UDC 666.97:004.942
DOI: https://doi.org/10.32347/tb.2024-41.0409

Rostyslav Rudyk,
Postgraduate student,
National University «Yuri Kondratyuk Poltava Polytechnic»
Pershotravneva Avenue 24, Poltava, 36011, Ukraine
ORCID: https://orcid.org/0000-0001-8386-977X
E-mail: rostyslavrudyk@nupp.edu.ua

Roman Salnikov,
Postgraduate student,
National University «Yuri Kondratyuk Poltava Polytechnic»
Pershotravneva Avenue 24, Poltava, 36011, Ukraine
ORCID: https://orcid.org/0009-0001-0408-4358
E-mail: roman.salnikov2952@gmail.com

ANALYSIS OF THE MIXER GEOMETRY AND RHEOLOGY IMPACT ON CONCRETE MIXTURE MIXING EFFICIENCY

Abstract. *The article discusses the problems associated with the mixing efficiency of concrete mixtures in gravity concrete mixers, which are widely used in construction sites due to their simplicity of design and mobility. Modern requirements for energy efficiency and quality control accuracy require the development of advanced methods that can ensure high homogeneity of concrete mixtures with minimal energy consumption. Considerable attention is paid to the influence of the geometry of the drum and the working bodies of the concrete mixer on the mixing process. Various approaches to mathematical modeling have been described, which take into account the physical and mechanical properties of the concrete mixture and the nature of its movement during rotation. The analysis of the rheological properties of concrete mixtures shows their significant impact on the mixing efficiency. Studies demonstrate that the proper selection of the drum rotation speed, the angle of inclination of the blades and the duration of mixing allows for an optimal balance between the various physical forces acting on the particles. Prospects for further research are highlighted, including the development of complex models that would take into account various factors and would allow predicting the behavior of the mixture in real conditions.*

Keywords: *gravity concrete mixer, mathematical modeling, mixing dynamics, rheological properties, blade geometry, numerical methods, mixing efficiency, energy efficiency, homogeneity of concrete mixture*

1. Problem statement. Gravity concrete mixers are widely used on construction sites due to their simple construction, mobility, and ability to effectively provide high-quality mixing of concrete mixtures. However, in the conditions of modern construction, where energy efficiency, rational use of materials and accuracy of control over the parameters of the mixture become especially important, there is a need to improve concrete preparation technologies.

The use of mathematical models makes it possible to investigate the influence of various factors, such as the speed of rotation of the drum, the humidity of the constituent materials and the mixing time, on the quality of the final product. However, the variety of approaches and models makes it difficult to choose the best option, which requires an in-depth comparative analysis. Scientists offer various modeling methods, from simple empirical dependencies to complex numerical models that take into account the physical processes inside the concrete mixer. Each approach has its own advantages and limitations, which depend on the conditions of application and requirements for the accuracy of the results.

The relevance of conducting a comparative assessment of these models is due to the growing requirements for the quality of construction work and the efficiency of equipment. Modern construction sites require technologies that provide not only consistently high quality concrete mixes, but also minimize the impact of the human factor and reduce energy costs. The article discusses the most common mathematical models, analyzes their features and effectiveness in practical application.

2. Analysis of recent sources and publications. Modern research is aimed at finding ways to improve the quality of mixing, reduce energy costs, as well as minimize the impact of factors that can negatively affect the final characteristics of the concrete mixture. In particular, models of mixture movement are actively studied in order to describe the dynamics of particles under different mixing conditions and to analyze the influence of geometric parameters of the working body on the efficiency of the process [1].

Work in recent years highlights the importance of blade geometry and drum shape of a gravity concrete mixer to intensify the mixing process. The authors of numerous publications point out that the optimization of these parameters allows you to achieve a more uniform distribution of the constituent components of the mixture and ensure the necessary homogeneity of the finished concrete. Using modern methods of numerical modeling, researchers were able to prove that certain combinations of design solutions increase the efficiency of the mixer by 10-15% [2].

