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MATHEMATICAL MODELING OF CONSTRUCTION MIXTURE PREPARATION AND TRANSPORT PROCESSES IN MECHANIZED SYSTEMS FOR DAMAGED BUILDING RESTORATION

The influence of vibration processes on operating efficiency of mechanized systems for preparation and supply of construction mixtures within integrated technological complexes for building erection and finishing operations has been investigated. It is shown that operation efficiency of concrete mixing, pumping, and plastering equipment functioning as an interconnected technological system is governed by coordinated operating modes of system components, rheological properties of concrete and mortar mixtures, and dynamic characteristics of drives and control systems. The effect of construction mixture adhesion to plastering unit bunker internal surfaces on material delivery uniformity disturbance and equipment productivity reduction has been substantiated. The effectiveness of vibration impact application on bunker walls for adhesion reduction and mixture transport stabilization has been confirmed. The importance of mathematical model development and control method improvement for processes of concrete mixture preparation and building mortar transport within complex mechanized technological systems considering vibration influence on plastering unit bunker has been established. Mathematical models describing processes of concrete mixture mixing and construction mortar transport taking into account variable material rheological properties, drive dynamics, and interaction between mechanized system components have been developed. Functional dependencies between technological process parameters, vibration influence parameters, and control system control actions ensuring mixture delivery uniformity improvement and equipment operating efficiency increase have been determined. The obtained results can be used for substantiation of rational operating modes and structural–technological parameters of plastering units within technological systems for mechanized preparation and supply of construction mixtures.

Keywords: *concrete mix, mortar, mathematical modelling, transportation, pumping, bunker, control, mechanized systems, vibration efficiency, vibration exciter*

Introduction

Modern construction production development is accompanied by increasing complexity in technological processes, higher requirements applied to construction material quality, and necessity ensuring stability in operating parameters characterizing mechanized equipment. Under these conditions, mechanized systems for preparation concrete mixtures and transport construction mortars acquire particular importance while functioning as components within a unified technological complex performing building and finishing operations.

Their operational efficiency largely depends on uniform material supply toward machine working elements, coordinated functioning modes among individual subsystems, and stability in rheological characteristics describing mixtures.

Violation of these conditions leads to a decrease in equipment performance, an increase in energy consumption and a deterioration in the quality of technological operations.

One characteristic problem during plastering unit operation involves adhesion of construction mixture to internal bunker surfaces, causing non-uniform material supply toward transporting and working elements within the installation. As a result, there are pulsations in the flow rate of the mixture, dynamic loads on the equipment drives increase and the efficiency of the mechanized system as a whole decrease.

This phenomenon is especially intensively manifested during the transportation of mixtures with increased viscosity or variable rheological properties characteristic of modern mortars. Conventional design solutions do not ensure complete removal of mixture residues from bunker walls, which requires application additional methods intensifying mixture movement process.

One effective direction for improving stability in construction mixture supply involves applying vibration impact on bunker walls, ensuring reduction in material adhesion forces acting along working chamber surfaces and intensification in material movement toward capture zone near working elements. Application controlled vibration oscillations enables reduction in mixture adhesion, improvement in uniformity during mixture

supply, and stabilization in operating modes characterizing plastering unit.

At the same time, mathematical description concerning bunker vibration influence on transport processes involving construction mixtures within complex mechanized systems remains insufficiently investigated. This determines necessity developing corresponding mathematical models and control methods for such processes considering vibration impact parameters. [3–7].

Analysis of Recent Research

Issues related to improving efficiency in processes involving preparation concrete mixtures and transport construction mortars are addressed in numerous scientific studies devoted to improving designs related to concrete mixing, pumping, and plastering equipment. Considerable attention is given to investigation influence from rheological characteristics characterizing mixtures on parameters describing their movement within machine working volumes and transport pipelines.

Studies [3–6] demonstrate that variation in viscosity and yield shear stress significantly influences energy consumption during processes involving mixing and transport concrete mixtures. Mathematical models enabling evaluation dependence between technological equipment productivity and mixture composition together with working element parameters were developed. However, most studies remain focused on stationary machine operating modes without considering additional dynamic impacts acting on material.

Studies devoted to investigation processes involving transport construction mortars using pumping installations pay considerable attention to determination hydraulic resistance in pipelines, conditions governing formation wall lubrication layer, and regularities describing variation in mixture flow parameters during pumping [5, 8–11]. Approaches for mathematical description concerning movement processes involving concrete mixtures in pipelines were proposed considering rheological properties characterizing materials together with structural parameters related to pumping equipment. Material supply stability was shown to depend largely on uniform material delivery toward pump working elements. At the same time, influence from interaction processes between mixture and receiving chamber surfaces in technological equipment remains insufficiently considered in these studies.

