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VIBROACOUSTIC MONITORING OF THE HOMOGENEITY AND WORKABILITY OF CONCRETE MIXES BY THEIR HYDROMECHANICAL STATE IN THE PROCESS OF MIXING

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The method of monitoring of the homogeneity and determination of the workability index of a concrete mix from the level of vibroacoustic vibrations excited in the mixer in mixing of concrete has been described. The vibration-level values dependent on the hydromechanical state of a concrete mix and its rheological characteristics in the process of mixing and formation of its vibroacoustic image have been measured at the check point of the lining of the concrete mixer and have mathematically been processed.

Keywords: *concrete mix, viscoplasticity, homogeneity, vibration.*

Introduction. One of the most important technological characteristics of a concrete mix is the workability index (or, alternatively, the grade of concrete-mix workability) characterizing the capacity of the mix for filling the volume provided to it [1]. This index is determined from the measurements of mobility and stiffness of concrete mixes [2] with the standard methods which, however, make it impossible to control these properties directly in the process of preparation of the mix, when it can still be corrected. The measurement of homogeneity as the index of compliance of a concrete mix to the required standards is envisaged at present neither in the process of mixing nor under stationary conditions, since there are no criteria of its determination. We know [3, 4] of the methods of determination of the workability of concrete mixes from the electrical conductivity of a concrete mix and from the power consumed by the engine of a concrete mixer, but they have a number of drawbacks. They include the variability of the salt proportions of the components of a concrete mix and the dependence of the measured values of electrical conductivity on the batch volume, the supply-line voltage, the granulometry of the components, and many other factors defying any attempts of allowance. These drawbacks retard widespread industrial use of these methods.

A vibroacoustic method making it possible to monitor the homogeneity and workability of a concrete mix in the process of its preparation has been developed at the State Enterprise "S. S. Ataev Scientific-Research and Engineering-Design Institute of the Construction Industry" of the Ministry of Architecture and Civil Engineering of the Republic of Belarus [5–8].

Dynamics of Mixing of Concrete. To evaluate the state of the mixed concrete, just as of any other substance, at any instant of time we must determine the velocity, pressure, and density fields. To solve this problem we consider an extended system consisting of equations of motion, continuity, energy, and state which prescribe the viscosity and the plasticity as functions of the parameters of state of the medium.

The process of mixing takes the concrete mix from the random state to that of steady-state motion. After the components of the concrete mix have been charged into the concrete mixer, the substance in the bowl of the concrete mixer represents a set of individual components nonuniformly arranged over the volume of the concrete-mixer bowl in a random order. The density of this substance is a function of the coordinates and time, i.e., a scalar density field is observed in the volume in addition to the vector velocity field. In the process of mixing, the pressure on the mix from the blades of the concrete-mixer reducer may be assumed to be a constant, whereas the concrete mix itself may be considered, in the first approximation, as an incompressible medium. The unsteady motion of the concrete mix can be described by the expression

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$$v_x = f_1(x, y, z, t)\,, \quad v_y = f_2(x, y, z, t)\,, \quad v_z = f_3(x, y, z, t)\,, \quad \rho = f_4(x, y, z, t)\,, \quad p = \text{const}\,. \tag{1}$$

As the components are mixed, they are uniformly distributed over the volume of the concrete-mixer bowl; the elements of fine fractions, entrained by the bowl, fill the volume between the elements of large fractions, thus diminishing the entrained-air volume.

By the time of stabilization of the flow of the concrete mix t_{stab} and of attainment of the homogeneity state by it, the gradient of the scalar field of density of the concrete mix tends to zero. The absence of the pressure and density fields characterizes the stead-state (stationary) motion of the medium; therefore, expression (1) will take the form

$$v_x = f_1(x, y, z)\,, \quad v_y = f_2(x, y, z)\,, \quad v_z = f_3(x, y, z)\,, \quad \rho = \text{const}\,, \quad p = \text{const}\,. \tag{2}$$

The process of mixing of a concrete mix as a result of the rotation of the concrete-mixer blade in a viscoplastic medium is characterized by the corresponding streamlines prescribing the vector field of velocity distribution of the components of the concrete mix. The streamline distribution allowing for the influence of the concrete-mixer walls, too, is of practical interest.