Particular attention is also paid to the study of the physical and mechanical properties of concrete mixtures, which affect the nature of their movement during the rotation of the drum [3]. A number of publications demonstrate that changes in the viscosity, density and other rheological properties of the concrete mixture can significantly affect the efficiency of the mixing process [4]. Separate studies analyze the effect of temperature, degree of humidity and exposure time of a mixture on its behavior during mixing. Through computer simulations and experimental studies, it has been found that the unevenness of mixing in the initial stages of the process is often associated with the adhesion of cement particles and inert materials due to the incorrect choice of rotation parameters and speeds [5].

3. Purpose of the work. The purpose of this article is to conduct a comparative evaluation of the various mathematical models applied to the concrete mix mixing process in a gravity concrete mixer, in order to identify the models that provide the greatest accuracy, efficiency and compliance with production conditions.

4. Discussion of research results. The mathematical description of the physical model of a gravitational concrete mixer (fig. 1) is based on a set of equations describing the dynamics of mixing a concrete mixture under the influence of gravitational and centrifugal forces, friction between the particles of the mixture, as well as the effect of frictional forces on the walls of the drum. The main goal of the physical model is to reproduce the mixing process in a mathematical format, taking into account the influence of geometric and kinematic parameters of the concrete mixer.

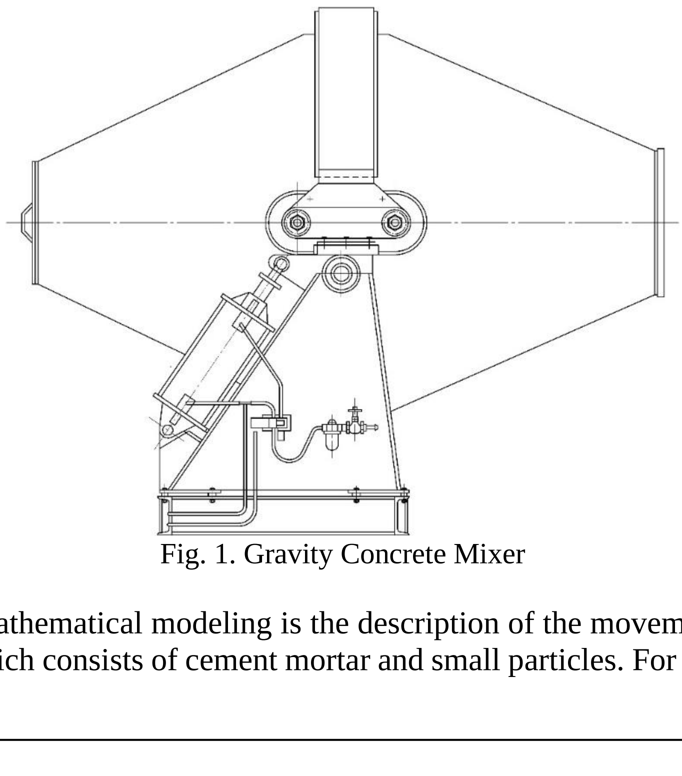

Fig. 1. Gravity Concrete Mixer

The basis of mathematical modeling is the description of the movement of aggregate solids in a viscous liquid, which consists of cement mortar and small particles. For this, the Navier-Stokes equations are used, describing the behavior of a viscous liquid under conditions of dynamic mixing [6]. The Navier-Stokes equation has the form:

$$\rho\left(\frac{\partial\vec{v}}{\partial t}+\vec{v}\cdot\nabla\vec{v}\right)=-\nabla p+\mu\nabla^{2}\vec{v}+\rho\vec{g}, \tag{1}$$

where: ρ — liquid density; $\vec{v}$ — velocity vector; p — pressure; μ — dynamic viscosity coefficient; $\vec{g}$ — gravitational acceleration vector.

These equations take into account internal forces, such as pressure and viscosity, as well as external forces, including gravity. The equations are used to describe the behavior of a cement mortar that interacts with solid particles.

The movement of solid particles in a concrete mixer is described by discrete element methods (DEM). Each particle is modeled separately, taking into account its mass, shape and interaction with other particles and drum walls [7]. The equation of motion of a particle is determined by Newton's second law:

$$m_i\frac{d^2\vec{x}_i}{dt^2}=\sum\vec{F}_{contact}+m_i\vec{g}+\vec{F}_{viscosity}, \tag{2}$$

where: m_i — Mass of the i-th particle; $\mathbf{x}_i$ — particle position; $\vec{F}_{contact}$ — the total force of contact with other particles and the surface of the drum; $\vec{F}_{viscosity}$ — liquid interaction force.