A separate research direction is associated with application vibration impact for intensifying movement granular and plastic materials in bunkers and transporting devices within technological machines. Vibration application enables reduction in material adhesion forces acting along working chamber surfaces, improvement in uniformity during material movement, and stabilization in material supply toward machine working elements. Available studies demonstrate effectiveness in applying controlled oscillations for preventing material arching in bunkers and improving transport conditions; however, application vibration impact to concrete mixtures and construction mortars in concrete mixers, mortar mixers, and equipment used for their pumping remains insufficiently investigated.

Thus, analysis results from previous studies indicate that existing mathematical models describing preparation and transport processes involving construction mixtures do not fully consider influence from vibration oscillations acting on bunker walls on stability in material supply toward working elements in construction equipment. This determines necessity developing mathematical models describing transport processes involving construction mortars considering vibration impact parameters influencing preparation concrete mixtures and construction mortars together with their pumping and evaluating resulting influence on efficiency characterizing mechanized system functioning as a whole.

Research Goal

The aim of this study is developing a mathematical model describing processes involving preparation concrete mixtures and transport construction mortars within mechanized systems performing building erection and finishing operations, considering vibration impact acting on bunker walls in concrete mixers, mortar mixers, and pumps used for their transport, and investigating resulting influence on reduction in mixture adhesion, stabilization in mixture supply toward machine working elements, and improvement in efficiency characterizing technological system functioning.

Methodology and Results

The study applies methods for mathematical modelling nonlinear and non-stationary technological processes, rheological models describing construction mixtures, as well as automatic control theory methods for forming control actions acting on operating parameters in the mechanized system. Additional consideration includes influence from vibration oscillations acting on bunker walls on mixture movement intensity and reduction in adhesion forces between mixture and internal surfaces inside the working chamber.

For describing functioning mechanized systems performing preparation concrete mixtures and transport construction mortars, it is reasonable to consider such systems as a set including interconnected subsystems: mixing subsystem, mixture supply subsystem, and construction mortar transport subsystem.

Within such systems, technological processes exhibit nonlinear and non-stationary behaviour caused by variation in mixture composition, rheological

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characteristics describing mixtures, and dynamic operating modes characterizing equipment drives. Therefore, the mathematical model must consider interrelation between technological parameters and control parameters characterizing the system.

The state of the mechanized system can be represented as a state vector

$$X = \{m, \omega, Q, p\}, \quad (1)$$

where m – mixture mass in mixer working volume, kg;

ω – mixer working body angular velocity, rad/s;

Q – pumping unit capacity, m³/s;

p – transport pipeline pressure, Pa.

The change in mixture mass inside the mixer is determined by material flow balance

$$\frac{dm}{dt} = Q_{in} - Q_{out}, \quad (2)$$

where Q_{in} – component supply rate into the mixer, kg/s;

Q_{out} – finished mixture delivery rate to the pumping unit, kg/s.

Rotation dynamics of mixer working elements are described by the motion equation

$$J\frac{d\omega}{dt} = M_d - M_r, \quad (3)$$

where J – drive inertia moment, kg·m²;

M_d – drive torque, N·m;

M_r – mixing resistance torque, N·m.

Mixing resistance torque depends on mixture rheological properties and mixture mass inside the mixer

$$M_r = k\,\mu_{ef}\,m, \quad (4)$$

where k – mixer structural coefficient;

μ_{ef} – mixture effective viscosity, Pa·s.

To describe the rheological properties of the concrete mixture, the Bingham model is used

$$\tau = \tau_0 + \mu\dot{\gamma}, \quad (5)$$

where τ – shear stress, Pa;

τ_0 – yield strength, Pa;

$\dot{\gamma}$ – strain rate, s^{-1};

μ – plastic viscosity of the mixture, $Pa \cdot s$.

This model enables consideration influence from rheological characteristics describing the material on mixing and transport processes.

The performance of the pumping unit is determined by the parameters of its working bodies

$$Q = \eta V n \quad (6)$$

where η – pump volumetric efficiency ratio;

V – working volume per cycle, m^3;

n – pump frequency, s^{-1}.

The pressure in the transport pipeline is determined by hydraulic losses

$$\Delta P = \lambda \frac{L}{D} \cdot \frac{\rho v^2}{2} \quad (7)$$

where λ – hydraulic resistance coefficient;

L –length, m;

D – pipeline diameter, m;

ρ – mixture density, kg / m^3;

v – material velocity, m / s.

