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VERIFICATION OF THE MATHEMATICAL MODEL OF THE MASS FLOW RATE OF MOIST BULK MATERIALS FOR CONCRETE MIXING PLANT FEEDING SYSTEMS

The object of this research is a mathematical model of mass flow rate of moist bulk materials (construction sand) in feeding systems of concrete mixing plants (CMPs). The subject of the research is the experimental verification of this mathematical model under real production conditions.

The problem addressed concerns the critical instability of mass flow rate when using natural washed sand. Increased moisture content (6–10%) changes the mass flow regime to a funnel flow and causes the formation of arches above the discharge opening. The coefficient of variation in dosing under such conditions reaches 12–25%, which is 4–8 times higher than the state standard for accuracy.

The mathematical model was verified using results obtained on a real CMP with a capacity of 60 m³/h, designed and commissioned by the authors and still in operation today. They confirm that installing an active loosener with a rotational speed of $\omega_{pr} \geq 2.5 \cdot \omega_{cr}$ completely solves the problem of stabilizing the dosage across the entire range of production moisture contents. Threshold rotational speeds have been established depending on moisture content (specifically, 87 rpm for 6%). A constructed three-dimensional response surface demonstrates that, for a guaranteed dosing error of $\leq 3\%$, the working speed of the loosener must be 2.5 times higher than the threshold. Adherence to this operating mode reduces the actual variation to 1.8%. A mathematical model of mass flow rate ($R^2 = 0.963$) was also statistically described, and empirical coefficients were determined: pin resistance in the material (1.12) and mechanism efficiency (2.8).

This effect is explained by the artificial, abrupt transition of the material from a vortex flow regime back to a bulk flow regime. Upon reaching the critical rotation speed of the pins, the capillary bonds between the grains are intensively broken, thereby reducing the effective angle of internal friction and completely eliminating stagnant zones in the hopper. All of this instantly restores stable, continuous gravitational flow.

The results are practically applicable to the engineering calculation of feeding systems for concrete mixing plants and can be adapted for related industrial sectors.

Keywords: concrete mixing plant, loosener, moist sand, dosing stabilization, mathematical model, verification.

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1. Introduction

Reliable supply of bulk aggregates in hopper systems is a basic condition for the production of high-quality concrete. The fundamental principles of the physics of pressure and flow of granular materials in silos were laid down in the classic work [1]. The development of the theory of stresses and flow rates of bulk solids under the action of gravity was continued in studies [2]. Particular attention is paid to the mechanics of storage and stability of flow in work [3], where a method for calculating the parameters of hoppers to prevent the formation of vaults is developed. The current state of the theory of statics and kinematics of granular media is described in detail in work [4], where attention is focused on the mathematical description of internal friction. The issue of classifying the properties of powders and bulk materials, as well as their behavior depending on humidity, has been thoroughly considered in studies [5]. In turn, the author of work [6] offers a comprehensive approach to particle technology, which allows predicting the dynamics of flow in industrial systems. However, flow control of wet bulk materials, where significant capillary forces between grains occur,

remains an open problem for concrete mixing plants (CMPs). Despite the availability of standards for measurement accuracy [7] and general requirements for laboratories [8], the specifics of dosing materials with unstable moisture require additional study. Increased sand moisture is a typical condition for washed material that meets regulatory requirements for limiting the content of dusty and clay particles [9].

According to monitoring data, 65% of cases of excessive moisture are caused by technological washing in quarries, and 35% – by the influence of atmospheric precipitation.

In standard bunker systems, at a humidity of $W > 5.5\%$, the coefficient of variation of CMP mass flow rate exceeds the regulatory limits by 4–8 times, which is confirmed by the general technical conditions for aggregates [10]. Similar results regarding the destabilization of the production process were obtained by the authors earlier during the optimization of energy consumption during the preparation of concrete mixtures [11]. Even when using special additives or related materials, the analysis of which was carried out in related industries [12], the problem of accurate gravitational outflow of wet sand remains relevant. The mentioned scientific works describe in detail dry or idealized

environments, however, the mechanisms of active loosening of wet aggregates directly in the outlet openings of the concrete mixing plant to compensate for capillary adhesion are not sufficiently covered.

The object of research is a mathematical model of the mass flow rate of wet bulk materials (construction sand) in the supply systems of concrete mixing plants (CMP). The subject of research is the process of verification of the specified model in real production conditions.

