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INCREASING THE EFFICIENCY OF GRAVITY MIXING FOR CONCRETE MIXTURES

ABSTRACT. *The article examines the impact of a gravity concrete mixer's geometric parameters and the concrete mixture's rheological properties on mixing efficiency. The kinematics of particles in the mixing drum are considered, taking into account gravitational, centrifugal and inertial forces. An analysis was conducted to assess the impact of blade angle, drum rotation speed, and mixture viscosity on component distribution uniformity and final material quality.*

The results of mathematical modeling confirmed that an increase in the rotation speed contributes to more active mixing, but its excessive value can lead to centrifugation of particles and a decrease in process efficiency. It has been established that the optimal angle of blades inclination ensures maximum circulation of particles and minimizes areas with weak mixing. A connection between the rheological characteristics of the mixture and the kinematics of its movement has been revealed, which allows optimizing the design parameters of the mixer to improve the mixing quality and reduce energy costs.

The results obtained can be used to improve the design of concrete mixers, as well as the development of adaptive mixing process control systems. It is advisable to focus further research on mathematical modeling of turbulent flows in the mixing chamber and the development of intelligent systems for regulating mixing parameters.

Keywords: *concrete mixer, rheology, particle kinematics, rotation speed, blades, mixing efficiency, mathematical modeling, process optimization.*

1. Problem statement. The process of mixing concrete mixtures in gravity concrete mixers is determined by the interaction of the mixture particles with mixer working bodies and with each other. The uniformity of component distribution directly affects the quality of the final material, including its strength, durability, and resistance to external influences. Despite the widespread practice of using gravity mixers, their effectiveness largely depends on design features and kinematic parameters.

One of the key aspects determining mixing quality is the dynamics of particle movement in the mixing drum. During the rotation of the drum, material particles are exposed to gravitational, centrifugal and inertial forces, which determines their trajectory and speed of movement. If particle interaction with the blades is not sufficiently effective, zones with weak material circulation may form, leading to the mixture's heterogeneity.

The geometry of the mixer blades and their angle of inclination significantly affect the particle velocity distribution and mixing intensity. The choice of rational blade parameters determines how evenly the concrete mixture components will be mixed, which is especially important when using highly active additives or modified binders.

The relevance of the study is due to the need to ensure high homogeneity of concrete mixtures, which directly affects their strength and performance characteristics. Gravity concrete mixers, which are widely used in construction, have disadvantages related to uneven mixing, which can lead to the formation of areas with weak material circulation. Determining the optimal design parameters of the mixer, such as blade geometry and drum rotation speed, is an important task for increasing mixing efficiency and ensuring uniform particle distribution. Research into the influence of these parameters, as well as the rheological properties of the concrete mix, will allow us to improve the concrete preparation process and improve the quality of building materials.

2. Analysis of recent sources and publications. Many studies highlight that mixing efficiency largely depends on the mixer's design parameters, particularly the blade shape and placement, drum rotation speed, and mixing chamber's inner surface geometry. Optimizing these parameters allows for uniform particle distribution and minimizes the formation of zones with low material circulation intensity [1-2].

Scientists also focused their research on analyzing the trajectories of concrete mixture particle movement under the influence of gravitational, centrifugal, and inertial forces. Studies show that the kinematic features of the mixing process directly affect the time it takes to achieve the required homogeneity of the mixture, as well as the uniform distribution of components throughout the drum volume. In particular, it has been found that too high a rotation speed leads to a centrifugation effect, when particles are pressed against the walls of the drum and the mixing process becomes significantly more difficult [3].

Particular attention was also paid to the influence of the rheological properties of the concrete mix on the mixing efficiency. Scientific studies show that the viscosity and density of the material determine the nature of its movement inside the drum and the degree of interaction with the working elements of the mixer. It has been shown that for mixtures with high viscosity it is necessary to increase the mixing intensity, which can be achieved by changing the geometry of the blades or the operating modes of the mixer [4].

3. Purpose of the work. The purpose of the study is to analyze the influence of the geometric parameters of the mixer and the rheological properties of the concrete mix on the efficiency of the mixing process in a gravity concrete mixer. The research is aimed at determining the optimal design characteristics of the mixer's working elements, ensuring uniform distribution of particles, reducing mixing time and increasing the homogeneity of the concrete mix.