Contact forces are determined based on models of elastic and plastic deformations, as well as friction coefficients. The viscosity force depends on the relative velocity between the particle and the surrounding liquid and takes into account the effect of the viscosity of the cement mortar.

One of the key factors affecting the mixing process is the speed of rotation of the drum. It determines what forces dominate during mixing: at low speeds, the mixture is predominantly exposed to gravity, which leads to mixing due to the falling particles. As the speed increases, centrifugal forces begin to dominate, creating the effect of particles "sticking" to the walls of the drum. For effective mixing, it is important to find a balance between these two modes, which is determined by the critical rotation speed [8]. The critical velocity is calculated using the formula:

$$\omega_{cr}=\sqrt{\frac{g}{R}}, \tag{3}$$

where: ω_{cr} — critical angular velocity; g — acceleration of free fall; R — drum radius.

When this speed is exceeded, centrifugal forces begin to prevail over gravitational ones, which reduces the mixing efficiency.

An important parameter in the model is also the mixing time. It determines the degree of homogeneity of the concrete mixture and depends on the dynamic characteristics of the system. To optimize the process, it is necessary to establish a relationship between the mixing time and the homogeneity indicators. This dependence can be described using the time-dependent function of distributing particles according to their position and velocity:

$$C(t)=C_0\exp\left(-\frac{t}{\tau}\right), \tag{4}$$

where: C(t) — concentration of particles in a certain volume at a point in time t; C_0 — initial concentration; τ — characteristic mixing time.

The value τ depends on the geometry of the drum, the viscosity of the cement mortar and the properties of the aggregate.

Another important factor is the coefficient of friction between the mixture particles and the walls of the drum, which affects energy loss and process efficiency. This ratio depends on the material of the drum walls and the characteristics of the mixture, such as moisture and particle size. Determining the coefficient of friction is an important task that affects the accuracy of the model.

The total energy expended in the mixing process can be defined as the sum of the kinetic energy of the particles, the energy of strain during collisions, and the energy loss due to friction [9]. The mathematical expression of the energy balance can be written in the form:

$$E_{tot} = \sum \left(\frac{1}{2} m_i v_i^2 \right) + \sum E_{str} + E_{friction}, \tag{5}$$

where: E_{tot} — total energy of the system; v_i — velocity of the i-th particle; E_{str} — strain energy on contact; $E_{friction}$ — energy lost due to friction.

Energy balance analysis helps to optimize the mixing process, reducing unnecessary energy loss and improving the homogeneity of the mixture.

The blades of the concrete mixer play a critical role in the mixing process, affecting the trajectory of the particles of the mixture, their speed and the forces acting on them. The mathematical description of this effect in the gravity concrete mixer model takes into account the geometric parameters of the blades, such as their angle of inclination, number, placement, and interaction with the components of the concrete mix. Each of these factors affects the distribution of forces in the system and the efficiency of mixing [10].

At a certain angle of inclination, the blades direct the mixture up and to the side, creating an effective distribution of components in the drum. The optimal angle of inclination depends on factors such as the speed of rotation of the drum, the viscosity and density of the mixture. Mathematical modeling of the effect of the angle of inclination can be done using equations that describe the direction and magnitude of the forces acting on a particle when it comes into contact with the blade. The components of the gravitational force that is split into components along and perpendicular to the surface of the blade are taken into account:

$$F_g = mg \sin(\alpha) \quad and \quad F_n = mg \cos(\alpha), \tag{6}$$

where: F_g — component of the gravitational force that contributes to the movement of the particle along the blade; F_n — a normal component that presses the particle to the surface of the blade; m — particle mass; g — acceleration of free fall; α — blade inclination angle.

These forces determine how fast and in what direction the particles will move when they come into contact with the blade. Increasing the angle of inclination results in greater particle lift, but at the same time can reduce mixing efficiency due to less interaction between particles.

