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DYNAMICS IN PREPARING AND PUMPING CONCRETE MIXES AND PLASTERING MORTARS WITHIN TECHNOLOGICAL SYSTEMS OF CONSTRUCTION MACHINES

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The article investigates dynamics in preparing and pumping concrete mixes and plastering mortars within technological systems of construction machines as interrelated stages of a unified technological cycle whose operational efficiency depends on coordination among kinematic, energy, and rheological parameters of the working process. Regularities governing formation of kinematic parameters for particle motion in a gravitational mixer are examined, and their influence on structural-mechanical characteristics of construction media determining conditions for further material transport through pipeline systems is established. An analytical approach for describing motion of concrete mixes and plastering mortars as Bingham media with consideration of yield shear stress and plastic viscosity is proposed, enabling consideration of specific rheological behaviour during pumping by pump equipment. Analytical relationships describing variation in flow velocity, pressure drop, and material flow rate depending on operating parameters of mixing equipment, pipeline system geometric characteristics, and physico-mechanical properties of the mixture are obtained. A relationship among intensity of component mixing within construction mixtures, degree of structural homogeneity, and energy consumption during material transport in technological systems of construction machines is established. It is shown that coordination between parameters of mixing and pumping processes increases stability of mixture supply, reduces hydraulic losses in pipelines, and ensures rational operating modes for technological equipment. The obtained results can be applied during design of mixing-transport systems for construction machines as well as during development of technologies for mechanized delivery of concrete mixes and plastering mortars, particularly in modern construction 3D printing systems.

Key words: concrete, concrete mix, mixing, transportation, pump, rheology, mathematical modelling, mortar, 3D printing, material consumption.

Relevance of the study. During mixing of concrete mixture components or plastering mortar components, formation of internal structure within the medium occurs, determining its rheological properties, particularly yield shear stress and plastic viscosity. Variation in these parameters significantly influences material flow behaviour in pipeline systems, pressure drop during transportation, and stability of mixture delivery to the working zone of construction operations [1].

At the same time, in most existing studies mixing processes of construction mixtures and their transport through pipelines are considered separately without accounting for mutual influence within a unified technological system of construction machines. Such an approach does not allow determination of regularities in variation of mixture motion parameters depending on operating modes of mixing equipment and conditions of subsequent pumping by pumping units [2, 3].

Particular relevance arises from accounting for interrelation between mixing parameters and transport parameters of construction mixtures during application of modern mechanized technologies for concrete and finishing operations, as well as during layer-by-layer formation of building structures using construction 3D printing methods, where stability of material supply parameters represents a decisive condition for ensuring continuity of the technological process.

In this regard, a need arises to investigate dynamics of preparation and pumping processes for concrete mixes and plastering mortars as interrelated stages within a technological system of construction machines, taking into account rheological properties of the medium and operating parameters for mixing and pumping equipment.

Analysis of Recent Studies and Publications. Studies on preparation processes for concrete mixes and plastering mortars are traditionally associated with analysis of kinematic parameters governing material motion in mixing machines and evaluation of component mixing intensity depending on design and operating characteristics of working elements. It is established that mixing efficiency depends on particle motion trajectories within the medium, velocity of their movement inside the mixer working volume, and circulation multiplicity of material, which directly influence mixture homogeneity and formation of its structural-mechanical properties [4].

Studies on preparation processes for concrete mixes and plastering mortars are traditionally associated with analysis of kinematic parameters governing material motion in mixing machines and evaluation of component mixing intensity depending on design and operating characteristics of working elements. It is established that mixing efficiency depends on particle motion trajectories within the medium, velocity of their movement inside the mixer working volume, and material circulation multiplicity, which directly influence mixture homogeneity and formation of its structural-mechanical properties [5, 6].

A separate research group includes works devoted to mathematical description of motion for construction mixtures treated as structured media with yield shear stress, enabling determination of flow velocity parameters and pressure drop during transport through pipelines with different lengths and diameters [7, 8]. Application of such approaches creates prerequisites for establishing interrelation between rheological characteristics of the medium and conveying equipment operating modes.

Despite a significant number of studies in these directions, mixing and transport processes for concrete mixes and plastering mortars are mostly considered as separate stages within the technological cycle without accounting for their mutual influence. At the same time, coordination between kinematic parameters of mixing equipment and conditions for subsequent mixture motion through the pipeline system remains insufficiently investigated, which complicates justification of rational operating modes for technological systems of construction machines as a whole.

Material and results. During preparation of concrete mixes and plastering mortars in gravitational mixers, formation of structural-mechanical characteristics of the medium is determined by kinematic parameters governing particle motion within the drum working volume. Mixture motion during mixer rotation has a complex circulation pattern and includes particle transport together with the inner drum surface followed by their subsequent free movement under gravity after reaching the limiting lifting height [9].