Taking into account the above dependencies, the functioning of a mechanized system can be described by a system of equations

$$\begin{cases} \frac{dm}{dt} = G_{in} - G_{out} \\ J\frac{d\omega}{dt} = M_d - M_r \\ M_r = k_1 m + k_2 \mu\omega \\ Q = \eta V n \\ \Delta P = \lambda \frac{L}{D} \cdot \frac{\rho v^2}{2} \end{cases}, \quad (8)$$

The obtained system describing equations characterizes interrelation between parameters governing mixing processes and transport processes involving construction mixtures.

To ensure stable system operation, control using feedback based on productivity and pipeline pressure is applied.

Control action applied to mixer rotation speed can be expressed as

$$\omega = \omega_0 + k_Q(Q_{ref} - Q), \quad (9)$$

where Q_{ref} – specified system performance, m^2 / s;

k_Q – adjustment coefficient, $rad \cdot s^2 / m^3$.

Similarly, for a pumping unit

$$n = n_0 + k_P(P_{ref} - P). \quad (10)$$

Application of such algorithms enables coordination operating modes between concrete mixing equipment and pumping equipment and ensures stability in the technological process.

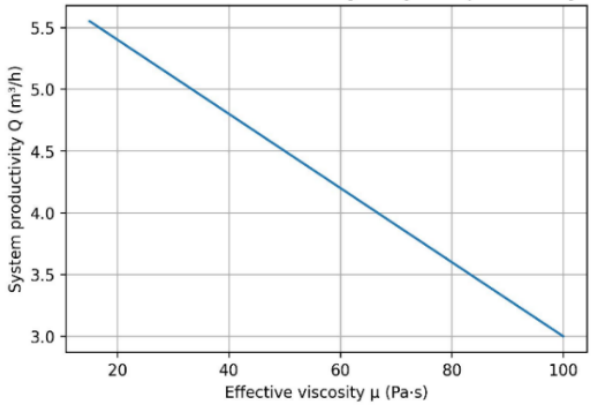

Fig. 1 Influence of effective mixture viscosity on productivity in the mechanized system

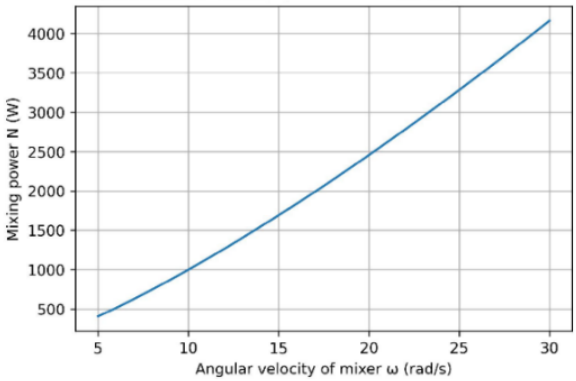

Fig. 2 Dependence of mixing power on the rotational speed of the working element

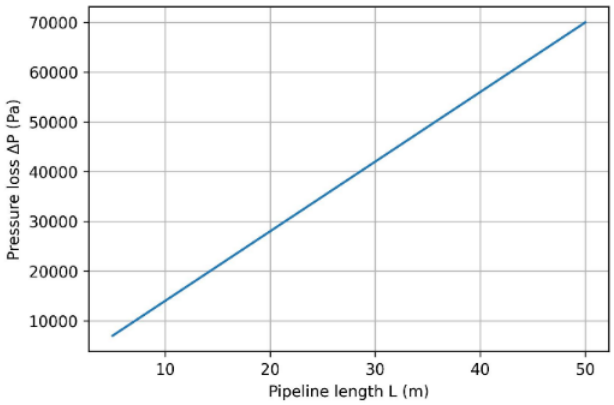

Fig. 3 Dependence of pressure losses during transportation of the construction mixture on pipeline length

As shown in Fig. 4, an increase in effective mixture viscosity leads to a decrease in productivity of the mechanized system. This is explained by an increase in hydraulic resistance during material transportation and an increase in mixing resistance torque.

Figure 4 presents simulation results describing variation in mechanized system productivity over time. As shown in the graph, significant fluctuations in mixture supply are observed in the absence of a control system. Application of feedback control enables stabilization of productivity and reduction in amplitude of technological parameter fluctuations.

