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[1]Mykola Nesterenko,
Candidate of Technical Sciences, Associate Professor of the Department of Industrial Engineering and Mechatronics, https://orcid.org/0000-0002-4073-1233, e-mail: nesterenkonikola@gmail.com

[1]Vasyl Vedmid,
Postgraduate student, https://orcid.org/0000-0003-1514-1212, e-mail: vvedmyd@gmail.com

[1]National University «Yuri Kondratyuk Poltava Polytechnic» Pershotravneva Avenue 24, Poltava, 36011, Ukraine

ТЕОРЕТИЧНІ ПОЛОЖЕННЯ ТА АНАЛІЗ РОБОЧОГО ПРОЦЕСУ УЩІЛЬНЕННЯ БЕТОННИХ СУМІШЕЙ

АНОТАЦІЯ. *У статті розглядаються основні параметри та режими вібраційного ущільнення бетонних сумішей, а також аналізуються ефективність різних типів вібрацій і їх вплив на фізико-механічні властивості матеріалів. Окрему увагу приділено питанням вибору амплітуди та частоти коливань, а також їх взаємодії з реологічними характеристиками суміші, такими як густина, модуль пружності та швидкість поширення хвиль. Автори підкреслюють важливість врахування змінних параметрів вібраційних процесів для досягнення оптимальних результатів ущільнення, зокрема в контексті зменшення енергоспоживання та часу обробки. Зокрема, обговорюється ефективність віброударних режимів і нових напрямків, таких як просторові коливання, що суттєво підвищують ефективність ущільнення завдяки напруженням зсуву. Результати експериментальних досліджень та теоретичний аналіз підтверджують необхідність комплексного підходу до вибору режимів вібрації в залежності від фізико-механічних властивостей матеріалу. Стаття має на меті сприяти розвитку більш ефективних технологій вібраційного ущільнення у будівництві та матеріалознавстві.*

Ключові слова: *вібраційне ущільнення, частота коливань, енергетична ефективність, реологічні характеристики, просторові коливання, ущільнення бетонної суміші, ефективність ущільнення.*

THEORETICAL PRINCIPLES AND ANALYSIS OF THE CONCRETE MIX COMPACTION PROCESS

ABSTRACT. *This article discusses the main parameters and modes of vibrational compaction of concrete mixtures, as well as analyzes the effectiveness of different types of vibrations and their impact on the physical and mechanical properties of materials. Special attention is given to the issues of selecting the amplitude and frequency of oscillations, as well as their interaction with the rheological characteristics of the mixture, such as density, modulus of elasticity, and wave propagation velocity. The authors emphasize the importance of considering the variable parameters of the vibration process to achieve optimal compaction results, particularly in the context of reducing energy consumption and processing time. Specifically, the effectiveness of vibro-impact modes and new directions, such as spatial vibrations, is discussed, which significantly improve compaction efficiency through shear stresses. Experimental research results and theoretical analysis confirm the necessity of a comprehensive approach to the selection of vibration modes depending on the physical and mechanical properties of the material. The article aims to promote the development of more efficient vibrational compaction technologies in construction and materials science.*

Keywords: *vibrational compaction, vibration frequency, energy efficiency, rheological characteristics, spatial vibrations, concrete mixture compaction, compaction efficiency.*

1. Problem statement. The process of compaction of concrete mixtures using vibrations is an important stage in the production of concrete products, as it directly affects the mechanical properties of the material, such as strength, structural stability and durability. However, to achieve optimal results in the compaction process, it is necessary to determine the most effective vibration parameters, such as amplitude, oscillation frequency, compaction time and energy characteristics, which is an extremely difficult task due to the interdependencies between these factors. In addition, various modes vibration influence can have different impact on physical and mechanical properties concrete mixtures, as well as on energy efficiency process.