Linear velocity of mixture particle motion within the mixer working volume is determined by the following relation

$$v = \omega \cdot R, \tag{1}$$

where v – linear velocity of the mixture particle, m/s;
ω – angular speed of mixer drum rotation, rad/s;
R – mixture particle rotation radius, m.

With increasing drum rotation speed, mixture particle motion intensity increases, which contributes to higher component mixing efficiency. At the same time, after reaching a certain angular velocity value, a particle pressing regime against the inner drum surface under centrifugal forces occurs, which reduces mixing process efficiency [10].

The limiting particle motion regime is determined by the condition of equality between centrifugal force and gravity, which is described by the following relation

$$\omega^2 \cdot R = g, \tag{2}$$

where g – acceleration of free fall, m/s².

From this relation, mixer drum rotation critical angular velocity equals

$$\omega_{кр} = \sqrt{\frac{g}{R}}. \tag{3}$$

Efficient mixture component mixing is ensured during mixer operation in the subcritical regime, when material particles perform multiple circulation movements within the drum working volume.

Average circulation motion velocity for mixture particles can be determined considering mixer working volume filling conditions and material movement pattern by the following relation

$$v_ц = k\,\omega R, \tag{4}$$

where $v_ц$ – average circulation velocity of the mixture particles, m/s;

k – coefficient accounting for mixer drum filling degree and material motion conditions within the working volume.

An increase in particle circulation velocity ensures mixing process intensification, accompanied by higher construction mixture homogeneity and stabilization of its structural-mechanical characteristics. Medium motion parameters formed at this stage determine conditions for subsequent material transport through pipeline systems and energy consumption magnitude during pumping by equipment.

After completion of the mixing process, concrete mixture or plastering mortar enters the pipeline system, where its motion occurs under pressure drop generated by pumping equipment. Mixture movement behaviour in the pipeline is determined by its structural-mechanical properties formed during the mixing stage, as well as pipeline geometric parameters and material transport operating modes [11].

For a cylindrical material volume moving in the pipeline, force equilibrium along the motion direction is determined by the relation between pressure force and internal resistance forces within the medium [12].

In this case, the tangential shear stress at the distance *r* from the pipeline axis is determined by the dependence

$$\tau = \frac{\Delta p\, r}{2L}, \tag{5}$$

where τ – tangential shear stress in the flow of the mixture, Pa;

Δp – pressure drop on the pipeline section, Pa;

r – current radial coordinate of the pipeline cross-section, m;

L – length of the pipeline section, m.

Maximum shear stress reaches its highest value at the inner pipeline surface where $r = R$. Then the stress on the pipeline wall is determined by the expression

$$\tau_{cm} = \frac{\Delta p\, R}{2L}, \tag{6}$$

where τ_{cm} – shear stress on the pipeline wall, Pa;

R – internal radius of the pipeline, m.

The obtained relations determine stress distribution law in the construction mixture flow cross section and serve as initial expressions for subsequent determination of material motion velocity gradient in the pipeline system.

Concrete mix and plastering mortar motion in pipeline systems is characterized by internal shear resistance determined by medium structure formed during the mixing stage. During material motion in the pipeline, a relation between tangential shear stress and velocity gradient is established

$$\frac{dv}{dr} = \frac{\tau - \tau_0}{\mu}, \tag{7}$$

where $\frac{dv}{dr}$ – flow rate gradient along the radius of the pipeline, s^{-1};

μ – coefficient of the medium plastic viscosity, Pa·s.

Substituting the previously obtained expression for tangential shear stress in the flow (4), we obtain an equation for determining mixture motion velocity gradient in the following form

$$\frac{dv}{dr} = \frac{1}{\mu}\left(\frac{\Delta p\, r}{2L} - \tau_0\right). \tag{8}$$

Integration of this equation with consideration of the no-slip boundary condition at the inner pipeline surface, namely

$$v = 0 \quad for \quad r = R, \tag{9}$$

allows obtaining an analytical expression for local construction mixture motion velocity at an arbitrary point in the pipeline cross section

$$v(r) = \frac{\Delta p}{4\mu L}\left(R^2 - r^2\right) - \frac{\tau_0}{\mu}(R - r), \tag{10}$$

where $v(r)$ – velocity of the mixture at a distance r from the pipeline axis, m/s.

The obtained expression describes flow velocity distribution in the pipeline cross section considering structural-mechanical properties of the construction mixture and allows determination of material velocity field variation depending on pressure drop, pipeline geometric parameters, and internal shear resistance within the medium.