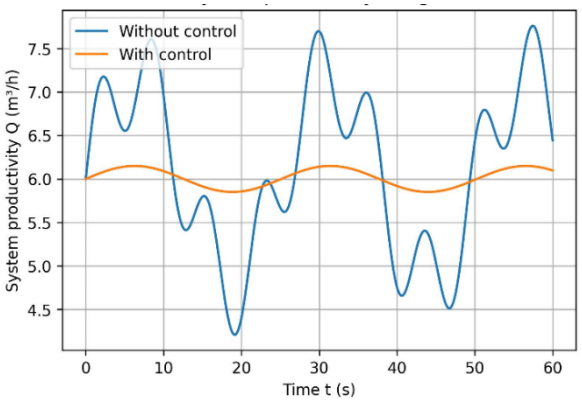

Fig. 4 Stabilization of mechanized system productivity using feedback control

An important factor influencing stability in construction mortar supply toward working elements in plastering units involves mixture interaction with internal surfaces inside the receiving bunker. During unit operation, mixture adhesion to bunker walls occurs, leading to disruption in supply uniformity and emergence of productivity pulsations in the system.

This phenomenon becomes especially pronounced during transport of mixtures with increased viscosity or variable rheological characteristics. As a result, energy losses during material movement increase and load non-uniformity acting on drives in transporting mechanisms also increases. To reduce influence from these factors, application of vibration impact on bunker walls is advisable.

Vibration impact ensures reduction in adhesion forces between the construction mixture and bunker surfaces and intensifies movement toward the capture zone near machine working elements. Action from harmonic oscillations acting on bunker walls can be described by the relation

$$x = A\sin(\omega_v t) \qquad (11)$$

where A - amplitude of bunker wall oscillations, m ;

ω_v - angular vibration frequency, rad / s ;

t - time, s .

The acceleration of vibrational motion is determined by the expression

$$a_v = A\omega_v^2 , \qquad (12)$$

where a_v - vibration acceleration, m / s^2 ;

ω_v - angular vibration frequency, rad / s ,

which characterizes the intensity of the dynamic impact on the layer of the building mixture in contact with the bunker walls.

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Taking into account the vibration effect, the effective friction force of the mixture on the surface of the hopper walls decreases and can be presented as a dependency

$$F = F_0(1 - k_v a_v), \qquad (13)$$

where F_0 - vibration-free adhesion force of the mixture to the wall, N;

k_v - coefficient describing influence of vibration parameters on adhesion force reduction, s^2 / m;

a_v - acceleration of vibration oscillations, m / s^2.

Reduction in adhesion force promotes increased mixture movement intensity within the bunker volume and ensures stabilization in material supply toward transporting mechanisms in the unit. Considering this, productivity of the construction mortar transport system can be represented by the relation

$$Q = Q_0(1 + k_a a_v), \qquad (14)$$

where Q_0 - system productivity without vibration impact, m^3 / s;

k_a - coefficient describing influence of vibration parameters on mixture supply productivity, s^2 / m.

The obtained relations make it possible to account for vibration impact parameters in mathematical descriptions of construction mortar transport processes within mechanized systems and to evaluate their influence on stability of plastering unit operation.

Figure 5 presents the dependence of relative adhesion force between the construction mixture and bunker walls on vibration acceleration.

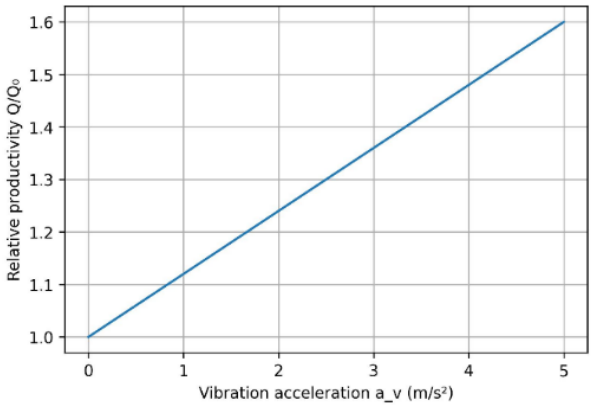

Fig. 5. Dependence of relative productivity of construction mortar supply on vibration acceleration acting on plastering unit bunker walls

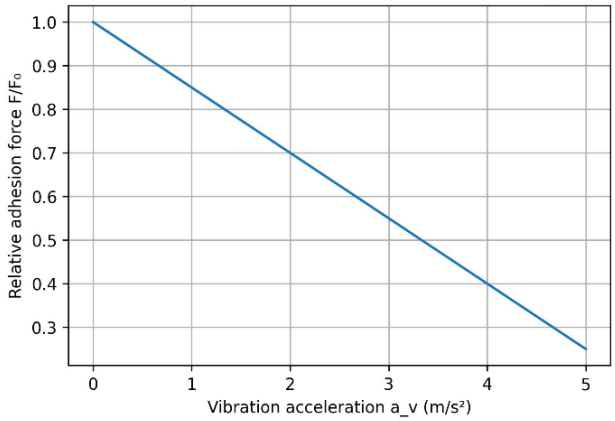

Fig. 6 Influence of plastering unit bunker wall vibration acceleration on reduction of adhesion force between the construction mixture and receiving chamber internal surfaces

As shown in Fig. 6, increasing vibration acceleration contributes to reduction of mixture adhesion force to bunker walls, which ensures improved uniformity of its supply to working elements of the unit.

