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Determination of the Main Performance Indicators of a Forced-Action Concrete Mixer Using Similarity Criteria

The study focuses on the improvement of a forced-action concrete mixer designed for the preparation of low-workability concrete mixtures. The methodology is based on the application of dimensionless similarity criteria and mathematical modeling. Analytical dependencies for calculating the output rate and drive power were derived based on the geometric and kinematic parameters of the mixer, considering the dynamics of multi-loop mixing. The obtained results enable model scaling without the need for full-scale testing. Further research is planned to optimize operational modes for continuous mixing machines.

Keywords: concrete mixer, drive power, energy consumption, forced-action mixing, low-workability mixture, mixing modeling, output rate, similarity criteria

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Introduction

In the context of modern construction technologies, the problem of improving the efficiency and reliability of equipment for concrete mixture preparation is gaining particular relevance [1–3]. One of the key units in this process is the forced-action concrete mixer, which ensures high mixing quality and consistency of mixture parameters. Despite their advantages, such mixers are characterized by complex kinematics and significant energy consumption. Therefore, their design solutions must rely not only on empirical approaches but also on scientifically grounded calculation methods that enable adaptation to specific operational conditions [4].

Review of the research sources and publications

Currently, the mixing equipment market offers a wide variety of technical solutions, with twin-shaft horizontal, turbulent, and planetary mixers being the most common. However, most of these machines demonstrate limited efficiency when operating with stiff and low-workability mixtures, thus necessitating specialized equipment for producing such concrete compositions [5]. A significant contribution to the formalization of mixing processes has been made through the application of similarity theory. Both domestic and foreign studies have explored the transition from model-scale to full-scale systems using dimensionless criteria. These criteria account for the physical and mechanical properties of mixtures, the geometric parameters of mixers, and the interaction dynamics between the mixing elements and the medium [6–9]. A systematic modeling approach has been shown to reduce the scope of experimental studies while maintaining the accuracy of technical assessments. Several studies propose criteria characterizing mixing power, dispersion level, and homogenization degree. Their application in the design of equipment for stiff mixtures enables the formulation of universal dependencies for predicting productivity and energy consumption [10].

Definition of unsolved aspects of the problem

Despite evident advantages, the use of similarity criteria in industrial equipment design has not yet become standard practice. This is due to the complexity of building accurate models and the need for a high level of specialist training. Therefore, studies combining experimental methods and theoretical modeling remain relevant and require further development [8].

Problem statement

The aim of this study is to determine the main performance indicators of a new-design forced-action concrete mixer based on the analysis of its structural and operational characteristics using similarity criteria. This approach enables scaling and parameter optimization during the transition from a laboratory prototype to an industrial-scale unit.

Basic material and results

The novelty of the research lies in the first-time adaptation and application of a system of dimensionless similarity criteria to a concrete mixer whose design is protected by a Ukrainian patent [11]. This system of criteria had previously been used in general form for evaluating processes in mixing devices but had not been applied to the calculation of output rate and energy consumption for a mixer with a triple-circuit mixing scheme. In this study, the similarity criteria were employed to derive formulas for determining the output rate and drive power without the need for full-scale experiments.

The mixer's working unit incorporates three horizontal shafts: the upper and lower blade shafts ensure the movement of mixture components and the breakdown of small agglomerates composed of soluble particles. The middle shaft, operating in zones I and II of the mixing chamber, first transports dry components and subsequently the prepared concrete mixture to the discharge zone (Figure 1).

All three shafts are involved in organizing multi-circuit material flow inside the mixer, resulting in a significant increase in the effective working volume, where intensive mixing occurs—up to the full volume of the mixing chamber. To utilize gravitational forces and enhance the cascading multi-circuit movement of the concrete mixture particles, the shafts are installed at an angle β at different vertical levels (Figure 1b)

For this mixer design, a system of dimensionless similarity criteria [12–15] was proposed and adapted to the specific features of a machine with a triple-circuit mixing scheme. For the first time, the combined influence of gravitational, inertial, elastic, surface-active, and turbulent effects was generalized and expressed through five criteria, C_{P1}–C_{P5}.

- **C_{P1}** – The ratio between the generalized pressure exerted by the mixing element and the dynamic pressure of the medium. It indicates the intensity of energy transfer to the mixture.

$$C_{P1} = \frac{P}{\rho \cdot v^2} \quad (1)$$

- **C_{P2}** – The ratio of gravitational force to the kinetic energy of the medium. It is an analogue of the Froude number (Fr), representing the effect of gravity on flow behavior.

$$C_{P2} = \frac{g \cdot l}{v^2} \quad (2)$$

- **C_{P3}** – The ratio of the medium's resistance to deformation (expressed via Pi) to its elastic recovery ability (modulus of elasticity, E). It characterizes how strongly the medium resists the mixing element.