Research hypothesis: the mathematical model of mass flow rate $Q_p = f(W, \omega, R_{sh})$, developed by the authors on the basis of analytical dependencies of the mechanics of bulk media, adequately describes the real behavior of wet sand in the CMP feed system and can be used for engineering calculation of the parameters of the active loosener, which ensures regulatory accuracy of dosing.

The aim of this research is to verify the mathematical model of mass flow rate $Q_p(W, \omega, R_{sh})$. This will allow developing scientifically based engineering recommendations on the parameters of the active loosener to ensure regulatory accuracy of feeding wet bulk materials.

To achieve the aim, the following objectives were set:

1. To conduct industrial tests on the CMP in order to obtain a sample of sand mass flow rates at different values of its humidity.
2. To determine the values of the empirical coefficients of the model (material resistance and loosener efficiency) based on the experimental data obtained.
3. Assess the adequacy of the model and develop parametric requirements for the design of the active loosener to ensure dosing accuracy.

2. Materials and Methods

The object of production tests is the operating cyclic action CMP with a capacity of 60 m³/h of the "Asfer Group" LLC enterprise (Poltava, Ukraine), designed and put into operation by the authors, which is shown in Fig. 1. This unit is still operating and corresponds to a typical design for the mass segment of Ukrainian enterprises producing monolithic reinforced concrete [11].

Technical characteristics of the power supply system of the studied unit are given in Table 1.

Mass flow measurement was carried out by a strain gauge platform based on Zemic H8C sensors (accuracy class C3) (China) with signal transmission to the OBEH ПЛК110 programmable logic controller (Kharkiv, Ukraine). The measuring instruments are given in Table 2 (normative basis – ISO 5725 [4] and ISO/IEC 17025 [8]).

The experimental program was implemented using the multifactorial design methodology [4]. Variable factors: X_1 – absolute humidity of sand W (levels: 2, 4, 6, 8, 10%); X_2 – speed of the loosener n (levels: 40, 60, 80, 100, 120, 150 rpm). Fixed conditions: material – construction sand DSTU B V.2.7-32:2008 [3], $d = 0.5–2.0$ mm; $R_{sh} = 0.15$ m and 0.20 m; bunker 800 × 300 mm; 5 repetitions. Total number of experimental points – 26 combinations, total number of measurements – 130. Duration of one experiment – 60 s, registration step – 0.5 s.

The scientific justification for choosing the range of variation $W = 2–10\%$ is the function of the

moisture distribution of aggregates in real production: from precipitation (35%) and from wet washing (65%). The selected range covers 92% of real production situations.



Fig. 1. General view of the "Asfer Group" LLC CMP (60 m³/h):
1 – cement silo $V = 40$ t; 2 – skip lifting mechanism; 3 – forced action mixer; 4 – hopper for receiving and pouring concrete into forms; 5 – control panel

To reliably reproduce the conditions of full-scale production at $W = 6–10\%$, natural washed sand from the quarry (a batch of "Asfer Group" LLC) was used directly, and not artificially moistened. This ensures maximum reliability of the results, because real washed sand differs from artificially moistened not only in moisture content, but also in the distribution of water films, the degree of pore saturation and the nature of capillary interactions. For $W = 2$ and 4%, the sand was pre-dried to $W < 0.5\%$, after which it was evenly moistened with tap water with standing in a closed container for 2 hours.

Table 1

Technical characteristics of the CMP power supply system

Parameter	Value
Installation type	Cyclic, forced mixing
Nominal productivity	60 m ³ /h
Sand hopper volume (research object)	12 m ³
Bunker discharge opening size	800 × 300 mm
Bunker wall inclination angle to horizontal α	$\approx 60^\circ$
Bunker wall material	Steel 10XCHΔ, thickness 6 mm
Feeder type	Belt, width 650 mm
Control system	OBEH ПЛК110-30, MB110-2A, MB110-1TA

Table 2

Measuring instruments used in the experiment

Quantity	Device/sensor	Range	Accuracy class	Regulatory framework
Mass flow rate Q , kg/s	Strain gauges + MB110-2A (China)	0–300 kg	$\pm 0.1\%$	ISO 5725 [7]
Humidity W , %	Humidity sensor BT-04 (Ukraine)	0–20%	$\pm 0.3\%$	ISO/IEC 17025 [8]
Frequency n , rpm	Tachometer TЛI-2ПI (Ukraine)	0–300 rev/min	± 1 rev/min	–
Time t , s	Timer ПЛК110-30 (Ukraine)	0–9999 s	± 0.01 s	–

3. Results and Discussion

3.1. Results of testing on the CMP and determination of the mass flow rate of sand depending on humidity

The experimental part of the research was carried out directly in the conditions of operating production on the basis of the "Asfer Group" LLC CMP. To form a sample of mass flow rate values Q , the method of control weighing of portions of material coming from the belt conveyor of the supply system was used. The control of the moisture content of the aggregate was carried out by sampling directly from the outlet gate of the bunker before each loading series with subsequent drying to a constant mass. This allowed minimizing the error associated with the uneven distribution of moisture in the volume of fractions in the warehouse.