4. Discussion of research results. Gravity concrete mixers are one of the most common types of equipment for preparing concrete mixtures directly on the construction site. They are characterized by their simplicity of design, reliability and efficiency in mixing a wide range of building materials. The basic principle of their operation is based on the rotation of a drum, inside which are installed blades that ensure the lifting and free fall of concrete mixture particles under the influence of gravity. This creates a cyclic mixing process, promoting uniform distribution of the mixture components [5].

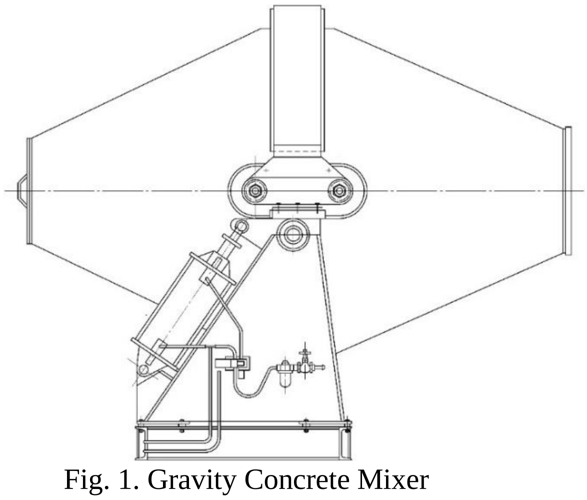

Fig. 1. Gravity Concrete Mixer

The efficiency of a gravity mixer largely depends on its design parameters, in particular the shape of the drum, the location of the blades and the rotation speed. Choosing the optimal parameters allows you to improve mixing quality, reduce mixture preparation time and reduce energy consumption. At the same time, insufficiently intensive mixing can lead to uneven distribution of components, the formation of zones with low material circulation and, as a result, to a decrease in the quality of the final product.

The rheological properties of the concrete mix also play a key role in the mixing process. Viscosity, density and solids content determine the nature of the material movement in the drum and the level of interaction of the particles with the working elements of the mixer. For low-viscosity mixtures, it is necessary to adjust the angle of the blades and the speed of rotation to prevent delamination of the material. In the case of more viscous compositions, on the contrary, the mixing intensity must be sufficient to overcome the internal resistance forces and ensure uniform distribution of the mixture components [6].

Modern research is aimed at optimizing the mixing process by improving the structural elements of the concrete mixer and developing new mathematical modeling techniques. This allows not only to improve the homogeneity of the final mixture, but also to increase the productivity of the equipment, minimize material losses and energy costs. The use of mathematical models and computer simulations allows to predict the behavior of particles in the mixing chamber and determine the optimal mixing modes depending on the properties of the mixture and operational requirements [7].

The process of small-scale mixing of the construction mixture in a gravity concrete mixer is determined by the complex movement of material particles along the inner surface of the drum under the action of gravity and inertia forces. This movement is based on the rotation of the drum with installed blades, which provide a change in the trajectory of the mixture and the formation of a uniform distribution of particles in the mixture.

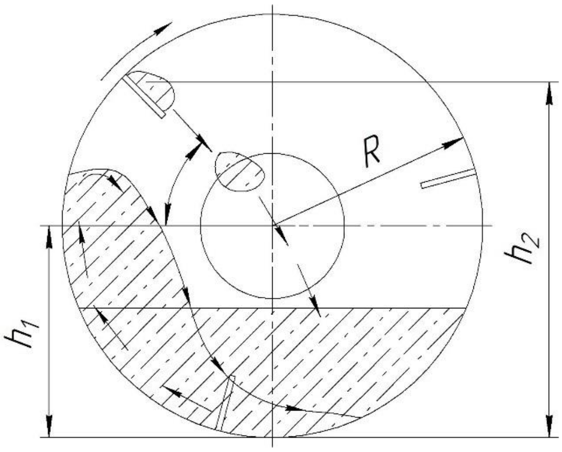

Fig 2. Blade interaction on the mixture

It is advisable to describe the trajectory of building mixture particles in a cylindrical coordinate system (R, φ, z), where R – drum radius, φ – angle of its rotation, and z – vertical coordinate counted from the base of the drum [8]. The kinematics of particles are determined by two main components: rotational motion together with the drum and translational displacement under the influence of gravity and centrifugal forces.