Despite the significant number research in this field field, there is a need for a more precise definition optimal parameters vibration compaction for specific production conditions, which will improve quality concrete mixtures, reduce energy costs and increase efficiency production. Thus, the development of new approaches to determining parameters vibration seals that will allow for the most accurate prediction final results and achieve the optimal balance between strength and productivity.

2. Analysis of publications on the research topic. The study of the process of vibration compaction of concrete mixtures is an important area of research in the field of construction, because the correct application of vibration significantly improves the mechanical and physical properties of concrete. Since the introduction of vibrations into the technology of compaction of concrete mixtures at the end of the 19th century, a large number of publications have appeared that consider various aspects of the vibration process and its effect on materials.

One of the main research directions influence amplitudes and frequencies vibrations on sealing characteristics concrete mixtures. Works Freysin (1899) and subsequent studies have shown the importance choice correct values these parameters to achieve optimal results in compaction. In particular, studies [1] emphasize the importance of an oscillation amplitude of at least 0.2 mm at a frequency of 314 s^{-1} to ensure effective consolidation concrete mixtures. At the same time, studies [2] suggest a wider range of values amplitude from 0.35 mm to 0.5 mm, which shows the need for fine tuning parameters depending on from production conditions.

Later works, such as [3], reveal the importance of considering amplitude and frequency. vibrations not as independent parameters, and in the relationship, because optimal parameters vibrations must consider comprehensive characteristics of the material. This confirm also research vibro-impact modes in which the oscillation frequency can be reduced to 5–10 Hz, but with significantly larger amplitude oscillations (up to 10 mm) [4, 5]. Such approach allows get significant energy efficiency, reducing compaction time at high productivity.

Special attention also deserve work that analyze influence horizontal vibrations and their combination with vertical oscillations. Works [1–5] and [8] consider the effects of resonant horizontal oscillations that allow effectively condense concrete mixture thanks to sliding tensions, which arise when using such modes. Additional vertical vibrations created special vibrators, too improve efficiency compaction due to dominance vertical component active forces.

Recent work [8-9] confirms that the mixed application horizontal and vertical vibrations with optimal parameters can substantially to increase energy efficiency process compaction, reducing costs energy when reaching required characteristics of concrete. However these research also indicate insufficient clarity in defining assessment methodologies energy characteristics, such as specific energy and coefficient energy efficiency, which needs further clarifications and development.

Thus, despite the significant amount scientific research, vibrational topic consolidation concrete mixtures still needs further research, especially regarding the precise choice optimal parameters vibration modes, methods of determination energy characteristics and applications new types vibration installations.

3. Purpose and objectives of the study. The purpose of the study is to optimize the parameters of vibration compaction of concrete mixtures to improve their energy efficiency and quality. The tasks are to analyze existing vibration modes, determine the influence of amplitude, frequency and energy characteristics on the compaction process, and develop recommendations for choosing optimal parameters for different production conditions. The study also includes an assessment of the effectiveness of mixed vibration modes and their influence on the physical properties of concrete.

4. Analysis of theoretical aspects of the process of compaction of concrete mixtures. The working process of compaction of building mixtures consists in transferring energy from the working body of the vibrating machine to the material structure. As a result, stresses arise that form deformations of the medium, which ensures the compaction of the mixture. To achieve optimal compaction conditions, it is important to know how the physical and mechanical properties of the medium change, which affect the interaction of stresses and deformations. The study of the properties of the medium includes the development of a mathematical model that establishes the relationship between stresses and deformations in the form of equations of state. This allows you to estimate the resistance of the medium to the working body. Based on the obtained data on the resistance of the medium, these characteristics are taken into account in the general equations of motion of the "machine - medium" system, which helps to determine the parameters of the operation of the machines. For example, the Hooke model is widely used for metals , and the Newton model for liquids. At the same time, the Hooke model is effective only within the limits of elastic deformations, while beyond these limits it is necessary to take into account the plastic and inelastic (dissipative) properties of materials. In fast-moving processes involving liquids, their elastic properties can clearly manifest themselves. The peculiarity of the concrete mixture, as well as other media, lies in its dependence on the magnitude and duration of the applied load. Unlike homogeneous solids, liquids or gases, the concrete mixture is a complex structured system that includes solid, liquid and air phases. During compaction, the amount of air and gas phases is significantly reduced, which changes the properties of the medium. In addition, the nature of the stress-strain state of the medium strongly depends on the geometric parameters of the load application zone. This process is influenced by both the physical and mechanical properties of individual phases and the mechanisms of their interaction.

