Computational experiment for modeling shock-impulse technology of concrete mixtures forming

S P Titov\textsuperscript{1}, Mong Thu Tran Thi\textsuperscript{1} and V I Kondrashchenko\textsuperscript{1}

\textsuperscript{1}Russian University of Transport, Obraztsova street 9, b.9, Moscow, Russia, 127994

Abstract. A mathematical model has been developed for modeling the technology of shock-impulse molding of concrete mixtures, according to the results of a computational experiment on which rational parameters of the rotor of the throwing device are determined in the form of two rotating cylinders with plates along their generatrices, intended for throwing the components of the concrete mixture onto the molded surface mechanically. A mathematical description of operation of such a device, interaction of individual particles with blades and their flight in the inter-rotor space up to the molding of the manufactured product is given. To stabilize the initial fractional composition of the aggregates, designs of rotors are proposed that provide portion capture of the concrete mixture or the use of the rubberized surface of rotors in the form of elastic tubular elements.

1. Introduction

For compaction of construction mixes the vibration method has got the most widespread application, which, in turn, has a number of significant drawbacks. They include high metal consumption and high energy consumption of production of concrete and reinforced concrete products; high levels of noise and vibration, which affect the working personnel unfavorably; narrow boundaries of mobility of the compacted concrete mixture and a number of other restrictions, in particular, when molding large-sized products, during production of which control over the compaction process of construction mixes is limited, etc.

In this regard an acute direction is development of methods for compaction of mixes, which are alternative to the vibration technology, such as, for example, pneumatic or mechanical spraying, the latter of which refers to the shock-impulse method of forming concrete mixtures, characterized by the lowest specific energy consumption and metal consumption at high productivity.

This raises the problem of determining the rational values of technological parameters of shock-impulse molding and the very design of technological equipment for its implementation. The most rational way to solve this problem can be obtained on the basis of a computational experiment using a structural-simulation model of a shock-impulse method for forming concrete mixtures. This approach, which excludes the laboriousness of making full-scale samples of equipment of irrational designs and carrying out long-term technological research with it, is distinguished by high efficiency, reduced terms for obtaining an optimal solution and reliability of the results obtained.
2. Formulation of the problem
Shock-impulse molding of concrete mixtures is carried out due to the capture of elementary portions of freely falling concrete mix by blades located along the generatrix of the rotating cylinder. This method of forming makes it possible to combine in a single technological cycle a number of operations, such as transportation, laying and compaction of construction mixes. At the same time, it is distinguished by such a feature as a change in the fractional composition of the aggregates due to their crushing upon contact with the metal elements of the throwing cylinders.

Known studies on the mechanical spraying technology relate mainly to determination of technological parameters of molding concrete mixtures without taking into account their structural features, i.e. the presence in its composition of at least two dissimilar components - a mortar part and a large aggregate, which interact in different ways with the surface of rotating cylindrical throwers [1-10].

This approach does not allow taking into account the features of the structure of compacted concrete mixtures, such as, for example, the crushing of a coarse aggregate, which directly affects the purpose of the initial and obtained in the process of shock-impulse forming of the concrete composition, as well as the choice of the type of working bodies of devices of this type. This problem can most reliably be solved by the method of structural-simulation modeling of technological processes, which is formulated in [7]. This approach is based on development of a mathematical model of shock-impulse forming, the main elements of which were described in [11], but in the form of a point model, i.e. without taking into account the size and shape of large aggregate particles, which is essential to ensure reliability of the developed mathematical model.

3. Solution of the problem
Structural and simulation modeling is based on construction of a mathematical model of shock-impulse compaction of a concrete mix followed by a computational experiment thereon. This approach allows determining rational parameters of the shock-impulse installation, in which rotating cylinders (rotors) can take various location relative to each other and the surface to be concreted depending on the type of the construction to be concreted (Figure 1).

![Figure 1](image)

**Figure 1.** Variants of arrangement of the shock-impulse installation

- a) for concreting horizontal surfaces ($h_1 = 0$); b) the same, vertical (upper rotor is a dispenser) ($b_1 = 0$); c) the same, sloping; $b_1$ – distance between the centers of the rotors; $b_2$ – the same, between the centers of the left-hand rotor and the drum of the tape feeder; $R$ – radius of the right-hand rotor along the blade edge; $r_l$ – the same, left-hand; $r$ – radius of the right-hand rotor along the drum edge; $r_1$ – the same, left-hand; $r_2$ – radius of the drum of the tape feeder; $h_1$ – distance between the centers of rotors; $h_2$ – the same, between the centers of the left-hand rotor and the drum of the tape feeder; $h_3$ – the same, from the rotor to the surface to be concreted.
The process of shock-impulse compaction is simulated by movement of two types of particles of a concrete mix: type 1 - particles of the mortar part of the concrete mixture formed by cement, mixing water and fine aggregate, and type 2 - coarse aggregate (dense or porous). In this case, the particles of the 1st type are absolutely plastic, and the 2nd type - absolutely elastic, which was taken into account when they interact with the elements of rotating rotors. At the same time, the possibility of destruction and fragmentation of large particles into smaller fractions was considered, leading to a change in the initial fractional composition of fillers.