The number of blades in a concrete mixer also affects the mixing process. With more blades, the mixture is more likely to be picked up and mixed, which contributes to the homogeneity of the mixture. However, an excessive number of blades can create a stagnation zone or, conversely, overload the system, which increases the resistance to the movement of the mixture and energy expenditure. The frequency of contact determines the number of mechanical pulses that particles receive in a given time and affects the kinetic energy they gain. The total amount of mechanical work performed by the blades depends on the total mass of the mixture and the geometry of the system.

An important aspect of the model is the gravity of the mixture on the blades, which puts a load on the concrete mixer and affects the mixing efficiency.

$$F_g = mg, \tag{7}$$

where: m — mass of the mixture acting on a specific shoulder blade; g — acceleration of free fall.

Gravity affects the mechanical work that the blades must do to lift and move the mixture. This load can contribute to intense mixing if its distribution is optimal, or cause significant energy losses in the event of an uneven load. Gravity also determines the maximum mass of the mixture that the blades can move efficiently without overloading the system.

The frictional force between the mixture particles and the blades counteracts the movement of particles along the surface of the blades and can both promote mixing and inhibit the process, depending on its magnitude. The frictional force is described by the equation:

$$F_{friction} = \mu F_n, \tag{8}$$

where: μ — coefficient of friction between the particles of the mixture and the material of the blades; F_n — normal force acting on a particle.

The amount of friction force depends on the material from which the blades are made and on the characteristics of the mixture, in particular its moisture content and graininess. A high coefficient of friction can lead to more efficient pick-up of particles by the blades, but also causes an increase in energy expenditure to overcome resistance.

To determine the total effect of the blades on mixing, all the forces mentioned in the context of the kinetic and potential energy of the system are taken into account. Each particle that moves in the concrete mixer interacts with the blades, gaining or losing energy, which allows you to build an equation of motion that takes into account the influence of all the forces acting [11]. To describe the change in the velocity of a particle during contact with a blade:

$$m\frac{d\vec{v}}{dt} = F_g + F_{friction} - F_{inertia}, \tag{9}$$

where: $\vec{v}$ — particle velocity; $F_{inertia}$ — the force of inertia resulting from the rotation of the drum.

This equation allows you to determine how the kinetic energy of a particle changes and how it contributes to the mixing process.

The overall mixing efficiency depends on the correct combination of the angle of inclination, the number of blades and the material from which they are made. If these parameters are optimally chosen, then the interaction between the particles and the blades leads to an even distribution of the components of the mixture, minimal energy consumption and high homogeneity of the finished concrete. Instead, incorrect parameters can cause the effect of "dead zones", where the mixture is practically not mixed, or overloading of individual blades, which causes wear and loss of efficiency.

In mathematical models of the mixing process involving the blades, special coefficients are often introduced that describe the influence of the geometric and dynamic characteristics of the blades on the mixing efficiency. The efficiency factor of the blades reflects how efficiently the blades carry and mix the mixture particles in the concrete mixer drum.

The coefficient k_{bl} can be expressed in the form of an empirical formula that includes parameters:

$$k_{bl} = f(\alpha, n, \mu, v), \tag{10}$$

where: α — angle of inclination of the blades; n — number of blades in the drum; μ — Coefficient of friction between the blades and particles of the mixture; v — drum rotation speed.

The rheology of concrete during mixing in a gravity concrete mixer is an important aspect that determines the characteristics and quality of the resulting concrete mixture. It describes how the concrete mixture reacts to the forces applied to it, including shear and gravitational, during the rotation of the concrete mixer drum. The main parameters affecting the rheological properties of a mixture include viscosity, plasticity, particle structure, their interconnection, and the influence of various physical factors. These characteristics can be described using rheological models such as Bingham's model, Newton's model, and more complex nonlinear models.

One of the most common models used to describe the rheological properties of a concrete mix is the Bingham model. It defines concrete as a pseudoplastic liquid that behaves like a solid at low stress values and goes into a fluid state only after a certain threshold shear stress is reached [12]. In mathematical form, this is expressed in terms of the equation:

$$\tau = \tau_0 + \eta\dot{\gamma}, \quad (11)$$

where: τ — shear stress; τ_0 — threshold shear stress; η — concrete mix viscosity; $\dot{\gamma}$ — shear speed.