For mathematical modeling of the properties of a concrete mixture, it is necessary to take into account the rheological equations of state of each individual phase, the nature of the interaction between these phases, as well as the change in phase ratios per unit volume during the compaction process. It is obvious that the intensity of changes in phase ratios in the volume is determined by the parameters of the finished product, in particular, the trajectories along which one phase moves relative to another. Thus, to describe the behavior of a concrete mixture, it is impossible to reduce all components to a single universal rheological equation. Such an equation must take into account not only the conditions of the applied load, but also the geometric characteristics of the compacted zone. Under such conditions, each point of the environment will have its own physical law that goes beyond the limits of classical rheological models. Based on the nature of the task, which may include the specifics of the applied load or the dimensions of the product, it is advisable to use simplified models. These models should be sufficiently close to the actual solution of a specific problem [1 – 4]. Next, we will analyze these theoretical approaches separately.

Corpuscular theory

The study of the patterns of movement of particles that make up the concrete mixture and interact with each other is inextricably linked to the analysis of the nature and mechanisms of destruction of interparticle This approach is a key element of the corpuscular theory, which is widely used in the rheological analysis of concrete mixtures, in particular in the works [1 – 6, 9].

Deep understanding of the mechanism of vibrational fracture of interparticle connections allows us to reveal the physical nature of the processes occurring in concrete mixtures and to determine the patterns of changes in their elastic and inelastic properties. In particular, this explains the transition of a vibrating mixture to a pseudo-fluid state, which is accompanied by a change in its viscous characteristics. The analysis of these phenomena is one of the central tasks of vibrorheology . Additionally, within the framework of this theory, complex processes are considered, such as the redistribution of liquid and gas phases in the mixture, as well as the reorganization of solid particles of different sizes.

The main purpose of the vibration effect on the concrete mixture is to reduce the adhesion forces between the particles of the solid phase. This contributes to the maximum removal of air, the share of which at the initial stage can reach 15-30% of the total volume of the system [6, 7], the formation of a dense structure with a uniform arrangement of solid particles, as well as the optimal distribution of the liquid and gas phases. As a result, the rheological characteristics of the mixture improve, in particular its fluidity, the ability to fill forms and reduce interparticle friction during the movement of solid particles. These provisions are considered generally accepted and do not require additional evidence. At the same time, some researchers [4, 5] question the significance of the corpuscular theory for the analysis of the movement of components of concrete mixtures.

Special attention is paid to hypotheses regarding the mechanisms of vibration destruction . Their analysis allows us to estimate the resistance forces, which are crucial in the development of highly efficient vibration machines for practical applications.

When analyzing the mechanism of particle binding in studies [1 – 4], an analogy with the behavior of colloidal solutions is used. It is believed that with an increase in shear stresses in the system, a thixotropic phenomenon occurs, which manifests itself in a decrease in viscosity. In this context, each particle is considered as a kind of "vibrator" that generates stresses, causing thixotropic changes. To achieve rarefaction in a certain zone, it is necessary that the shear stresses exceed the established limit value. That is why it is proposed to introduce restrictions on the parameters of the speed or amplitude of oscillations that ensure the fulfillment of this condition.