A concrete mix represents a viscoplastic coarse-grained substance whose state can be described by the Shvedov–Bingham equation. If the shear stresses are

$$\tau > \tau_0 + \mu\sigma\,, \tag{3}$$

the strains of viscous flow will be developed [9].

In the construction industry, for evaluation of the rheological properties of a concrete mix, the generalized parameter "grade of concrete-mixer workability" (or briefly — workability) is used instead of the physical characteristic "viscosity" [1].

The structural viscosity η_{str} is not a constant and varies with the velocity gradient [10]. However, since the rotational frequency of the outlet link of the reducer of any concrete mixer is constant (the rotational velocity of the outlet link of the SB-138 concrete-mixer reducer is 22.7 rpm), the quantity η_{str} may be considered as a constant for a fixed velocity of motion of the components of the concrete mix for a given period of mixing. Consequently, in the first approximation, the problem of determination of the character of streamlines in the case of concrete-mix flow past a plane plate (mixer blade) located near a stationary wall can be reduced to solution of the Navier–Stokes equation for viscoplastic incompressible media.

In accordance with the mechanical relativity principle, the process of interaction of the body moving uniformly and linearly with a velocity v in a stationary medium with the medium is equivalent to the process of interaction of the stationary body with the medium's flow incident on it. Thus, the problem of determination of the characteristics of the concrete-mix flow in the concrete mixer in the process of mixing is reduced to consideration of the problem of concrete-mix flow past the plane plate (concrete-mixer blade) near a stationary wall.

From the reference data, the structural viscosity of concrete mixes η_{str} with a water-to-cement ratio of 0.325 to 0.65 is 10 to 100 Pa·sec. The velocity of motion of the mixer blades v with a period of revolution of the shaft of 2.5 sec around the circle of radius 1 m is 2.5 m/sec. The linear dimension of the blades is $a \approx 0.1$ m; the density of the concrete mix is $\rho = 2300$ kg/m^3. For these conditions, the Reynolds number [11]

$$\text{Re} = \frac{va\rho}{\eta_{\text{str}}} \tag{4}$$

is no higher than 50, i.e., flow is laminar.

To model the process of concrete-mix flow past the concrete-mixer blades we use the standard model of stationary laminar motion of an incompressible viscous substance from the FemLab software package; the model is based on partial differential equations. The sketchiness of the process of modeling is in qualitative description of the character of change in the flow of a moving substance past an obstacle as a function of the rheological indices of the substance without considering the specific values of other physical parameters and the geometric dimensions of the model.

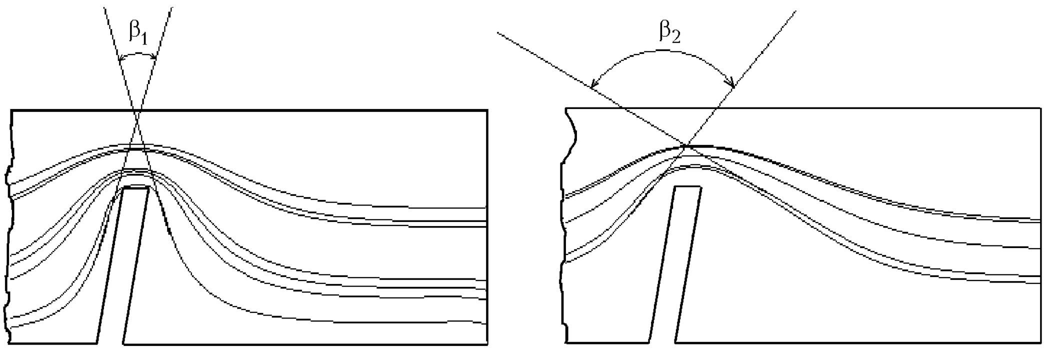

Fig. 1. Character of change in the streamlines of the modeled process. The influence of the substance viscosity is η_{1str}/η_{2str} = 50.