Provided that the drum rotates with an angular velocity ω, the particles of the mixture acquire the corresponding rotational speed:

$$v_{\varphi} = \omega R \tag{1}$$

where R – distance from the axis of rotation to the particle,ω – angular speed of the drum rotation.

However, under the influence of gravitational forces, the particles carry out a vertical displacement along the inner surface of the drum, forming a movement characteristic trajectory. The vertical movement of particles can be mathematically described as follows:

$$z(t) = h_1 - \frac{1}{2} g t^2, \tag{2}$$

where h_1 – initial particle height, g – acceleration of free fall, t – movement time.

The blades affect the trajectory of the particles by changing their direction, which contributes to separation from the surface of the drum and subsequent movement in space. The trajectory of this separation can be modeled in a curve form, which is described by the parabolic form equation:

$$z = R\tan(\beta)\cos(\varphi), \tag{3}$$

where β – blade angle, φ – angular coordinate of the particle.

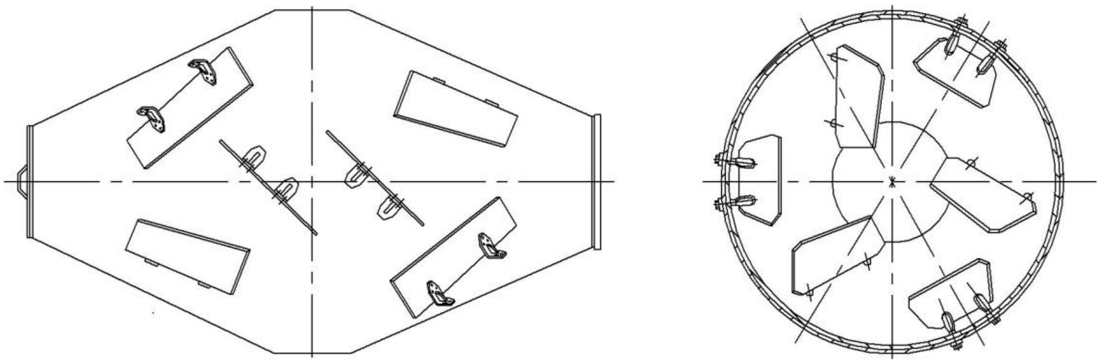

Fig 3. Layout of the blades in the mixing drum

For a mathematical description of building mixture movement in a horizontal plane, it is advisable to use kinematic relationships that relate the radius R, angle speed ω and separation angle φ_0, in which the particle separates from the surface of the drum:

$$\varphi_0 = \arcsin\left(\frac{g}{\omega^2 R}\right). \tag{4}$$

Based on these parameters, it is possible to formulate a general equation that describes the surface of particles trajectory in the drum:

$$z = R\tan(\beta)\cos(\omega t) - \frac{1}{2}gt^2. \tag{5}$$

Optimal angle of blades inclination β is determined in such a way as to promote the maximum separation of the particle from the drum surface, ensuring its uniform distribution throughout the volume. Generally, to achieve effective mixing angle β taken in the range of 30°–45°. Within these limits, the particle receives sufficient kinetic energy to break away, while at the same time its trajectory remains controlled:

$$\beta_{opt} = \arctan\left(\frac{gt_{\det}^2}{2R}\right), \tag{6}$$

where t_{det} – The time elapsed until the particle detaches from the blade is determined by the condition of equality of centrifugal force and gravity:

$$\omega^2 R\cos(\beta) = g. \tag{7}$$

Hence the optimal angular speed of drum rotation ω_{opt} equals:

$$\omega_{opt} = \sqrt{\frac{g}{R\cos(\beta)}} \tag{8}$$

From the resulting equation it follows that the mixing time decreases with increasing angular rotational velocity ω and radius reduction R. However, excessively increasing the rotation speed can cause a "centrifugation" effect, in which particles are pressed against the walls of the drum, which leads to a decrease in mixing efficiency. In this regard, there is a critical value of angular velocity ω_{cr} [9], to which particles cease to come off the walls:

$$\omega_{cr} = \sqrt{\frac{g}{R}}. \tag{9}$$

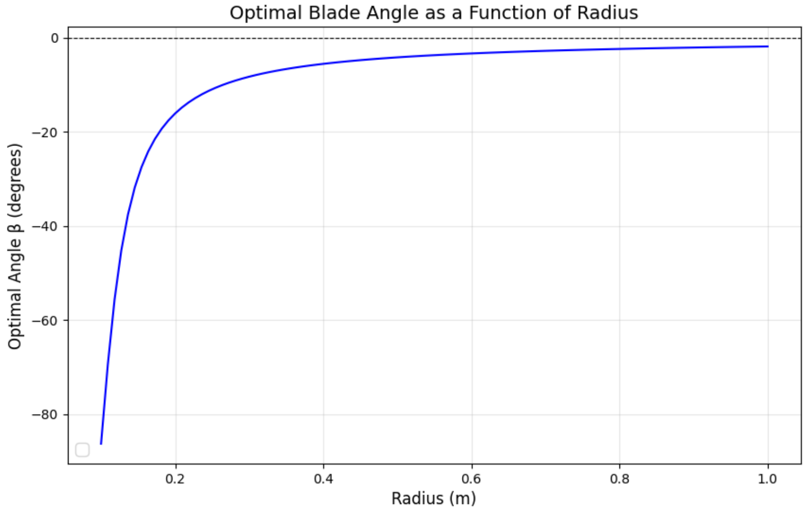

Fig 4. Optimal blade angle to drum radius

To achieve effective mixing, the angular rotational speed must remain below the critical value ω_{cr}, while providing enough energy to detach particles from the surface of the drum:

$$\omega_{opt} = 0,6 \div 0,8\omega_{cr}. \tag{10}$$

Solving this system of equations allows us to determine the parameter values that ensure minimum mixing time and maximum process efficiency. For gravity concrete mixers with a standard drum diameter within 0,6 m ≤ D ≤ 1,5 m the optimal angular speed of rotation is 10–20 rpm [10].

The time required for a particle to reach the surface of the drum, taking into account the vertical component of motion, is determined by the following expression:

$$t_{ver} = \sqrt{\frac{2h_1}{g}}. \tag{11}$$

For a particle moving along a blade, the moving time is additionally determined by the blade inclination angle β [11]. This case, the particle movement occurs under the action of the projection of the gravitational force onto the direction of the blade. The velocity of the particle in this direction can be written as $v = \sqrt{2gh\sin\beta}$, from where the time of particle movement along the blade is equal to:

$$t_{bl} = \frac{L}{\sqrt{2gh\sin\beta}}, \tag{12}$$

where L – particle trajectory length along the blade, h – the height from which the particle begins its movement.

The general motion equation for a particle on the blade's surface is determined by force balance conditions:

$$m\frac{d^2\vec{r}}{dt^2} = \vec{F}_{inert} + \vec{F}_{grav} + \vec{N} \tag{13}$$

where m – particle mass, $\vec{F}_{inert}$ – inertial force resulting from the drum rotation, $\vec{F}_{grav}$ – gravity force, $\vec{N}$ – reaction of the supporting blade surface.

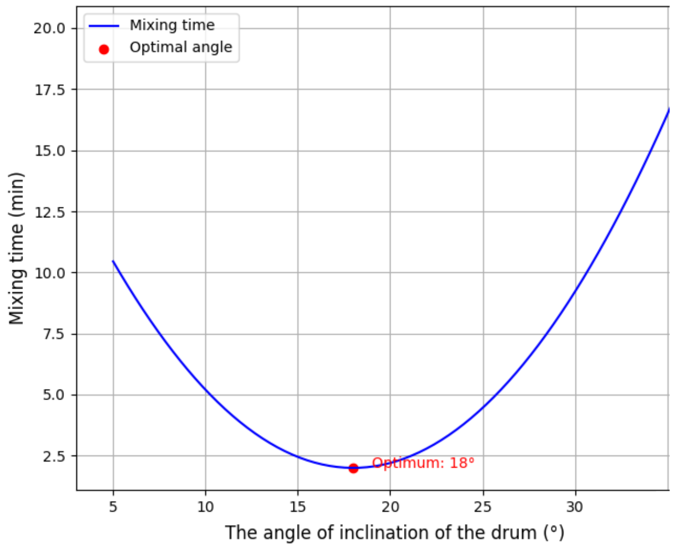

Fig 5. Dependence of mixing time on the drum inclination angle

Resistance reaction N is perpendicular to the blade surface and balances the normal component of the forces acting on the particle. Accordingly, the projections of particle motion equation onto the radial, angular and vertical coordinates can be presented in the appropriate form:

$$m\frac{d^2r}{dt^2} - mr\omega^2 = -mg\sin\beta + N_r, \tag{14}$$

$$mr\frac{d^2\phi}{dt^2} = 0, \tag{15}$$

$$m\frac{d^2z}{dt^2} = -mg\cos\beta + N_z. \tag{16}$$

Since the particle remains on blade surface, its movement is limited by the fact that it does not break away from the surface. This means that the centrifugal force of inertia should not exceed the projection of gravity on the radial direction. Based on this condition, it is possible to determine the appropriate dependencies for the motion of a particle:

$$m\omega^2 r \le mg\sin\beta. \tag{17}$$

The trajectory of the particle on blade surface has a helical shape, which is determined by the speed of drum rotation and the blade geometric parameters. To describe the movement of a particle along the blade, we can use the parametric equation of its trajectory in cylindrical coordinates:

$$r(t) = r_0 + v_r t, \quad \phi(t) = \omega t, \quad z(t) = z_0 + v_z t, \tag{18}$$

where r_0 and z_0 – initial coordinates of the particle, v_r and v_z – components of the particle velocity in the radial and vertical directions, respectively.

The particle's trajectory takes on a parabolic shape under the influence of gravity and the angle of blade inclination. Accordingly, the equation of its motion can be represented in the appropriate mathematical form:

$$z(r) = z_0 - \frac{g}{2\omega^2}\left(r - r_0\right)^2 \tan\beta \tag{19}$$

The speed of particle movement along the blade is determined by the angle of the β inclination and frictional force between the particle and blade surface. Given the frictional force, you can write an expression for velocity:

$$v_{bl} = \sqrt{2gr(\sin\beta - \mu\cos\beta)}\ , \tag{20}$$

where μ – friction coefficient.

If a particle moves without slipping, its trajectory is completely determined by the geometry of the blade. In the event of slipping, energy losses due to friction must be taken into account, which affect the overall efficiency of the mixing process. The trajectory of a particle in the x-y plane is described by the solution of differential motion equations:

$$m\frac{d^2x}{dt^2} = F_x, \quad m\frac{d^2y}{dt^2} = F_y, \tag{21}$$

where F_x and F_y – projections of the total force on the corresponding axes.

These projections take into account the influence of inertial forces, gravity, friction and normal pressure. Depending on the interaction conditions, the trajectory of particles can be either smooth (provided that they are in constant contact with the blade) or discontinuous (in the case of a particle being detached from its surface).

The energy transferred from the blades to the particles is determined by the contact area and the mechanical properties of the material. Increasing the speed of drum rotation or decreasing the angle of blade inclination increases the action intensity of the blades on the mixture, which can contribute to improving the process efficiency. However, an excessive increase in rotational speed can lead to stratification of the mixture or its uneven mixing.

To optimize the particles interaction with the blades, it is necessary to take into account parameters such as the height of the mixture on the blades, the attack angle of the particles and the pressure distribution over the blade surface. The lifting height h is determined by the formula:

$$h = R\sin\phi, \tag{22}$$

where ϕ – the angle at which the mixture rises along the blade.

For particles running into the blade, the velocity field is formed by external forces, in particular gravity, frictional forces, and inertial and centrifugal forces [6]. The general dynamics of particle motion can be described by the Navier-Stokes equations, which for an incompressible liquid are as follows:

$$\rho\left(\frac{\partial\vec{v}}{\partial t} + \vec{v}\cdot\nabla\vec{v}\right) = -\nabla p + \mu\nabla^2\vec{v} + \rho\vec{g}, \tag{23}$$

where ρ – material density, $\vec{v}$ – velocity vector, p – pressure, μ – dynamic viscosity.

The speed of particles movement in the parietal layer near the surface of the scapula usually decreases due to the frictional forces action. To describe the velocity profile in this layer, the laminar flow equation can be applied:

$$v(z) = \frac{\tau_w}{\mu} z, \tag{24}$$

where τ_w – tangential stress on the blade surface, z – distance from the spatula surface.