Air bubbles play an important role in this process. Those that create a lift force that exceeds the shear resistance are released from the mixture, while the less active ones remain stationary. Further studies [8] show that the decrease in interaction between particles is associated with an increase in volume due to the excitation energy entering the system. This, in turn, leads to the formation of a velocity gradient between neighboring particles - a phenomenon without which a decrease in the structural viscosity coefficient is impossible.

In addition, there are alternative hypotheses [1, 3] that suggest that during vibration, the reduction of the coupling between particles causes forces similar to Coulomb friction.

In work [4], the mechanism of vibrational failure of a material is analyzed through successive stages of compaction:

Particle rearrangement – at the initial stage, dry friction appears, and air is gradually removed from the pores.

Particle convergence – during the compaction process, zones with elastically compressed air are formed, the mixture is partially liquefied, and a transition from dry friction to viscous occurs.

Compression sealing – characterized by uniform distribution of water vapor at the contacts between particles and partial compression of the material.

Analysis of this hypothesis in the context of the influence of the resistance forces of the environment on the dynamics of the vibratory machine prompts us to consider the process as one characterized by the complex nature of hydrodynamic interaction, with time-varying pressure on the processed mixture and, potentially, with variable vibration modes. In particular, this process can cover modes ranging from low frequencies and increased amplitudes of oscillations (which corresponds to a relatively small pressure) to a significant increase in frequencies and decrease in amplitudes (which is accompanied by a significant increase in pressure on the mixture). But does this correspond to a real physical model? It is obvious that for an adequate description of this phenomenon, in particular the mechanisms of vibrational destruction of interparticle connections and subsequent compaction of the mixture, it is necessary to use nonlinear models for evaluating resistance forces, including both elastic and dissipative aspects. In the case of using linear models, this approach implies the need for appropriate refinement of the coefficients of elasticity and dissipative resistance to ensure modeling accuracy.

Phenomenological theory considers concrete mixture as a continuous system, the state of stress and deformation of which is determined by equations obtained from the conditions of continuity, as well as Newton's and Hooke's laws . However, the use of such a model as the initial one gives rise to the problem of choosing elastic and inelastic characteristics, which is the basis of the phenomenological (continuous) approach. It is obvious that these characteristics change not only under the influence of the composition of the material and vibration modes, but also in the process of its compaction. This significantly complicates the determination of the numerical values of these parameters and the laws of their change, despite the relative simplicity of solving the problem of motion of the system " vibrator - medium" in a linear formulation and in the absence of a break in contact between the working body and the medium.

Analysis of research in this direction demonstrates that in works [1, 2, 4] the Kelvin- Voigt elastic-viscous body model is used to approximate the curves of vertical settlement of concrete mixture during compaction . These works present the dependences of the compaction rate, however, they remain uncertain due to the variability of the characteristics of the mixture when its bulk density changes.

At the final stage of compaction, when the density of the concrete mixture stabilizes, it is possible to use an elastic-viscous model with constant coefficients, which allows you to evaluate the dynamic process in the environment. For example, in studies [3, 9], the laws of wave propagation in closed volumes of the concrete mixture are studied, taking into account the reflection and interference of waves. This leads to the formation of nodes and antinodes in the mixture along the direction of wave stresses and deformations.

Despite the considerable number of studies based on the elastic-viscous model, doubts arise as to their full correspondence to real processes. This is due to the fact that the viscous drag coefficient, according to experimental data, is not constant and depends not only on the frequency [2, 5], but also on the amplitude of oscillations [9]. In addition, breaks in the continuity of the mixture [9] have been recorded at points of extreme values of the wave distribution of the amplitude of oscillations. In these zones, ultrasonic studies have revealed a reduced density of the material.

The problem of breaking the continuity of the concrete mixture is also considered in a number of other works [1, 3, 5]. Based on the results obtained, a limitation of the height of the concrete mixture layer was proposed, if observed, such breaks can be avoided. This point of view is also supported by the authors of works [1, 2, 4].