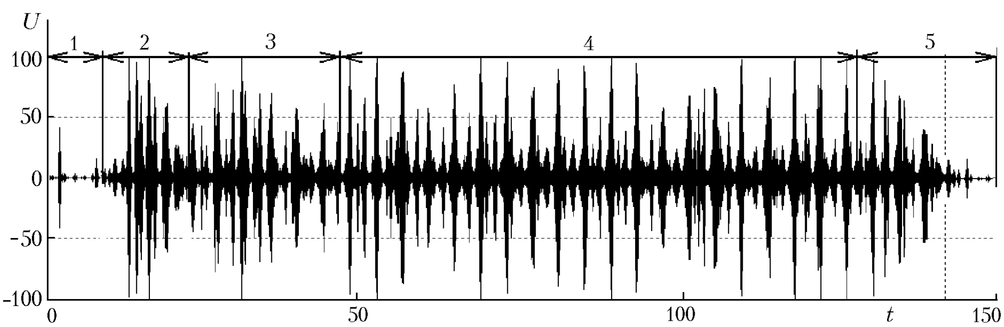

Fig. 2. Change in the signal amplitude in one cycle of mixing of concrete in the SB-138 concrete mixer. U, mV; t, sec.

The character of distribution of the streamlines of the modeled process is given in Fig. 1. The values of the structural viscosity of substances 1 and 2 differ by 50 times. An analysis of the character of change in the streamlines shows that the angle of flow β increases with decrease in the viscosity of the substance in connection with the decrease in the energy absorption. Thus, realization of the possibility of monitoring the character of change in the streamlines would enable us to determine the grade of a concrete mix directly in the process of mixing in the concrete mixer.

Technical implementation of direct visualization of the character of change in the streamlines in the concrete mixer is impossible. However, change in the interaction of the concrete mix moving along the streamlines with the armor lining of the concrete mixer enables us to indirectly, by the character of vibroacoustic oscillations exited in it, monitor flow of the concrete in the process of its mixing and consequently determine its grade of workability.

In the process of mixing, the components of the concrete mix interact with the mixer blades and walls and with each other. Acoustic noise and vibration are one result of this interaction. As has been shown in [12], the noise and vibrations resulting from the interaction of the concrete mix and the concrete-mixer walls are basic and determining; the amplitude of a vibroacoustic signal U excited in the armor lining of the concrete mixer is dependent on the parameters of the components of the concrete mix

$$U = a_1 \, (\rho v_{\text{avd}})^{3/5} \, D^{4/5} R_{\text{avd}}^{1/2} . \tag{5}$$

For experimental investigations on measurement of the amplitude and frequency characteristics of vibroacoustic signals excited in the armor concrete-mixer lining in mixing concretes with different grades of workability, we have developed and manufactured an experimental setup incorporating vibration transducers, preamplifiers, a multichannel sound recorder, and a personal computer. A vibroacoustic signal excited in the armor concrete-mixer lining in mixing of concretes is converted to an electric signal by the vibration transducers secured on the mixer; the electric signal is amplified by the preamplifiers to the nominal level of sensitivity of the multichannel sound recorder, is digitized, and is stored in the data storage in the form of data files.

TABLE 1. Parameters of the Signal and the Factors of Influence on Them

Parameter	Factor of influence			
	Uniformity	Workability	Batch volume	Site of installation
Signal amplitude in one mixing cycle	—	+	+	+
Signal amplitude in one revolution of the concrete-mixer shaft	—	+	—	+
Instantaneous signal power in one mixing cycle	—	+	—	+
Average signal power in one mixing cycle	—	+	+	+
Change in the spectrum of the signal in one mixing cycle	—	+	+	+
Accumulated spectral signal density in one mixing cycle	+	+	—	+
Peak signal frequency in one mixing cycle	—	—	—	+
Statistical characteristics of the change in the peak signal frequency fin one mixing cycle	—	—	—	+

Note. "+" and "–" mean the influence of the parameter on the vibroacoustic image of a concrete mix and the absence of it.