The average speed of particles in the field allows you to estimate the mixing efficiency and is calculated by the formula:

$$\vec{v} = \frac{1}{V}\int_V v\,dV, \tag{25}$$

where V – the volume of the control zone in which the speeds are calculated.

Particular attention should be paid to the zone of particles direct contact with the scapula, since this is where the energy transfer from the scapula to the particles takes place. In this region, the velocity field is characterized by significant gradients [12]. The gradient of velocities in the z direction is determined by the expression:

$$\frac{\partial v}{\partial z} = \frac{\tau_w}{\mu}. \tag{26}$$

The determination of the velocity field allows you to estimate the stratification phenomenon, which can occur in the event of a significant difference in particles velocities in different layers. To prevent this effect, it is necessary to ensure velocity uniformity of the field in contact area of the mixture with the blades.

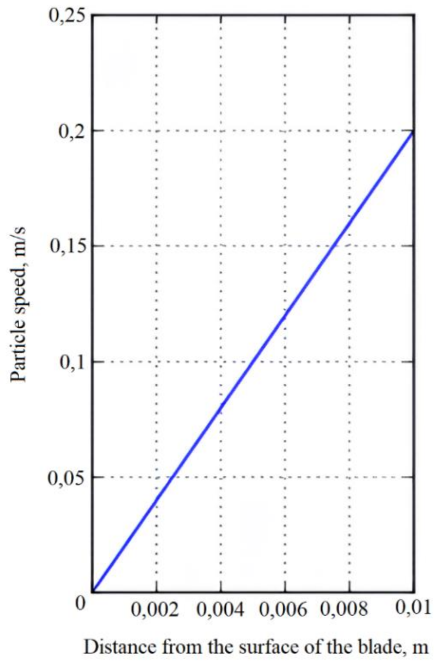

Fig 6. Distribution of particle velocity over the blades distance

The projection of the particle velocity field through the site projection makes it possible to estimate the distribution of particle velocities in space and take into account the influence of the working surface geometry of the blade and their movement trajectory [13]. For this purpose, coordinate systems are used that reflect the spatial orientation of the site, as well as methods for projecting vector quantities. In this case, the total velocity of the particle is determined by the formula:

$$v = \sqrt{v_x^2 + v_y^2 + v_z^2}. \tag{27}$$

In addition, the projection of the vane area onto the coordinate plane makes it possible to take into account the influence of its inclination on the spatial distribution of particle velocities, which allows for a more accurate assessment of particles movement peculiarities and their interaction with vane surface:

$$S_{xy} = S \cdot \cos\alpha. \tag{28}$$

where S – surface area of the blade, α – angle of inclination between the blade and the plane.

To visualize the particle velocities distribution, a vector field is constructed that displays both the direction and magnitude of the particle velocities at each point on the vane surface.

For the xy coordinate plane, the vector field makes it possible to analyze the trajectories of particles, determine areas with maximum velocity concentrations, and evaluate the influence of vane geometry on flow dynamics. The vector field is given as follows:

$$\vec{v}_{xy}(x,y)=(v_x(x,y),v_y(x,y)). \tag{29}$$

Shear zones form local regions with high velocity gradients, contributing to intensive interaction between particles of the building mixture. These zones occur in areas of direct contact between particles and drum blades, as well as in adjacent layers of the mixture subjected to shear forces [14]. To effectively describe shear zones, it is crucial to consider the velocity distribution within the mixture, where the velocity gradient defines spatial velocity changes and is represented as a tensor containing partial derivatives of velocity components. The intensity of the mixing process in a gravity concrete mixer largely depends on the local rotational movements of particles within these shear zones, characterized by rotor velocities. This parameter quantifies the degree of particle rotation around the axis and reflects the medium's dynamic properties. Analyzing the rotor velocity enables the evaluation of turbulent structure formation in the contact zone of particles with the blades and helps determine the uniformity of particle mixing throughout the drum volume. The velocity gradient tensor can be expressed as:

$$\nabla v=\begin{bmatrix}\frac{\partial v_x}{\partial x} & \frac{\partial v_x}{\partial y} & \frac{\partial v_x}{\partial z}\\ \frac{\partial v_y}{\partial x} & \frac{\partial v_y}{\partial y} & \frac{\partial v_y}{\partial z}\\ \frac{\partial v_z}{\partial x} & \frac{\partial v_z}{\partial y} & \frac{\partial v_z}{\partial z}\end{bmatrix}. \tag{30}$$