On the other hand, based on wave representations, for higher columns of concrete mixture it is proposed to reduce the oscillation frequency to 25 Hz [4]. This is explained by the fact that with increasing wavelength the number of inflection zones increases. In general, the determination of conditions that prevent the violation of continuity depends on the relationship between dynamic and static pressure, as well as the force load in the contact zone between the working body, the form and the concrete mixture.

In addition to the elastic-viscous model, some studies [2, 5] use an elastic-plastic model, where the characteristics and parameters are determined by experimentally obtaining the "stress-strain" curve. It is worth noting that during vibration, the concrete mixture does not demonstrate unlimited plastic properties - when reaching a critical deformation, each component loses its integrity. At the same time, this approach is useful for analyzing the stress-strain state of the material.

To determine the optimal modes of vibration compaction, a solid body model is used in some works [1, 9]. In this approach, the equation of motion of the vibration machine takes into account the value of the specific power of the impacts. However, the zones in which elastic properties are manifested (pre-resonant and resonant regions) do not allow this model to be fully used for calculating stresses and strains.

In [1, 2], a continuum model is used that takes into account wave processes in a concrete column. According to this concept, the resistance coefficient is calculated as the ratio of the energy dissipated in the mixture during one oscillation cycle to the maximum potential energy during the same cycle. The method of solving the problem according to the Sorokin hypothesis has an advantage over the Kelvin- Voigt model due to the use of complex numbers, which significantly simplifies the calculations. However, in linear vibration systems with a fixed oscillation frequency, the amplitudes of the calculations must remain identical regardless of the chosen method.

It should be noted that within the framework of the phenomenological theory it is proposed to take into account the resistance of the medium in the form of dry friction [3]. In a number of studies [7, 9] mathematical models are formed by interpolation of experimental data involving several variables. For this purpose, a matrix of experimental parameters is created, the limits of their variation are determined, the experimental plan is formalized, and the processing results are presented in the form of regression equations. This approach can ensure the achievement of the desired result for a specific problem. However, there is a risk of losing the possibility of a full-fledged analysis of physical phenomena in a mixed medium, which is key for the further development of the theory of the working process, improvement of calculation methods and creation of more efficient machines of a new generation.

Analysis of the most common theoretical approaches to assessing the stress-strain state of concrete mixtures and determining the optimal modes and parameters of their compaction allows us to draw the following conclusions:

– The corpuscular theory used to study the rheology of concrete mixtures under vibration is focused mainly on studying the mechanisms of bond destruction in the mixture. It also determines the dependence of viscosity coefficients on the composition of the mixture, as well as on the parameters and modes of the vibration process.

– The phenomenological model has gained wider application in the study of the stress-strain state due to the use of well-known hypotheses and the analysis of wave phenomena in the medium. It is currently more popular compared to the corpuscular approach.

– The practical implementation of a particular theory requires the establishment of specific functional dependencies and the analysis of numerical characteristics. This includes amplitudes and frequencies of oscillations, acoustic parameters (elastic moduli, wave propagation velocity, dissipative properties), as well as energy indicators and vibration modes.

5. Analysis of parameters and modes of vibration compaction of building mixtures

Since the introduction of vibration in construction technology (Freysin, 1899), the task has been to determine the optimal parameters of the work process that would ensure maximum strength and productivity, while minimizing the duration of compaction and energy consumption. However, the simultaneous achievement of all these criteria is impossible due to their contradictions: for example, maximum strength is not always achieved in the minimum time, and high productivity may require compromises in other aspects.

The process of compaction of concrete mixtures is extremely complex and dynamic. Already at the initial stage, when the density of the material changes from 1200 kg/m³ to 2400 kg/m³, there is a significant decrease in air content - from 15...30% to 2...3%. This means that at each stage of compaction (initial, intermediate or final) the material actually changes its physical characteristics, energy absorption and interaction dynamics.