The character of change in the signal amplitude in a wide frequency band during the cycle of mixing of concrete in an SB-138 single-shaft concrete mixer with a vertically arranged mixer shaft is shown in Fig. 2. The signal amplitude during the cycle of mixing of concrete in a SIMEM-1500 double-shaft concrete mixer with horizontally arranged mixer shafts changes analogously. The signal has characteristic zones corresponding to different stages of mixing of the concrete:

(1) waiting for the charging of the components;

(2) charging of the components;

(3) first phase of mixing;

(4) second phase of mixing;

(5) discharging.

The performed analysis of the amplitude and frequency characteristics of vibroacoustic oscillations excited in the armor lining of the concrete mixer in mixing of concretes shows the following:

(1) the character of change in the parameters of a vibroacoustic signal in a wide frequency band is virtually identical in concrete mixers of different structures during the mixing cycle, which enables us to create a basis independent of the type of concrete mixer for construction of the algorithm of processing of the vibroacoustic signal;

(2) the presence of the noise caused by the operation of the concrete-mixer reducer, industrial noise, vibrations from the impacts of the aggregate elements in the immediate vicinity of the concrete-mixer armor, and the noise caused by the jamming of the elements of the aggregate fractions between the blade and armor lining of the concrete mixer determines the need for prefiltration of the signal before its processing;

(3) it has been established that the band of signal-processing frequencies of 10,000 to 20,000 Hz for concrete mixes with any grade of workability is optimum.

We have determined the degree of influence of different experimental factors on the parameters of the signal (see Table 1). For information on the degree of homogeneity and workability of the mixed concrete, it is expedient to process the signal by the change in the signal amplitude in one revolution of the concrete-mixer shaft and the change in the instantaneous signal power in one mixing cycle.

With mixing of the concrete the character of the streamlines will tend to a stationary one. The moving concrete mix excites a vibroacoustic signal in the armor lining of the concrete mixer. Since the concrete-mixer shaft rotates with revolution period T_0, the dependence of the amplitude of the signal U of the vibration transducer installed on the outside of the armor concrete-mixer lining on the time t can be represented in the form

$$U(t) = U\left(t - \frac{t}{IT_0}\right) + \delta_U(t)\,. \tag{6}$$

The values of $\delta_U(t)$ characterize the amplitudes of the signals corresponding to each of the periods of revolution of the concrete-mixer shaft I following one another and dependent on the degree of inhomogeneity of the concrete mix:

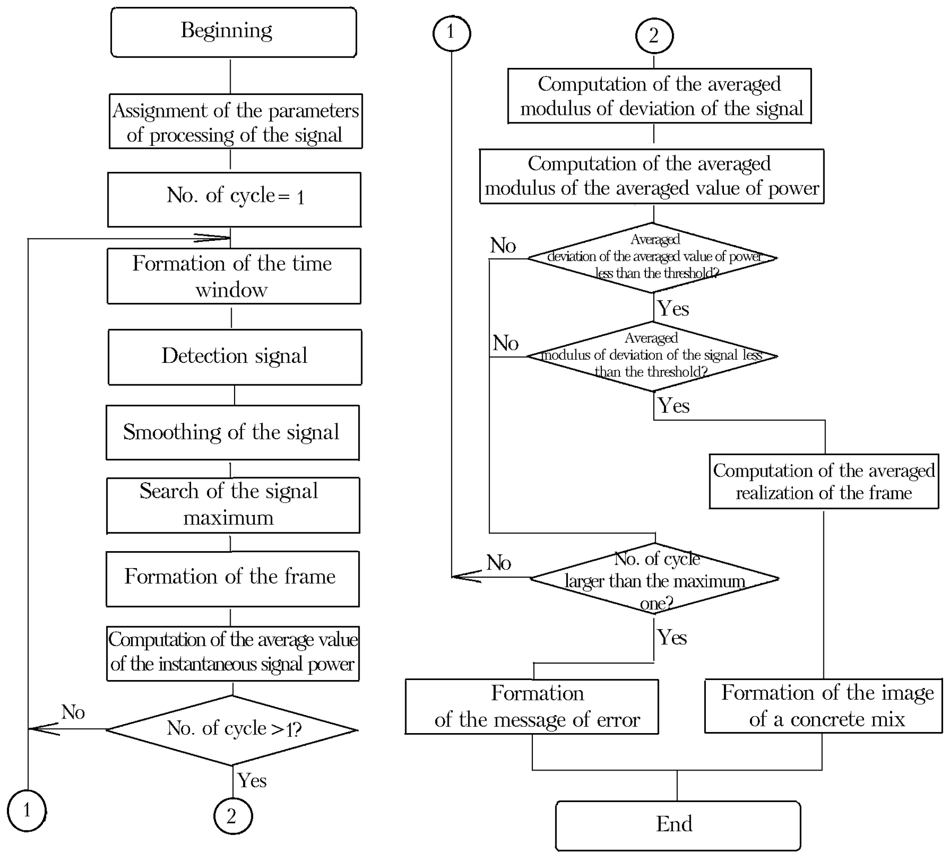

Fig. 3. Algorithm of formation of the vibroacoustic image of a concrete mix.

$$\delta_U (I, t) = U (t - IT_0) - U [t - (I - 1) T_0] . \tag{7}$$

As the concrete is mixed and attains a more homogeneous state, the value $\delta_U(t)$ decreases and will tend to its minimum $\delta_{U_{\min}}$. All indices of the process of mixing will take a more ordered character, and the instant at which they attain a stable change will correspond to the attainment of the homogeneity state by the concrete mix.

Formation of the Vibroacoustic Image of a Concrete Mix. The form of the streamlines of the mixed concrete as a function of its workability index enables us to introduce the notion of the vibroacoustic image of a concrete mix, i.e., the set of the change in the signal amplitude in one revolution of the concrete-mixer shaft and the change in the instantaneous signal power during the mixing cycle at the instant it attains a homogeneity state.

In discrete form, the dependence of the amplitude of the signal U of the vibration transducer installed on the outside of the armor concrete-mixer lining on the time t can be represented in the form of the data array

$$U [I, i] , \quad I \in \left\{1, ..., I_{\text{fin}}\right\} , \quad i \in \left\{1, ..., n\right\} . \tag{8}$$

The algorithm of formation of the vibroacoustic image of a concrete mix is given in Fig. 3. A time window covering two periods of revolution of the concrete mixer U_s is formed on each cycle of processing of the signal. To separate the signal envelope we carry out program detection by computation of the absolute value of the amplitude with the formation of the array of the detected signal U_d:

$$U_d [I, i] = \left| U_s [I, i] \right| . \tag{9}$$

To diminish the influence of the signal bursts from the random noise we smooth the data array U_d $[I, i]$ within the time window and form the array $U_{\text{sm.d}}[I, i]$. To diminish the amount of the processed data we thin out the data array within the time window with thinning coefficient K_{th}. The thinning results in the array

$$U_{\mathrm{w}}[I, i] = U_{\mathrm{sm.th}}[I, iK_{\mathrm{th}}], \quad i \in \{1, \ldots, n_{\mathrm{s}}\}. \tag{10}$$

To separate the values corresponding to one revolution of the concrete-mixer shaft from the array of the time-window data we seek the maximum value of the signal in the first half of the time window in the form of the dependence

$$U_{\max}[I, k] = \max\{U_{\mathrm{w}}[I, i]\}, \quad i \in \{1, \ldots, n_{\mathrm{p}} + 1\}. \tag{11}$$

From the array $U_{\mathrm{w}}[I, i]$, we obtain an array of processing frame $U_{\mathrm{fr}}[I, i]$ equal in duration to one period of revolution of the concrete-mixer blades:

$$U_{\mathrm{fr}}[I, i] = U_{\mathrm{w}}[I, i + k], \quad i \in \{1, \ldots, n_{\mathrm{p}}\}. \tag{12}$$

To evaluate the signal power we compute the average value of the instantaneous signal power U_{av}^2 over the processing frame I:

$$U_{\mathrm{av}}^2(I) = \frac{1}{n_{\mathrm{p}}} \sum_{i=1}^{n_{\mathrm{p}}} U_{\mathrm{fr}}^2[I, i]. \tag{13}$$

