – the velocity of the vibration machine movement; η_{pr} – the efficiency of the drive.

Thus, we have obtained the expressions making it possible to substantiate the vibration impact modes and the rational parameters of low-power-consuming and highly efficient vibration machines for compacting concrete mixtures meeting the up-to-date requirements.

The analysis of the shown dependences (28 – 34) reveals that the vibration processes and machines performing concrete mixture compacting at the direct contact of the vibrating tool with the concrete medium are the least power-consuming. First of all, they include deep vibration compacting machines and mechanisms, then the surface vibration compacting tools making a vibratory action on the surface of the laid concrete mixture. High power consumption is characteristic of table vibrators used for the formation of concrete products.

3. Conclusion

Thus, we have specified the existing and proposed a more general power hypothesis of the process of vibratory compacting of concrete mixtures, applicable to the description of the vibratory process of compacting and treatment of concrete media by various vibration mechanisms, tools and machines. We have obtained the analytical dependences making it possible to determine the law of growth of the density of the compacted medium and the duration of the vibratory impact depending on the amount and type of the compacting specific work, to assess the efficiency of the vibratory process of compacting and treatment, and also to set rational modes of vibratory impact on the compacter medium and determine the basic parameters of the vibratory machines of different technological purpose.

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