Block diagram of the throwing unit of the shock-impulse installation, shown in Figure 1a, is shown in Figure 2 and includes the main geometrical parameters that characterize the throwing head of the installation and are used in the developed structural-simulation model of the shock-impulse molding of concrete mixtures.

![Figure 2. Layout of the throwing unit of the shock-impulse installation](image)

- Geometrical parameters: $H, a, d, H_1, b$ - determined the position of the centers of rotors and the mouth of the feeder; $R, R_1$ - radii of the outer edges of blades; $r, r_1$ - radii of the drum surfaces; $n, n_1$ - number of blades of rotors; $\omega, \omega_1$ - angular speeds of rotation of rotors (index 1 refers to the left rotor, parameters of the right rotor are indicated without the index).

In case of particle motion in $xOy$ (Figure 2) the initial parameters of the process of imitation of particle motion are the random variables of the type of particle, its mass, coordinate $x_0$ and the moment $t_0$ of appearance of a particle at the section d of mouth of the rotor.

The flight of particles in inter-rotor space at the initial stage occurs at low speed and, neglecting the air resistance, the particle coordinate will be $y = -gt^2/2 + H$, and its speed $V = \sqrt{2g(H - y)}$.

The position of the blades of the right rotor is determined at the random moment $t_0$ of appearance of a particle in the mouth at an angle $\phi_0$, which is counted counterclockwise from the axis $0y$.

Let the angle of the $n$-th blade be the angle $\phi = \omega t + \phi_0$ with the axis $0y$. The conditions for intersection of the trajectory of a particle with rotor elements (at time $t_A$) are given by the system of equations

$$y_A = \rho_A \cos(\omega t_A + \phi_0),$$
$$x_A = x_0 = \rho_A \sin(\omega t_A + \phi_0),$$

from which the coordinates of intersection - time $t_A$ and radius $\rho_A$ are determined. And if $r < \rho_A \leq R$, then the particle contacts with the blade, if $\rho_A < r$, then with the drum.

If the particle hits not on the blade, but on the drum, then the moment of meeting $t_B$ with the surface of the drum is determined from the condition

$$\left(-\frac{gt_B^2}{2} + H\right)^2 + x_0^2 = r^2.$$
The collision of particles occurs as they move in the inter-rotor space. The initial data for the calculations are angular velocities of two particles before impact $\bar{\omega}_1$, $\bar{\omega}_2$, and the velocities of their centers of mass $\bar{V}_{1z}$, $\bar{V}_{2z}$; the masses of the colliding bodies $m_1$ and $m_2$ and their moments of inertia about the central axes $I_{x1}$, $I_{y1}$, $I_{z1}$, $I_{x2}$, $I_{y2}$, $I_{z2}$; coefficients of recovery of the velocity $k$ of materials of colliding bodies.

![Figure 3](image_url)

**Figure 3.** Schemes for problems on the collision of a particle with a rotating blade rotor (a) and the collision of a particle with a rotating rotor (b).

Particular solutions for particle collisions were obtained:

a) with a rotating rotor blade (Figure 3a): the after-impact particle speed

$$U_1 = \bar{V}_1 + S_{\text{imp}} \cdot \bar{n}_1 / m_1 ,$$

and speed of the rotor blade

$$U_2 = \bar{V}_2 + S_{\text{imp}} \cdot \bar{n}_2 / m_2 ,$$

where index 1 indicates the particle of the concrete mix, and 2 – the rotor blade (after the collision with the rotor blade, then particle makes free flight in inter-rotor space);

b) with a rotating rotor (Figure 3b), the particle velocity after impact in projections on the ordinate axes is

$$U_{1x} = V_{1x} + S_{\text{imp}} n_{1x} / m_1 ,$$

$$U_{1y} = V_{1y} + S_{\text{imp}} n_{1y} / m_1 ,$$

(here $V_{1x} = \sqrt{2g(H - y_B)}$, $V_{1y} = -gt_B^2/2 + H$ – projections on the ordinates of the particle velocity before the collision; impact impulse $S_{\text{imp}} = -E(1 + k) / D = V_i \cos \phi (1 + k) / D$).

Further, the particle makes free flight in the inter-rotor space.