The obtained construction mixture motion velocity distribution graph along the pipeline radius shows

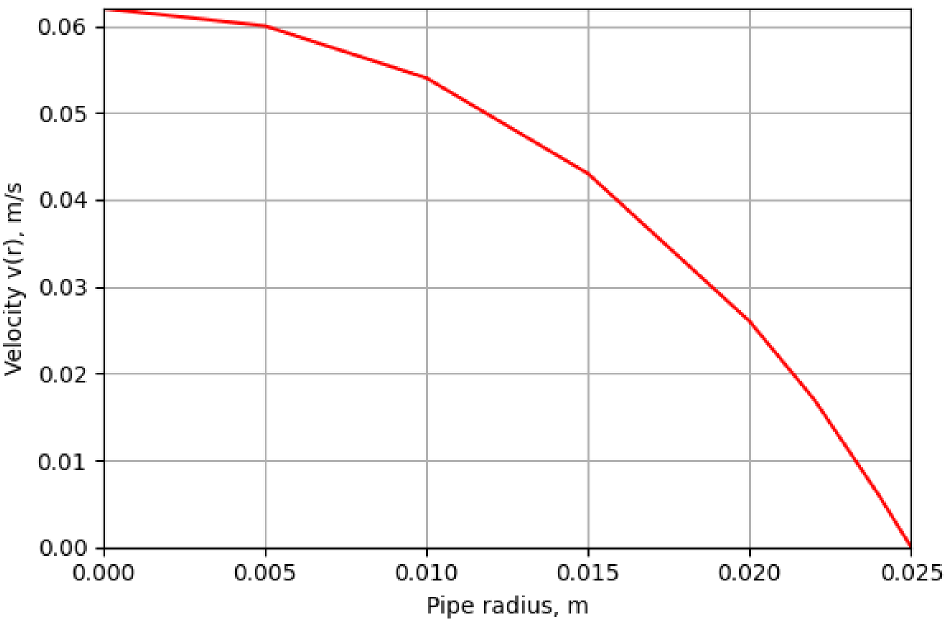

Fig. 1. Construction mixture motion velocity distribution in the pipeline cross section

that maximum flow velocity occurs in the central cross-section region, whereas toward the inner pipeline surface it gradually decreases and reaches zero at the wall. Presence of a non-uniform velocity field indicates significant influence of structural-mechanical properties for concrete mixes and plastering mortars on transport conditions through pipeline systems, which must be considered when determining rational pumping equipment operating modes.

For subsequent determination of construction mixture flow rate through the pipeline, average material motion velocity across the flow cross section must be established [13]. Average velocity is determined by integration of the local velocity distribution over the pipeline cross-sectional area and can be written in the following form

$$v_{cp} = \frac{2}{R^2}\int_0^R v(r)\, r\, dr, \tag{11}$$

where v_{cp} – building mixture movement average speed in the pipeline, m/s;

Substituting the previously obtained expression for local flow velocity (9) and integrating along the pipeline radius, we obtain an analytical expression for average construction mixture motion velocity

$$v_{cp} = \frac{\Delta p R^2}{8\mu L} - \frac{\tau_0 R}{3\mu}. \tag{12}$$

The obtained relation shows that average flow velocity is determined by pressure drop in the pipeline, its geometric parameters, and structural-mechanical characteristics of the construction mixture formed during the mixing stage.

Construction mixture flow rate through the pipeline is determined by the product of average flow velocity and pipeline cross-sectional area

$$Q = v_{cp}\pi R^2, \tag{13}$$

where Q – volumetric consumption of the building mixture, m³/s.

Substituting the obtained average velocity value into this expression, we finally obtain a relation for determining mixture flow rate through the pipeline

$$Q = \frac{\pi R^4 \Delta p}{8\mu L} - \frac{\pi R^3 \tau_0}{3\mu}. \tag{14}$$

The obtained expression establishes an analytical relationship between construction mixture flow rate, pressure drop in the pipeline, its geometric parameters, and structural-mechanical characteristics of the medium and can be applied for justification of rational pumping equipment operating modes during transport of concrete mixes and plastering mortars in technological systems of construction machines.

During mixing of concrete mixes and plastering mortars, initial structural bonds between solid-phase particles are destroyed, moisture redistribution occurs within the material volume, and a homogeneous spatial medium structure is formed. With increasing mixing intensity, internal material shear resistance decreases, which is reflected in reduction of yield shear stress and effective plastic viscosity.

Considering the previously obtained expression for average mixture particle circulation velocity in the mixer (4), medium structure formation intensity can be assumed to be determined by mixer drum angular rotation velocity. In this case, material yield shear stress can be expressed in the following form

$$\tau_0 = \tau_{00} - a\,\omega, \tag{15}$$

where τ_{00} – ultimate shear stress of the mixture in the mixing absence, Pa;

a – Coefficient characterizing structural bond destruction intensity in the material during mixing.