To evaluate the similarity of the dynamics of change in the signal in the running frame of processing I and the dynamics of change in the signal in the previous frame of processing $I - 1$ we compute the moduli $\delta_U(I)$ of deviation of the value of the signal amplitude and the deviation $\delta_{U^2}(I)$ of the average value of the instantaneous signal power in the frames that follow:

$$\delta_U(I) = \sum_{i=1}^{n_{\mathrm{p}}} \left| U_{\mathrm{fr}}[I, i] - U_{\mathrm{fr}}[I - 1, i] \right|, \tag{14}$$

$$\delta_{U^2}(I) = \left| U_{\mathrm{av}}^2(I) - U_{\mathrm{av}}^2(I - 1) \right|. \tag{15}$$

Beginning from the second cycle of processing, we compute the averaged deviation of the average value of the instantaneous signal power $\delta_{U^2_{\mathrm{avd}}}(I)$ and the average value of the modulus of deviation of the signal amplitude $\delta_{U_{\mathrm{avd}}}(I)$. They are compared to the threshold values σ_{U^2} and σ_U established experimentally and with the simultaneous meeting of the requirements

$$\delta_{U^2\mathrm{avd}}(K) < \sigma_{U^2}, \quad \delta_{U\mathrm{avd}}(K) < \sigma_U, \tag{16}$$

we determine the condition of stabilization of the parameters of the concrete mix for the Kth cycle of processing.

If the number of processing cycles exceeds the maximum prescribed value $I_{\max}$ and condition (16) is not fulfilled, this suggests the unstable character of mixing of the concrete and demonstrates that it is impossible to form its vibroacoustic image. One reason for the unstable character of mixing of the concrete can be the failure of the concrete-mixer blades. Once condition (16) has been fulfilled, we compute the array of realization of the frame, averaged over the last three processing cycles $U_{\mathrm{fr.avd}}$.

To eliminate the influence of the batch volume and the granulometric composition of the batch on the formed vibroacoustic image we normalize each instantaneous value of the amplitude to the period-average value

$$U_{\mathrm{n.fr.avd}}[i] = \frac{U_{\mathrm{fr.avd}}[i]}{\sqrt{U_{\mathrm{av}}^2(I)}}, \quad i \in \{1, \ldots, n_{\mathrm{p}}\}.$$

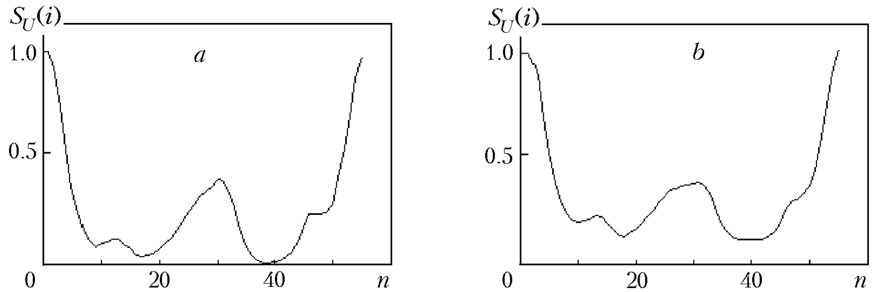

Fig. 4. Amplitude components of the vibroacoustic images for the grade of concrete-mix workability: 1) Zh1; b) P1. $S_U(i)$, rel. units.

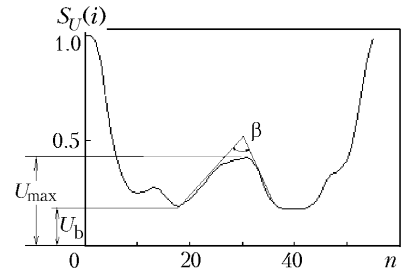

Fig. 5. Criteria of difference of the amplitude components of vibroacoustic images: β is the angle of concrete-mix flow past the concrete-mixer blade, U_b is the amplitude of the background level of the signal, and U_{max} is the maximum amplitude of the signal from the blade. $S_U(i)$, rel. units.