This equation shows that the mixture only begins to flow when the applied stress exceeds the value of τ_0. In the context of a gravity concrete mixer, Bingham's model describes how the blades and walls of the drum create shear stresses sufficient to bring the mixture into a fluid state. The values τ_0 and η depend on the composition of concrete, water-cement ratio, aggregate granularity and temperature.

The viscosity of a concrete mixture is an important rheological parameter that determines its yield resistance. In a gravity concrete mixer, viscosity affects how easily the cement and aggregate particles move relative to each other under the forces created by the blades. The toughness of concrete can be thought of as a function of the water-cement ratio, where more water reduces the viscosity and improves the fluidity of the mixture, but can reduce its strength after hardening. On the other hand, a decrease in the water-cement ratio increases the viscosity, complicates the mixing process and can lead to uneven particle distribution. In rheological models, this is reflected as the dependence of viscosity on the concentration of solid particles in the liquid phase:

$$\eta = \eta_0(1 + k\phi)^n, \quad (12)$$

where: η_0 — viscosity of pure liquid (water); k and n — constants depending on the type and distribution of particles; ϕ — volume fraction of solid particles in the concrete mixture.

The interaction between particles in a concrete mixture plays a key role in its rheological properties. Cement and aggregate particles form a complex network of bonds and structural interactions that determine how the mixture reacts to mechanical stress. The shear stresses created by the blades can destroy these structures, reducing viscosity and improving fluidity (rheological rarefaction). However, if the stress decreases, the structure can recover and the viscosity increases again. This effect is called thixotropy and can be described mathematically through changes in viscosity over time:

$$\eta(t) = \eta_0(1 + \theta \exp(-t / \lambda)), \quad (13)$$

where: $\eta(t)$ — viscosity at a point in time t; θ — thixotropy coefficient; λ — characteristic relaxation time of the structure.

To describe the plastic deformation of the mixture, equations are used that take into account the elastic and viscous components of the reaction of the material. The viscoelastic model of concrete includes both instantaneous and slow reaction of the mixture to the applied stress. This is especially important in the context of a gravity concrete mixer, where the applied forces can change over time due to the rotational motion of the drum. Viscoelastic equations have the form:

$$\sigma(t) = E\varepsilon(t) + \eta\frac{d\varepsilon(t)}{dt}, \quad (14)$$

where $\sigma(t)$ — tension; E — modulus of elasticity; $\varepsilon(t)$ — deformation; η — viscosity.

This model describes how a mixture accumulates stress when deformed and how quickly it returns to its original state after stress is relieved.

Another important factor in the rheological description of concrete is the distribution of particles of different sizes in the mixture. Large aggregates can create additional resistance to stirring, while small particles fill gaps and facilitate fluidity. This equation allows you to accurately estimate how different particle sizes and shapes affect the rheological properties of the mixture:

$$\eta = \int_0^\infty f(r)\eta_r\, dr, \quad (15)$$

where: f(r) — radius distribution function of particles r; η_r — viscosity corresponding to radius particles r.

The analysis of existing approaches shows that mathematical modeling of the movement of the concrete mixture allows for a deeper understanding of the dynamics of mixing, especially taking into account the influence of gravitational and centrifugal forces, as well as the characteristics of particles. The complexity of the interaction of components in the mixing process necessitates the use of both classical hydrodynamic models and the latest methods of numerical modeling, which describe physical and mechanical processes with high accuracy.

An in-depth study of the effect of drum rotation speed on mixing efficiency allows us to understand how to achieve an optimal balance between gravitational and centrifugal forces acting on particles. Critical rotational speed analysis reveals the key points at which the mixing process switches from one mode to another. At the same time, much attention is paid to the geometric characteristics of the drum and blades, because their design features can significantly improve or, conversely, worsen mixing.

Thus, the presented material reflects the current state of research in the field of mathematical modeling of the mixing process in gravity concrete mixers. Although significant progress has been made in understanding the physical processes that occur during mixing, the question of choosing the best methods and approaches for practical application remains relevant. Further improvement of models that take into account the interaction of geometric and rheological factors is a promising direction for increasing the efficiency of equipment and improving the quality of concrete mixtures.