*The particle movement along the rotor blade* (Figure 4a) occurs during an inelastic collision of the particle with the rotor’s blade, i.e. for particles of the 1st ($k = 0$) type. The projections of the absolute velocity of the particle on the $0x$ and $0y$ axis at the moment of its descent from the blade will be determined by the equations

$$V_{1x} = V_r(t_L) \sin \varphi(t_L) + \omega R \cos \varphi(t_L) ,$$

$$V_{1y} = V_r(t_L) \cos \varphi(t_L) - \omega R \sin \varphi(t_L) ,$$

and the coordinates of the particle descending point (Figure 4b) –

$$x_L = R \sin \varphi(t_L) , \quad y_L = R \cos \varphi(t_L) .$$
The adequacy of the developed structural-simulation model of the shock-impulse compaction was established by carrying out field experiments using a throwing device with asymmetrically located rotors. At the same time, the correspondence of the calculation model to the experiment was established by identifying the simulated flow to the real movement of discrete particles of concrete mixture, which was visualized using accelerated shooting with the SKS-1M camera at a frequency of 3800-4000 frames/s.

Figure 5 shows the results of a computational experiment to simulate the movement of concrete mix particles during its rotary compaction. For particles of the 2nd type - filler, after free fall in section 1-2 (see Figure 5a), it is repeatedly reflected from the blade of the left rotor (point 2), the cylinder of the right rotor (point 3) to its blade (point 4) and further from the left rotor blade (point 5) to the concreting surface (point 6).

For a particle of the 1st type of the mortar part of concrete, after free flight in section 1-2 (see Figure 5b), it is captured by the blade of the left rotor in point 2, after which the particle is displaced along the blade to its edge and in point 3 it breaks off, moves in section 3-4 in the inter-rotor space and in point 4 falls on the blade of the right rotor, by inertia it shifts to the base of the blade and in point 5 is inhibited by the surface of the right rotor, and then in section 5-6 moves along the surface of the same blade up to point 6 of separation, after which the particle already moves to point 7 of contact with the concreted surface.

Comparison of the results of the carried out numerical and field experiments shows the correspondence of the developed structural-simulation model to the real process of shock-pulse compaction of the concrete mixture. The difference between the behavior of an array of concrete mixture particles and its representation in the model as a discrete particle flux can be corrected by extrapolating the results of a computational experiment with an increase in the frequency of particle generation at the mouth of the inter-rotor space of the throwing device.
With the used structural-simulation modeling, a computational experiment was carried out to determine the rational parameters of the throwing device, which were set according to the angle of dispersion of the flow of the concrete mixture $\beta$, at the outlet of the rotating rotors. The computational experiment was carried out using equal $R_r/R = 1$ and symmetrically located rotors (Figure 1a) with the ratio of the inner $r$ and the outer $R$ radii of the rotors $r/R = 0.95$, the distance to the concreted surface $h_3 = 5R$ with the ratio of particles of the 1$^{st}$ and the 2$^{nd}$ types as 1.2: 1.0, and the angle dispersion $\beta$ was taken equal to the angle of the sector vortex covering 90% of the flow of discrete particles.

From the results of the computational experiment shown in Figure 6, it follows that the use of short blades leads to a decrease in the angle of dispersion and for minimization $\beta$ the blade width should be limited to 5-8% of the inner radius $r$ (Figure 6a). If we consider the ratio of the length with the intense concentration of particles to the total length of the zone of dispersion as the parameter $\delta$, then the value $\delta$ sharply increases with the approach of the rotors to the concreted surface (Figure 6b). Therefore, the rotors of the throwing device must be located as close as possible to the surface of the molded product. The use of rotors of different diameters results in dispersion of particles (Figure 6c), as well as an increase in the asymmetry of their arrangement, characterized by the angle $\alpha$ (Figure 6d).

**Figure 6.** The influence of the parameters of the throwing head on the angle of dispersion of particles $\beta$ (solid line - average values of indicators, dotted line - the range of their permissible values, other explanations are given in the text).

According to the computational experiment, it was found that to minimize the angle $\alpha$, a throwing head with symmetrically located identical rotors and short blades located in the immediate vicinity of the surface to be concreted should be used. However, such rotors do not ensure preservation of the initial fractional composition of the aggregates, for which it is necessary to measure their design, in particular, due to a change in the surface relief of metal rotors (Figure 7a) [12] or a decrease in the rebound of a large aggregate from the elements of the throwing head by a decrease in the surface elasticity rotors due to the use of rubberized tubular elements (Figure 7b) [13].
4. Conclusions and recommendations

Thus, using structural-simulation modeling by conducting a computational experiment on a mathematical model of shock-impulse forming of concrete mixtures, rational parameters of the rotor throwers of the installation were determined by their power spraying, which were implemented in a throwing device with symmetrically located rotors of the same size, in which metal blades are replaced by elastic tubes with a radius ratio \( r/R \approx 0.96-0.98 \) [13].

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