$$C_{P3} = \frac{P_i}{E \cdot l^2} \quad (3)$$

- **C_{P4}** – The ratio of surface activity to external pressure. This criterion accounts for interfacial interactions in mixtures containing additives or surfactants.

$$C_{P4} = \frac{\sigma_\alpha \cdot l^2}{P} \quad (4)$$

- **C_{P5}** – A generalized Reynolds number adapted for concrete mixing. It reflects the ratio of inertial to viscous forces in the process.

$$C_{P5} = Re = \frac{\rho \cdot n}{P} \quad (5)$$

Where:

P – generalized specific pressure from the mixing element;

ρ – density of the medium;

v – velocity of medium (concrete mix) movement;

g – gravitational acceleration;

l – characteristic cross-section of the loaded microvolume;

Pi – generalized resistance of the medium;

E – modulus of elasticity of the medium;

σ_α – surface activity of the substance.

These criteria, established based on general laws governing the interaction between working elements and the surrounding medium, allowed the derivation of scale transition coefficients from a baseline model to a full-scale industrial machine.

To solve the system of equations and obtain the transition coefficients, the following structural parameters were used:

r – blade rotation radius;

d – blade width;

b – blade height;

as well as operating parameters:

ω – angular velocity of the mixing unit;

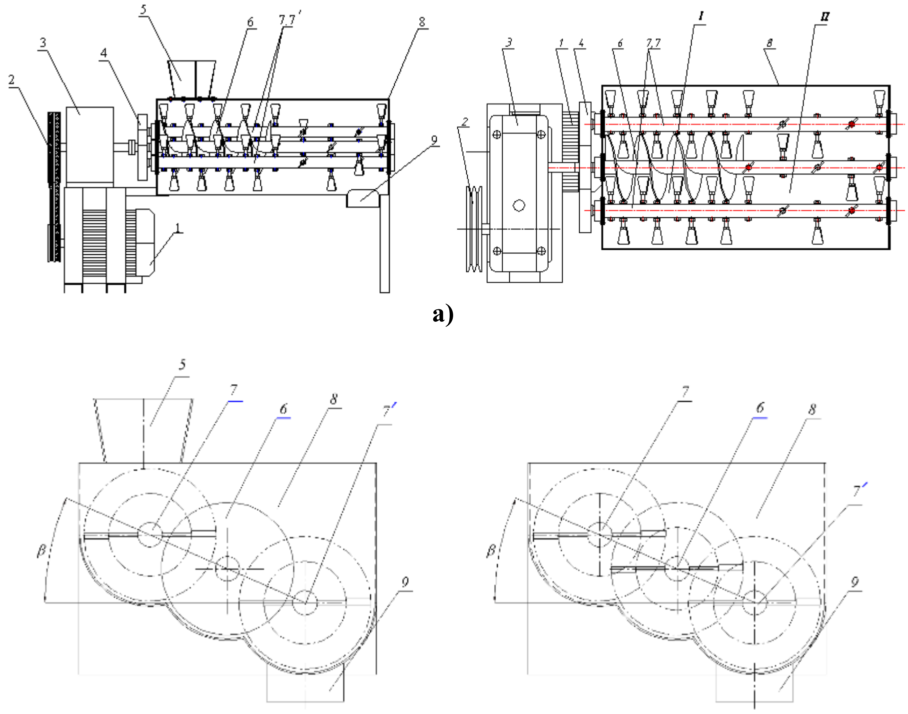
W – total mixing energy of the baseline model;

and the physical-technical characteristics of low-workability concrete mixtures.

$$C_{P1} = \frac{P}{\rho \cdot v^2} = 2{,}18; \quad (5)$$

$$P = dF \cdot z_b;$$

$$dF = c \cdot \rho \cdot d \cdot b \cdot r \cdot \frac{\omega^2 \cdot r^2}{2};$$



a)

b)

Figure 1 – Structural diagram of the concrete mixer
a) concrete mixer; b) arrangement of shafts inside the mixer housing; 1 – electric motor; 2 – V-belt drive; 3 – gearbox; 4 – open gear transmission; 5 – loading hopper; 6 – screw shaft; 7, 7′ – upper and lower blade shafts; 8 – mixer housing; 9 – discharge pipe with gate valve; I – dry component mixing zone; II – concrete preparation zone with a specified water-cement ratio.

$$C_{P2} = \frac{g \cdot l}{v^2} = 32\ ; \qquad (6)$$

$$C_{P3} = \frac{P_i}{E \cdot l^2} = 10{,}56\ ; \qquad (7)$$

$$P_i = c \cdot \rho \cdot b \cdot \frac{\omega^2}{2} \int_{r_{in}}^{r_{ex}} r^2 \cdot dr\ ;$$

$$P_i = \cdot\, \rho \cdot b \cdot \frac{\omega^2}{2} \cdot \left(\frac{{r_{ex}}^3 - r_{in}}{3}\right);$$

$$C_{P4} = \frac{\sigma_\alpha \cdot l^2}{P} = 0{,}68; \qquad (8)$$

$$\sigma_\alpha = \frac{\Sigma W}{\Sigma P_{w.b}};$$

$$C_{P5} = Re = \frac{\omega \cdot r \cdot i \cdot \rho}{\mu} = 46{,}1\ . \qquad (9)$$

Eqs (6)–(9) describe the derived relationships. Based on the analysis and obtained results, a series of calculations were carried out using an established methodology for determining the key parameters of the working machine.