The change in velocity between adjacent layers of the mixture forms shear zones, the intensity of which is determined by the symmetrical part of the ∇v velocity gradient tensor. This symmetrical part describes the deformation processes in the mixture and characterizes the rate of change in the relative particles displacement without taking into account the rotational components of motion:

$$D=\frac{1}{2}\left(\nabla v+(\nabla v)^T\right), \tag{31}$$

where D – shear velocity tensor.

To assess the intensity of the process, a speed rotor module is used:

$$|\nabla v|=\sqrt{\left(\frac{1}{r}\left(\frac{\partial v_z}{\partial \phi}-\frac{\partial v_\phi}{\partial z}\right)\right)^2+\left(\frac{\partial v_r}{\partial z}-\frac{\partial v_z}{\partial r}\right)^2+\left(\frac{1}{r}\left(\frac{\partial}{\partial r}(rv_\phi)-\frac{\partial v_r}{\partial \phi}\right)\right)^2}. \tag{32}$$

This parameter characterizes the total intensity of rotational movements at each point in space. The maximum values of the velocity rotor modulus are generally observed in the parietal layer near the blades, where the largest velocity gradients occur.

The mixing intensity can be estimated using the volumetric integral of the speed rotor module, which takes into account the rotational movements in drum entire volume. This indicator is determined as follows:

$$I=\int_V |\nabla v| dV, \tag{33}$$

where V – mixture volume in the drum.

In shear zones, the velocity rotor is associated with viscous forces that facilitate the transfer of energy between particles layers. To analyze this relationship, the relationship between the rotor and the energy dissipation is used, which is defined as:

$$\varepsilon = \mu\left(\nabla v\right)^2, \tag{34}$$

where ε – energy dissipation intensity.

For turbulent flow, the velocity profile becomes nonlinear and is characterized by increased velocity gradients. This contributes to more intensive mixing, but can also cause local delamination of the material due to the unevenness of the velocity fields [15].

The intensity of mixing determines the distribution uniformity of particles in the mixture and, accordingly, the final product quality. During the mixing process, each particle of the building mixture is exposed to shear, inertia and friction forces, which change its trajectory and ensure that the components are evenly distributed throughout the drum volume.

If the mixing intensity is insufficient, individual particles may remain in local areas with low turbulence, which causes uneven distribution of components and a decrease in the quality of the mixture. The particles distribution uniformity in a mixture is estimated using the homogeneity coefficient, which is defined as the ratio of concentration standard deviation of the components to the average concentration.

$$C_u = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(C_i - \bar{C})^2}}{\bar{C}}, \tag{35}$$

where C_i – concentration of the component at the i-th point, $\bar{C}$ – average concentration, N – number of measurement points.

The quality of the final mixture is determined by the particle distribution homogeneity, which ensures optimal mechanical and physical product properties. In concrete mixtures, the uniform distribution of cement, sand, and water contributes to achieving uniform strength and crack resistance of the finished material. Uneven component distribution can lead to the formation of zones with excess or insufficient cement content, negatively affecting the material's performance characteristics, particularly its strength, durability, and resistance to cracking.

5. Conclusions. In the course of the study, it was found that the efficiency of mixing concrete mixtures in gravity concrete mixers largely depends on the geometric parameters of the working bodies and the rheological properties of the mixture. Optimization of blade angle, drum speed and kinematic characteristics ensures uniform particle distribution and improves mixture uniformity.

The results of mathematical simulations confirmed that excessively high drum rotation speeds can lead to centrifugation of particles and reduced mixing efficiency. At the same time, insufficient mixing intensity contributes to the formation of zones with weak material circulation. The optimal balance between these factors ensures the high quality of the final product.

The results obtained confirm the feasibility of using mathematical modeling to analyze the mixing process and develop new design solutions. The use of computer simulation allows you to predict the dynamics of particle movement in the mixing chamber and optimize the parameters of the equipment.

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