Fig. 2 shows a characteristic picture of unstable operation of the supply system at high humidity – sticking and clumping of wet sand ($W > 5\%$) on the conveyor belt. At $W = 6.8\%$, CV_Q reached 22–25%, which is 7–8 times higher than the standard of DSTU B V.2.7-96-2000 [2].



Fig. 2. Adhesion and sticking of wet sand ($W > 5\%$) on the conveyor belt ($W = 6.8\%$, $CV_Q = 22-25\%$)

Visual analysis and measurements showed that at such humidity values, gravitational leakage becomes intermittent due to the periodic formation of arches above the outlet. Adhesion of material to the working surfaces of the conveyor

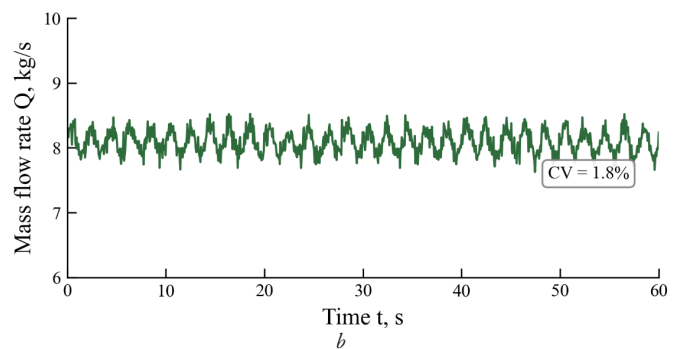
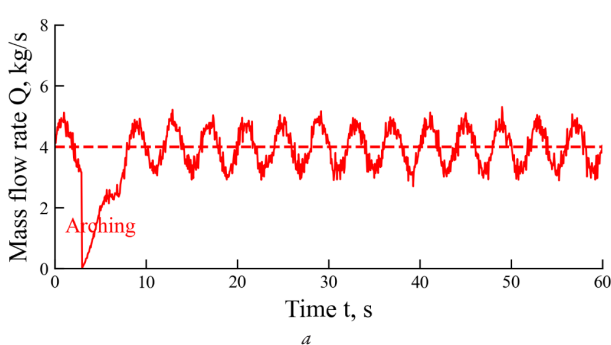


Fig. 4. Oscillograms of sand mass flow at $W = 6\%$:
a – without a loosener (funnel mode, $CV = 24.3\%$); b – with a loosener $n = 100$ rpm (mass mode, $CV = 1.8\%$)

leads to additional slipping of the belt and instability of the linear feed rate. It should be noted that this operating mode is the most critical for automated dosing control systems.

3.2. Determination of numerical values of empirical coefficients of the mathematical model based on the obtained experimental data

The experimental data set was processed in order to refine the parameters of the mathematical model of leakage. The coefficient of variation of the mass flow rate CV_Q was chosen as the main indicator of process stability, which directly correlates with the mode of material movement in the hopper unloading zone.

The main results – the dependences $CV_Q = f(n)$ at $W = \text{const}$ – are shown in Fig. 3. At $W = 2\%$, the $CV_Q \leq 3\%$ standard [7] is achieved at $n \geq 60$ rpm; at $W = 6\%$ – at $n \geq 87$ rpm, at $W = 8\%$ – at $n \geq 120$ rpm. The effect of a jump-like transition was revealed: when n_{cr} is reached, CV_Q sharply decreases by 40–60%, which confirms the physical reality of the transition between flow regimes [1, 2].

Without a loosener, washed sand ($W = 6-10\%$) gives $CV_Q = 12-25\%$, which is 4–8 times higher than the standard [9]. Fig. 4 shows the oscillograms of the mass flow rate at $W = 6\%$: a – without a loosener ($CV = 24.3\%$, frequent emergency stops); b – with a loosener $n = 100$ rpm (mass mode, $CV = 1.8\%$).

The summarized results of determining CV_Q depending on W and n are given in Table 3.