As noted in recent studies [9], these parameters directly depend on the vibration modes. At the same time, changes in the material structure affect the resistance forces that arise during the movement of vibrating equipment. Thus, the "machine-environment" system is in a constant dynamic state, which complicates its control and prediction. This once again emphasizes the need for a detailed analysis of the parameters and modes of vibration compaction for each specific case.

As mentioned earlier, the main parameters of the workflow are:

Amplitude and frequency of oscillations;

Speed and acceleration;

Sealing time;

Energy characteristics (extinction coefficient, resistance coefficient, energy, specific energy and power);

Rheological characteristics of the medium (density, elastic modulus, stress, deformation, wave propagation velocity);

Elastic-inertial parameters (elasticity coefficient, mass);

Power indicators of working bodies (coercive force, static moment, pressure, weight);

In the work [3] it is recommended to take the amplitude of oscillations not less than 0.2 mm at a frequency of 314 s^{-1}. These values became the starting point for further research into the parameters of the amplitude and frequency of oscillations. Subsequently, in subsequent works, larger values of amplitudes were proposed - from 0.3 to 0.5 mm. In the study [7,9] it is indicated that the optimal amplitude is 0.5–0.7 mm at the same frequency of 314 s^{-1}.

Comparing the data from [1] and [7], one can see a difference of more than three times in the values of the amplitude of oscillations. This indicates differences in the approaches to the assessment of compaction parameters. At the same time, in further studies [7], it was suggested that the amplitude and frequency of oscillations should not be considered separately as independent parameters. Instead, in [8], a methodology for assessing the speed of oscillations was proposed, which is considered a more comprehensive indicator of compaction efficiency.

$$v = x_0\omega \text{ , m/s,} \tag{1}$$

where x_0 is the amplitude of oscillations; ω– frequency of oscillations, or acceleration [3,8]

$$a = x_0\omega^2,\ м \cdot с^{-2} \ . \tag{2}$$

When designing vibration machines that provide a certain work process, the key parameters remain the amplitude and frequency of oscillations, and it is impossible to avoid this. However, research into alternative relationships between amplitude and frequency continued. As a result, various combinations were proposed: $x_0{}^2\omega^2$ or $x_0{}^2\omega^3$, which by their physical nature are specific values of energy. For example,

$$x_0{}^2\omega^3\text{[m2/s3]} = [\ \frac{м^2 \cdot Н}{с^3 \cdot Н}\ ]=[\ \frac{Н \cdot м}{с} \cdot \frac{м \cdot с^2}{с^2 \cdot кг \cdot м}\ ]= [\ Вт / кг\ ]. \tag{3}$$

A detailed analysis of these and other criteria will be discussed below. However, it is already obvious at this stage that neither the amplitude nor the frequency of oscillations, separately or in combination, can unambiguously determine rational, let alone optimal (desired) compaction modes.

This thesis is supported by the results of studies of vibro-impact regimes, in which the oscillation frequency was significantly reduced (up to a two- or even five-fold decrease) with increasing amplitude. Such changes significantly affected the compaction efficiency.

Table 1 provides recommendations for selecting compaction parameters according to the results of research conducted at the Yuriy Kondratyuk Poltava Polytechnic Institute.

Table 1. Numerical values of amplitudes and frequencies of oscillations

Amplitude, mm	4.0-7.0	0.7-1.0	0.9-1.2	0.6	0.5	0.35	0.1
Frequency, rad/s	70	150	200	240	300	314	600

Based on the presented numerical data, two key features can be noted: with increasing frequency, the amplitude of oscillations decreases, and its numerical values vary within limits that in some cases can differ by a factor of two.

For a long time, the main focus in vibratory compaction technology was on harmonic vertical oscillations, as indicated in sources [3, 4, 5, 7]. The exception was deep vibrators with circular motion of unbalance [11].

In work [3] it was proposed to change the direction of influence on the processed medium by using horizontal vibration installations with resonant operation mode. At that time, technological research in this direction was absent. However, the creation of such installations actually gave impetus to the development of a new direction in the theory of concrete vibration forming .