The vibroacoustic image S_m of the concrete mix, which consists of the array of values of the signal amplitude in one revolution of the concrete mixer $S_U(i)$ and the array of average values of the instantaneous signal powers in the entire cycle of mixing of concrete $S_U{}^2(I)$, is formed:

$$S_m = \begin{cases} S_U(i) = U_{\text{n.fr.avd}}[i], & i \in \{1, ..., n_p\}; \\ S_U{}^2(I) = U_{av}^2(I), & I \in \{1, ..., K\}. \end{cases}$$

Figure 4 gives the amplitude components of vibroacoustic images for the stiff and plastic concrete mixes, which have been obtained using the developed "P_Obraz" program. Their difference is determined by the character of change in the streamlines in the steady-state regime.

The basic parameters of the difference in the amplitude characteristics are marked in Fig. 5. The formalized parameters β, U_b, and U_{max} are dependent on the character of concrete-mix flow past a moving concrete-mixer blade. Experimental data fully confirm the above theoretical results (see Fig. 1).

Conclusions. The results of investigation of the regularities of change in vibroacoustic signals in mixing of concretes enable us to introduce the notion "vibroacoustic image of a concrete mix" S_m in full measure describing its state in the process of mixing.

The function S_m includes two arrays: the array of values of the signal amplitudes in one revolution of the concrete mixer $S_U(i)$ and the array of averaged values of the instantaneous signal powers in the entire cycle of mixing of concrete $S_U{}^2(I)$. As the experimental data have shown, the vibroacoustic images of concrete mixes with different grades of workability have pronounced characteristic differences of the parameters β, U_{max}, and U_b.

A correlation analysis of the vibroacoustic images of concrete mixes with different parameters shows that the dominant factor influencing the form of the vibroacoustic images of concrete mixes is their grade of workability.

NOTATION

a, linear dimension of the concrete-mixer blade, m; a_1, proportionality factor; D, generalized coefficient dependent on the Poisson coefficients and the Young modulus of the armor lining of the concrete mixer and the particles of the concrete-mix aggregate; I, No. of revolution of the concrete-mixer shaft; I_{fin}, No. of final revolution of the concrete-mixer shaft in the cycle of mixing of concrete; k, index of the array element having a maximum; K_{th}, coefficient of thinning of samples of the signal (resampling coefficient); n, number of samples of the signal of the period of revolution of the concrete-mixer blades; n_s, number of samples of the signal within the time window; n_p, number of points in the image of the concrete mix; p, pressure, Pa; R_{avd}, averaged radius of the particles of the concrete-mix aggregate, Re; Reynolds number; $S_U(i)$, amplitude component of the vibroacoustic image of the concrete mix; $S_{U^2}(I)$, power component of the vibroacoustic image of the concrete mix; S_m, vibroacoustic image of the concrete mix; t, time, sec; T_0, period of revolution of the concrete mixer, sec; U, amplitude of the vibroacoustic signal; U^2_{av}, average value of the instantaneous signal power; v, linear velocity of motion of the concrete-mixer blade, m/sec; v_{av}, averaged velocity of motion of concrete-mix particles; x, y, z, Cartesian coordinates; $\delta(I)$, deviation of the value of the signal amplitude; $\delta_U(t)$, function determined by the degree of inhomogeneity of the concrete mix; $\delta_{U^2}(t)$, deviation of the value of the signal power; η_{str}, structural viscosity of the concrete mix, Pa·sec; μ, coefficient of friction in the concrete mix; ρ, density of the concrete mix, kg/m^3; σ, normal stress in the concrete mix, Pa; σ_U, threshold value of the deviation of the signal amplitude; δ_{U^2}, threshold value of the deviation of the signal power; τ, stress required for displacement of the concrete mix, Pa; τ_0, limiting shear stress, Pa. Subscripts and superscripts: s, sample; d, detected; fr, frame; fin, final; w, window; th, thinning, resampling; sm.d, smoothed detected; m, mix; av, average; str, structural; p, point; fr.avd, frame-averaged; n.fr.avd, normalized frame-averaged; avd, averaged; b, background; max, maximum; sgn, signal; stab, stabilization; min, minimum.

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