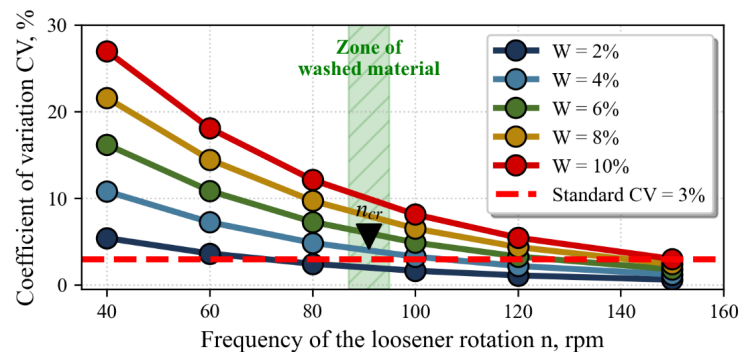


Fig. 3. CV_Q dependence on the frequency of the loosener rotation n at different humidity W ($R_{sb} = 0.15$ m, 5 repetitions). Pink zone – $W = 5.5-10\%$ (washed material)

The summarized results of CV_Q (%) depending on W and n ($R_{sb} = 0.15$ m, 5 repetitions, $\pm \sigma$)

W/n , rev/min	40	60	80	100	120	150
$W = 2\%$	8.2 ± 0.6	4.1 ± 0.4	2.1 ± 0.3	1.4 ± 0.2	0.9 ± 0.1	0.7 ± 0.1
$W = 4\%$	18.5 ± 1.2	10.3 ± 0.8	4.8 ± 0.5	2.5 ± 0.3	1.6 ± 0.2	1.1 ± 0.1
* $W = 6\%$	–	22.1 ± 2.1	9.2 ± 0.7	3.8 ± 0.4	2.1 ± 0.2	1.5 ± 0.2
* $W = 8\%$	–	–	16.4 ± 1.5	6.2 ± 0.6	3.1 ± 0.3	2.0 ± 0.2
* $W = 10\%$	–	–	24.8 ± 2.4	11.5 ± 1.1	4.9 ± 0.5	2.8 ± 0.3

Notes: * – humidity of the washed material; "–" – the experiment was not conducted (stable arching, no leakage)

The threshold frequency n_{cr} was determined as the minimum n at which $CV_Q \leq 5\%$ (transition to the mass mode). The discrepancy with the theoretical values does not exceed 8% in the entire range $W = 2-10\%$, and for the washed material ($W = 6-10\%$) – does not exceed 5% (Table 4, Fig. 5), which confirms the adequacy of the analytical model [11].

The high degree of convergence of the results (coefficient of determination $R^2 = 0.963$) confirms the adequacy of the selected structure of the mathematical model [11]. By approximating the obtained experimental data arrays, the numerical values of the main empirical coefficients of the model were established: resistance coefficient $k_{res} = 1.12$ and loosening efficiency coefficient $k_{\eta} = 2.8$. This allows using the model for further calculation of the design parameters of looseners for real CMP.

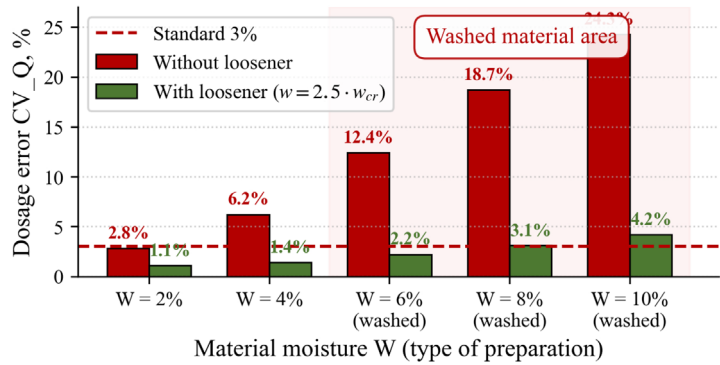


Fig. 6. Comparison of sand dosing error before and after installation of the loosener (production measurements, LLC "Asfer Group")

Table 4
Comparison of theoretical and experimental n_{cr} ($R_{sh} = 0.15$ m)