Modern research confirms that the presence of shear stresses contributes to the compaction of the concrete mixture. This is explained by the fact that more efficient laying of the material occurs due to the dominance of the vertical component of the acting forces. In the zone of gravity, the structure, geometry and volume of the future product are formed.

For vibrating machines with horizontal oscillations, the following values were proposed:

Amplitude of horizontal oscillations: 0.5–1 mm

Frequency: 24-30 Hz

Due to the special design of the vibrator or its installation at an angle, additional vertical vibrations with an amplitude of 0.2–0.3 mm were generated. Later, such vibrating platforms, which mainly generated horizontal vibrations, were called spatial vibration equipment [4 , 5].

Also known is the mode of horizontal oscillations with simultaneous vibration on the product using two frequencies: f_1 = 25 Hz , f_2 = 50 Hz.

Vibration and impact modes

Horizontal vibrations remain relevant today. A significant number of studies [1, 7] are devoted to vibration-shock regimes, which are divided into two areas:

Low-frequency compaction (f = 5–10 Hz) → amplitude 4–7 mm

Mid-frequency compaction (f = 20–25 Hz) → amplitude 0.5–1.2 mm

Table 2. Numerical indicators of the energy intensity of the mixture compaction process under the influence of medium-frequency vibration mode.

Compaction mode				Intensity vibrations Iint , m ^{2} s $^{-2}$	Power vibrotactile on1 м^3 mixtures P $_E$, kW m $^{-3}$	Specific costs summary energy E $_n$, kW h m $^{-3}$	Specific absorbed costs mixture energy E $_{p.s.}$, kW · h m $^{-3}$	Coefficient Energy efficiency regime $\eta = \frac{E_{n.c.}}{E_n}$
Frequency f , Hz	Amplitude oscillation x $_0$ 10 $^{-3}$, м	Acceleration a, m s $^{-2}$	Time consolidation t , c					
50	0.20	20	40	1.2	2.88	0.032	0.86	2.68
50	0.50	50	40	7.74	18.5	0.206	1.70	0.82
50	0.81	80	40	20.30	48.6	0.540	1.68	0.31
50	0.50	50	60	7.74	18.5	0.308	1.08	0.31
50	0.50	50	120	7.74	18.5	0.616	1.23	0.20

Table 3. Numerical indicators of the energy intensity of the mixture compaction process under the influence of the impact mode of the machine operation

Compaction mode				Intensity vibrations Iint , m ^{2} s $^{-2}$	Power vibrotactile on1 м^3 mixtures P $_E$, kW m $^{-3}$	Specific costs summary energy E $_n$, kW h m $^{-3}$	Specific absorbed costs mixture energy E $_{p.s.}$, kW · h m $^{-3}$	Coefficient Energy efficiency regime $\eta = \frac{E_{n.c.}}{E_n}$
Frequency f , Hz	Amplitude oscillation x $_0$ 10 $^{-3}$, м	Acceleration a, m s $^{-2}$	Time consolidation t , c					
3	8.0	120…180	40	0.42	1.08	0.012	3.80	31.60
5	8.0	120…180	40	1.98	4.75	0.052	3.90	7.48
7	8.0	120…180	40	5.44	13.05	0.145	4.40	3.03

Tables 2-4 present experimental results on the energy intensity of compaction of concrete mix with cone settlement OK = 1–2 cm at different vibration modes [5, 8, 9, 11]. The intensity of the process was determined by the formula [3].

$$I_{инт} = x_0^{\,2} \cdot \omega^3 \;,\; м^2 \cdot c^{-3} \;, \tag{4}$$

and the equivalent power of the supplied energy calculated per 1 м3concrete mix:

$$P_E = \frac{I_{инт} \cdot G}{g \cdot v} \cdot 10^{-3} \;,\; кВт \cdot м^{-3} \;, \tag{5}$$

specific energy consumption during compaction:

$$E_n = \frac{P_E \cdot t}{3600}\ ,\ кВт \cdot год. \cdot м^{-3} \qquad (6)$$

Table 4. Numerical indicators of the energy intensity of the mixture compaction process under the influence of the shock-vibration mode of operation