Productivity (PR) for the concrete mixer:

For the **baseline model** (laboratory mixer):

$$PR_{tech} = 3600 \cdot \frac{\pi}{4} \cdot (D^2 - d^2) \cdot b \cdot n \cdot z_b \cdot sin\alpha \cdot k_l^{av} \cdot k_{ex}^{II} = 4{,}28 m^3/h \qquad (10)$$

For the **industrial mixer**:

$$PR_{tech} = 3600 \cdot \frac{\pi}{4} \cdot (D^2 \cdot C_{P1} - d^2 \cdot C_{P1}) \cdot (b \cdot C_{P1}) \cdot n \cdot z_b \cdot sin\alpha \cdot k_l^{av} \cdot k_{ex}^{II} = 31 m^3/h \qquad (11)$$

Formulas (10) and (11) consider the geometric characteristics of the working volume and kinematic parameters, incorporating analogues of similarity criteria: namely, inertial effects (via Re), gravitational influence (via Fr), and interactions involving surface-active components.

In formulas (12) and (13), used to determine the **drive power**, the following components are considered:

DP₁ – energy expenditure to overcome gravitational forces (related to Fr);

DP₂ – energy required to move the mixture within the volume (related to Re and CP1);

DP₃ – energy consumed by shear deformation and elastic resistance (related to CP3).

Drive power (DP) for the concrete mixer:

Baseline model:

$$DP = \frac{\lambda(DP_1 + DP_2 + DP_3)}{1000 \cdot \eta}; \qquad (12)$$

$$DP = \frac{1{,}2(803 + 1537 + 1591)}{1000 \cdot 0{,}85} = 5{,}53\ kW.$$

Industrial mixer:

$$DP = \frac{\lambda(DP_1 + DP_2 + DP_3)}{1000 \cdot \eta}; \qquad (13)$$

$$DP = \frac{1{,}2(1318 + 5672 + 11460)}{1000 \cdot 0{,}85} = 21\ kW.$$

Where:

λ – power reserve coefficient of the electric motor;

η – efficiency of the drive system;

DP_1, DP_2, DP_3 – generalized power components.

Conclusions

This study proposes a validated approach for evaluating the main performance characteristics of a newly designed concrete mixer through the use of an adapted system of dimensionless similarity criteria. Unlike previous studies, the criteria referenced in [12–15] were, for the first time, integrated into a calculation methodology for determining both output rate and drive power of a machine with a triple-circuit mixing mechanism, implemented in a patented design [11].

This approach enables the transition from a laboratory-scale model to an industrial prototype without the need for full-scale testing.

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Визначення основних показників роботи бетонозмішувача примусової дії з використанням критеріїв подібності

Удосконалення конструкцій змішувального обладнання для приготування жорстких бетонних сумішей є ключовим напрямом підвищення ефективності будівельного виробництва. У роботі застосовано метод теоретичного моделювання з використанням безрозмірних критеріїв подібності, що дозволяє виконати масштабування робочих параметрів від лабораторного зразка до промислового бетонозмішувача. Проведено структурно-функціональний аналіз нової триконтурної схеми перемішування, що включає роботу трьох горизонтальних валів з різними функціями транспортування та деструкції компонентів суміші. Запропоновано п'ять адаптованих критеріїв подібності (аналог Fr, Re та інших), які враховують гравітаційні, інерційні, в'язкі, пружні й міжфазні сили, що діють у робочому об'ємі змішувача. На основі отриманих критеріїв виведено формули для розрахунку продуктивності (output rate) та потужності приводу (drive power), що включають геометричні параметри мішального простору, кутову швидкість (ω) і коефіцієнти енерговитрат. Уперше обґрунтовано енергетичний баланс приводу з урахуванням втрат на гравітаційне переміщення, зсувну деформацію й опір середовища. Результати підтвердили можливість використання запропонованого підходу для проектування бетонозмішувачів з урахуванням специфіки жорстких сумішей, без проведення повномасштабних експериментів. Перспективним напрямом подальших досліджень є розширення системи критеріїв для машин неперервної дії з автоматизованим регулюванням режимів перемішування.

Ключові слова: бетонозмішувач, енергоспоживання, змішування примусової дії, критерії подібності, малорухома суміш, моделювання процесу змішування, потужність приводу, продуктивність

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