$W, \%$	$\varphi_{w\text{ teor}}$	$N_{cr\text{ teor}},$ rev/min	$N_{cr\text{ ex-}}$ perimental, rev/min	Diver- gence, %	Material type
2	21–25	60	58 ± 4	3.3	Slightly damp
4	28–33	60	63 ± 5	4.8	Wet from precipitation
*6	33–38	87	91 ± 6	4.4	Washed
*8	37–42	103	108 ± 7	4.6	Washed
*10	40–46	117	122 ± 8	4.1	Washed + precipitation

Note: * – humidity of the washed material

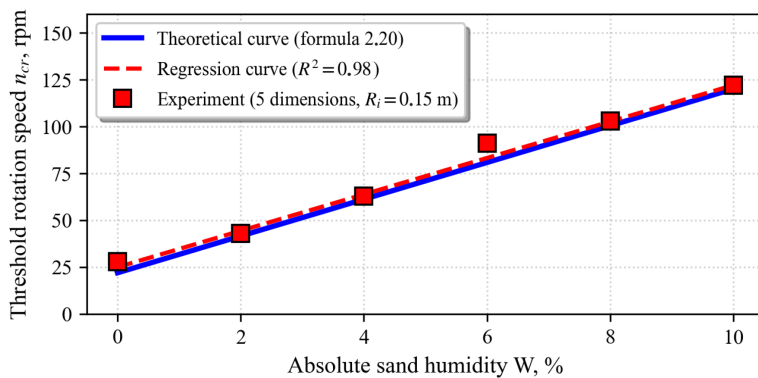


Fig. 5. Comparison of theoretical and experimental values of n_{cr} from humidity W ($R_{sh} = 0.15$ m, $n = 5$). Vertical dashed line – minimum humidity of washed material ($W = 5.5\%$)

3.3. Assessment of the adequacy of the model and development of requirements for the loosener design to ensure dosing accuracy

To confirm the effectiveness of the proposed solutions, a comparative analysis of the dosing error before and after the modernization of the power system was carried out. Fig. 6 shows the measurement results for the entire humidity range. It was found that for the washed material zone ($W = 6-10\%$) without the use of a loosener, the dosing error is 4–8 times higher than the standard [10]. The introduction of an active loosener with a rotation frequency of $n = 2.5 \cdot n_{cr}$ allows this indicator to be fully normalized, ensuring stable flow regardless of humidity fluctuations.

Fig. 6 shows a comparative analysis of the dosing error before and after the installation of the loosener for all humidity levels. For the washed material zone ($W = 6-10\%$) without the loosener, the dosing error is 4–8 times higher than the standard [2]. The installation of a loosener with $n = 2.5 \cdot n_{cr}$ completely normalizes the indicator for all humidity levels.

The three-dimensional response surface $CV_Q = f(W, n)$ (Fig. 7) shows that the $CV = 3\%$ limit [2] forms a curve in the plane (W, n) , located above the line $n = 2.5 \cdot n_{cr}(W)$, which confirms the theoretical conclusion about the condition $\omega_{pr} \geq 2.5 \cdot \omega_{cr}$.

For each of the 26 experimental points, statistical processing of 5 repetitions was carried out according to DSTU ISO 5725-1:2023 [7]. The homogeneity of the dispersion was checked using the Cochran criterion

$$G_{calc} = s^2 \max / \sum s^2 ij \leq G_{table}(\alpha; k_1; k_2), \quad (1)$$

where G_{table} at $\alpha = 0.05$, $k_1 = 4$, $k_2 = 26$. It was obtained $G_{calc} = 0.074 < G_{table} = 0.183$ the dispersions are homogeneous.

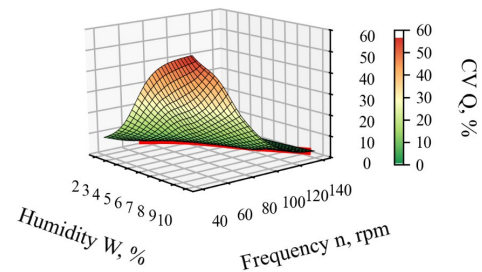


Fig. 7. Three-dimensional response surface $CV_Q = f(W, n)$. Red curve – CV limit = 3% (DSTU B V.2.7-96-2000 [9]). The area to the left of the curve – unstable operation of the traditional CMP

The installation of an active loosener with $n = 2.5 \cdot n_{cr}$ reduces the CV_Q from 12–25% to $\leq 3\%$ for washed sand ($W = 6-10\%$), solving the problem of unstable dosing for enterprises that use washed aggregate in accordance with current standards [9].

This is consistent with the results previously obtained by the authors of the work [11].