Compaction mode				Intensity vibrations Iint , m ^{2} s $^{-2}$	Power vibrotactile on1 м^3 mixtures P_E, kW m $^{-3}$	Specific costs summary energy E_n, kW h m $^{-3}$	Specific absorbed costs mixture energy $E_{p.s.}$, kW · h m $^{-3}$	Coefficient Energy efficiency regime $\eta = \frac{E_{n.c.}}{E_n}$
Frequency f , Hz	Amplitude oscillation $x_0 10^{-3}$, м	Acceleration a, m s $^{-2}$	Time consolidation t , c					
10 … 50	5.66…0.45	2.24…44.2	33	8.0	19.2	0.176	1.89	1.08
10 … 50	5.66…0.45	2.24…44.2	45	8.0	19.2	0.,240	2.86	1.19
10 … 50	5.66…0.45	2.24…44.2	133	9.0	19.2	0.711	4.41	0.62

Dependencies for specific energy consumption absorbed by the mixture E.p. are not given in [6], however, graphs of stress-strain changes for the experiments described in the same work are presented. It can be assumed that the specific energy of absorption was determined by calculating the areas under these graphs. However, this remains only a hypothesis, since the authors do not specify the method for determining the potential energy of the system, and there are no relevant references to sources in the text of the work. On the other hand, based on the summarized data in Tables 2-4, it is possible to conclude about the effectiveness of the alternating vibration mode.

The discrepancy in the numerical data is an important point. It is not clear why for the first mode at frequency f = 50 Hz and amplitude x0 = 0.2 mm, the energy efficiency ratio is 2.8, while in the fourth study, where the amplitude is halved, this ratio decreases by an order of magnitude.

It is also worth noting that the equivalent power of the RE is essentially the same as the intensity, since the intensity is defined as the specific energy divided by the unit mass, while the equivalent power corresponds to the specific energy per unit volume.

Analysis of the work [6, 12] shows that the residual strain, which is a key parameter for assessing the state of the material, remains almost unchanged for all vibration modes. At the same time, the stress levels change significantly. It is known that there is a clear relationship between stress and strain, which casts doubt on the reliability of the graphs presented. However, it can be considered reasonable to conclude that the vibro-shock mode is the most effective among other types of vibrations. This conclusion is confirmed by tabular data. However, it would also be advisable to present the specific values of efficiency within the amplitude-frequency spectrum.

Particular attention in the context of the analysis should be paid to the spatial oscillation regime, which demonstrates a significant manifestation of shear stresses, which undoubtedly contribute to the acceleration of the compaction process of the concrete mixture.

6. Conclusions. As a result of the analysis of theoretical and experimental studies of the parameters and modes of vibration compaction of concrete mixtures, important aspects were identified that significantly affect the efficiency of the process. In particular, it was found that the amplitude and frequency of vibrations, although they are key parameters, cannot be considered independent, since their interaction largely determines the results of compaction. Changing the vibration mode, in particular the use of vibro-shock and spatial vibrations, proved to be effective in improving the quality of compaction, reducing energy consumption and achieving the optimal structure of the concrete mixture.

The results of the research confirm that the efficiency of compaction largely depends on the specific vibration modes, including the amplitude, frequency and type of oscillations. In this context, in order to achieve optimal parameters of the working process, it is necessary to take into account the relationship between the rheological, energy and mechanical characteristics of the mixture. Further research should be aimed at a deeper study of the influence of vibration compaction parameters on the physical and mechanical properties of concrete mixtures, as well as at the development of new approaches to modeling and optimizing this process to achieve even higher production efficiency.

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