Conclusions

The article considers processes of concrete mixture preparation and construction mortar transportation within complex mechanized systems for building erection and finishing as an interconnected technological system whose operational efficiency is determined by coordination of operating modes of concrete mixing, pumping, and plastering equipment. It is shown that one of the key factors ensuring stable operation of such systems is uniform supply of the construction mixture to working elements of transporting mechanisms, which largely depends on material rheological characteristics and interaction conditions with internal surfaces of technological equipment receiving chambers.

Mathematical models of concrete mixture mixing processes and construction mortar transportation processes have been developed that account for variable rheological properties of materials, dynamic characteristics of drives, and interaction between individual elements of the mechanized system. The obtained relationships make it possible to establish functional relationships between technological process parameters, equipment operating modes, and control actions in automated control systems, providing a basis for improving efficiency in construction mechanization complexes.

It has been established that one of the main causes of reduced productivity in plastering units of this type is adhesion of the construction mixture to internal receiving-bunker surfaces, which leads to disrupted material supply uniformity, occurrence of mixture flow pulsations, and increased energy consumption during the transport process.

An approach considering vibration impact on plastering unit bunker walls has been proposed that enables reduction in construction-mixture adhesion forces to working-chamber surfaces and ensures stabilization of its supply to transporting mechanisms. Analytical relationships describing influence from harmonic bunker-wall oscillation parameters on mixture adhesion force variation and transport system productivity were obtained, enabling evaluation of vibration impact effectiveness at equipment design and operation stages.

It is shown that introducing vibration impact as an additional controlled parameter in the technological system enables improved uniformity in construction-mixture supply to working elements of the unit, reduced energy losses during its transport, and ensured stability of operating modes of the mechanized system as a whole.

The proposed approach to mathematical modelling of concrete mixture preparation and construction mortar transport processes, considering vibration impact on working chambers of technological equipment, creates prerequisites for further development of integrated control methods for mechanized construction-production systems and improvement of their energy efficiency.

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МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ ПРОЦЕСІВ ПРИГОТУВАННЯ ТА ТРАНСПОРТУВАННЯ БУДІВЕЛЬНИХ СУМІШЕЙ У МЕХАНІЗОВАНИХ СИСТЕМАХ ВІДНОВЛЕННЯ ПОШКОДЖЕНИХ БУДІВЕЛЬ

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Досліджено вплив вібраційних процесів на ефективність функціонування механізованих систем приготування та подачі будівельних сумішей у складі інтегрованих технологічних комплексів зведення та опорядження будівель. Показано, що ефективність роботи обладнання для змішування бетонних сумішей, їх перекачування та нанесення штукатурних розчинів, яке функціонує як взаємопов'язана технологічна система, визначається узгодженістю режимів роботи її складових, реологічними властивостями бетонних і розчинних сумішей, а також динамічними характеристиками приводів і систем керування. Обґрунтовано вплив налипання будівельних сумішей на внутрішні поверхні бункера штукатурного агрегату на порушення рівномірності подачі матеріалу та зниження продуктивності обладнання. Підтверджено ефективність застосування вібраційного впливу на стінки бункера для зменшення налипання та покращення умов транспортування суміші. Встановлено важливість розроблення математичних моделей і вдосконалення методів керування процесами приготування бетонних сумішей і транспортування будівельних розчинів у складі складних механізованих технологічних систем з урахуванням впливу вібрації на бункер штукатурного агрегату. Розроблено математичні моделі процесів змішування бетонних сумішей і транспортування будівельних розчинів з урахуванням змінних реологічних властивостей матеріалів, динаміки приводів і взаємодії складових механізованої системи. Встановлено функціональні залежності між технологічними параметрами процесів, параметрами вібраційного впливу та керуючими діями системи керування, що забезпечують підвищення рівномірності подачі суміші та ефективності роботи обладнання. Отримані результати можуть бути використані для обґрунтування раціональних режимів роботи та конструктивно-технологічних параметрів штукатурних агрегатів у складі технологічних систем механізованого приготування та подачі будівельних сумішей.

Ключові слова: *бетонна суміш, будівельний розчин, математичне моделювання, транспортування, перекачування, бункер, управління, механізовані системи, ефективність вібраційного впливу, віброзбуджувач*

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