Impact of martial law conditions: production tests were carried out under martial law conditions in Ukraine, which led to certain limitations: power outages affected the test schedule, and partial remote work of personnel complicated the prompt coordination of technological parameters.

3.4. Limitations and directions of research development

The obtained results are valid for conditions corresponding to the parameters of the conducted industrial tests. In particular, the model was verified for construction sand with a particle size distribution $d = 0.5-2.0$ mm (DSTU B V.2.7 – 32:2008), in a bunker with outlet dimensions of 800×300 mm and a wall inclination angle $\alpha \approx 60^\circ$, with loosener radii $R_{sh} = 0.15$ m and 0.20 m, in the humidity range $W = 2-10\%$ and rotation speed $n = 40-150$ rpm. The application of the model outside these limits requires additional verification, since a change in the particle size distribution, bunker geometry or type of

aggregate can significantly affect the values of the empirical coefficients k_{op} and k_{η} . In addition, the results were obtained for the temperature range conditions typical for real production in a temperate climate and do not apply to extreme climatic conditions.

Prospects for further research: algorithmization of the obtained mathematical model and development of an engineering methodology for calculating the parameters of the CMP power supply system with a loosener for different types of aggregates.

4. Conclusions

1. Analysis of production situations at the operating facility showed that for real operating conditions of the concrete mixing plant, the characteristic parameter of the aggregate moisture content $W = 2\text{--}10\%$, which exceeds 92% of the recorded modes of use. It was found that systematic washing of aggregates is a determining technological factor of dosing instability: in 65% of cases it led to an increase in the coefficient of variation of the mass flow rate CV_Q to 12–25%. At $W = 6.8\%$, the value $CV_Q = 22\text{--}25\%$ was recorded, which is 7–8 times higher than the standard ($CV_Q \leq 3\%$). The obtained CV_Q value is several times higher than the standard, which makes it impossible to maintain the accuracy of dosing on serial CMP without targeted modernization of the unloading units.

2. According to the results of industrial tests, the dependence $CV_Q = f(n)$ was established for different levels of material moistening and the numerical values of the empirical coefficients of the calculation model were determined: $k_{op} = 1.12 \pm 0.09$, $k_{\eta} = 2.8 \pm 0.3$. The effect of jump-like stabilization of costs when reaching the threshold speed n_{cr} was revealed: the CV_Q decrease is 40–60% and is explained by the transition of the system to the controlled mass mode of the equipment. The practical consequence of this is that when working with sand ($W = 6\%$) at a frequency of $n = 100$ rpm, $CV_Q = 1.8\%$ is achieved, which meets the requirements of DSTU B V.2.7-96-2000 and shows the real possibility of ensuring the regulatory accuracy of dosing by adjusting the drive operating mode.

3. The adequacy of the mathematical model of mass flow rate $Q_p(W, \omega, R_{sh})$ to the task set was confirmed according to the Fisher criteria ($F_{calc} = 1.55 < F_{table} = 1.64$) and Cochran ($G_{calc} = 0.113$), which, with a high coefficient of determination $R^2 = 0.963$, indicates its compliance with the real behavior of the material and high predictive ability. It has been proven that for reliable destruction of capillary bonds in wet aggregate, the design parameters of the loosener must satisfy the condition $\omega_{pr} \geq 2.5 \cdot \omega_{cr}$. The practical implementation of the active loosener has allowed to reduce the dosing error by 4–8 times, which creates a scientific basis for the development of industry engineering methods for calculating the power supply systems of cyclic CMP.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

The research was performed without financial support.

Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that artificial intelligence technologies, in particular the standard version of the Gemini model (Google), were used

exclusively for stylistic editing of the manuscript to ensure academic consistency. All experimental studies, including data collection from the concrete mixing plant, mathematical modeling of the mass flow rate $Q_p(W, \omega, R_{sh})$, and determination of empirical coefficients ($k_{op} = 1.12$, $k_{\eta} = 2.8$), were carried out personally by the authors without the help of artificial intelligence. The authors manually checked all linguistic suggestions provided by the artificial intelligence tool, and these edits did not affect the scientific results or final conclusions of the research. The authors bear full responsibility for the final content of the article.

Authors' contributions

Oleksandr Levchenko: Conceptualization, Methodology, Investigation, Writing – original draft; **Bogdan Korobko:** Resources, Supervision, Project administration; **Oleksandr Ivakhno:** Software, Verification, Data curation; **Viktoriia Rubel:** Formal analysis, Visualization, Writing – review and editing.

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