5. Conclusions. In the process of studying mathematical models of the movement of the concrete mixture in a gravity concrete mixer, it was found that effective mixing depends on a number of key factors, including the geometric parameters of the working body, the speed of rotation of the drum, the rheological properties of the mixture and the interaction between the particles. Optimization of these parameters can significantly improve the uniformity and quality of finished concrete, while reducing energy costs. The use of modern methods of numerical modeling allows you to describe physical processes with high accuracy and offer design solutions to improve the efficiency of equipment.

The development and improvement of mathematical models of the gravity concrete mixer is of great importance for improving the quality and efficiency of construction work. Further research should be aimed at creating complex models that take into account the influence of various factors and allow predicting the behavior of the concrete mixture under different mixing conditions. The use of these models in practice will contribute to the development of innovative mixing technologies that will meet modern construction requirements for energy efficiency, environmental friendliness and high quality of building materials.

References:

1. Maoqiang Jiang, Yongzhi Zhao, Gesi Liu, Jinyang Zheng (2011). Enhancing mixing of particles by baffles in a rotating drum mixer. Particuology, 3 (9), pp 270-278. https://doi.org/10.1016/j.partic.2010.06.008.
2. Nazarenko Ivan, Klymenko Mykola (2015). Evaluation of the energy balance and workflow criteria of the “drum mixer-concrete mixture” system. Mining, Construction and Reclamation Machinery, 85, pp. 59-65.
3. Nazarenko I., Klymenko M., Svidersky A., Pechersky V. (2017). Definition of rational parameters of drum concrete mixers. GBDMM, 90, 67-72.
4. Serhii Burlaka, Ihor Kupchuk, Serhii Shapovaliuk, Mykola Chernysh (2023). Analysis of the influence of the geometry of the blade mixer on the turbulence and intensity of liquid mixing. Machinery energeties transport of agribusiness, 2 (121), pp 16-22. DOI: 10.37128/2520-6168-2023-2-2.
5. Yu Liu, Marcial Gonzalez, Carl Wassgren (2017). Modeling Granular Material Blending in a Rotating Drum using a Finite Element Method and Advection-Diffusion Equation Multi-Scale Model. AIChE Journal, 9 (64).

6. Yong Yuan, Xiaoyun Wang, Xi Chen, Peng Xiao, Eduardus Koenders, Ying Dai (2023). Mathematical models of apparent viscosity as a function of water–cement/binder ratio and superplasticizer in cement pastes. Scientific Reports, 13, 22301. https://doi.org/10.1038/s41598-023-48748-4.
7. Hamed Hoorijani, Behrad Esgandari, Reza Zarghami, Rahmat Sotudeh-Gharebagh, Navid Mostoufi (2023). Predictive modeling of mixing time for super-ellipsoid particles in a four-bladed mixer: A DEM-based approach. Powder Technology 430. https://doi.org/10.1016/j.powtec.2023.119009.
8. Holub G., Achkevych O. (2017). Optimization of the angular velocity of drum-type mixers. Bulletin of ZhNAEU, No. 1 (58), p 194-202.
9. Nazarenko Ivan, Klymenko Mykola (2020). Application of general energy assessment criteria for preparing building mixtures. KHNADU Bulletin, 2 (88), pp 37-42. DOI: 10.30977/BUL.2219-5548.2020.88.2.37.
10. Jian-Ping Pan, Ting-Jie Wang, Jun-Jie Yao, Yong Jin (2006). Granule transport and mean residence time in horizontal drum with inclined flights. Powder Technology, 162, pp 50–58. https://doi.org/10.1016/j.powtec.2005.12.004.
11. Rudyk Rostyslav, Virchenko Viktor, Salnikov Roman, Bidanets Serhii (2024). The effect of the blades on mixing the concrete mixture. Materials of the 76th Scientific Conference of Professors, Teachers, Researchers, Postgraduate Students and University Students, Poltava, pp. 270-271.
12. Ahmet Bilgil (2012). Estimation of slump value and Bingham parameters of fresh concrete mixture composition with artificial neural network modelling. Scientific Research and Essays, 5(8), pp. 1753-1765. DOI: 10.5897/SRE10.415.