Similarly, construction mixture plastic viscosity depends on the mixing regime and can be written in the following form

$$\mu = \mu_0 - b\,\omega, \tag{16}$$

where μ_0 – plastic viscosity of the medium at the initial state of the mixture structure, Pa·s;

b – coefficient characterizing the change in the plastic viscosity of the material during the mixing process.

Substituting the obtained relations into the expression for determining construction mixture flow rate (13), we obtain a generalized analytical expression establishing a relationship between material flow rate, pressure drop in the pipeline, and mixer operating regime

$$Q = \frac{\pi R^4 \Delta p}{8L(\mu_0 - b\omega)} - \frac{\pi R^3(\tau_{00} - a\omega)}{3(\mu_0 - b\omega)}. \tag{17}$$

The obtained relation shows that increasing mixer drum angular rotation velocity reduces internal resistance to construction mixture motion and ensures higher material flow rate during transport through the pipeline system.

The obtained analytical relations allow establishing interrelation between mixer operation kinematic parameters and construction mixture motion velocity characteristics in the pipeline system. This enables consideration of preparation and transport processes for concrete mixes and plastering mortars as interrelated components within a unified technological process in which mixing regime variation directly influences material motion parameters during delivery by pumping equipment.

The obtained graphical dependences show that increasing pressure drop in the pipeline system leads to higher average motion velocity for concrete mixes and plastering mortars, while velocity variation behaviour is determined not only by hydrodynamic transport conditions but also by mixer operation kinematic parameters. An increase in mixer drum angular rotation velocity is accompanied by reduction in yield shear stress and plastic viscosity within the medium, which ensures more intensive material motion in the pipeline at identical pressure drop values.

Thus, flow velocity characteristics for construction mixtures in the pipeline system are determined

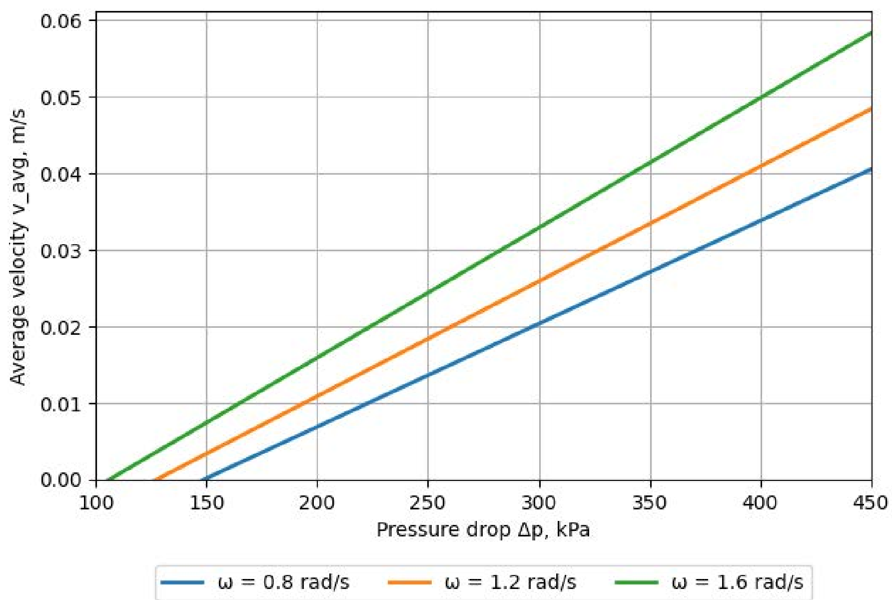

Fig. 2. Construction mixture average motion velocity dependence in the pipeline on pressure drop at different mixer drum angular rotation velocities

by conditions of preliminary mixing, while variation in mixing equipment operating regimes directly influences material transport parameters. This confirms the necessity of coordinated selection of mixing kinematic parameters and pumping equipment operating regimes during design of technological systems for construction machines intended for preparation and delivery of concrete mixes and plastering mortars.

As a result of the conducted study, analytical relations describing interrelation between gravitational mixer operation kinematic parameters and motion velocity characteristics for concrete mixes and plastering mortars in pipeline systems are obtained. It is established that increasing mixing intensity reduces medium structural resistance and ensures higher average transport velocity at identical pressure drop values. It is shown that construction mixture motion parameters in the pipeline are formed under the influence of preliminary treatment conditions in the mixer, which confirms the necessity of integrated consideration of preparation and material delivery processes as a unified dynamic technological process of construction machine operation.

Conclusions. The article investigates dynamics of preparation and pumping processes for concrete mixes and plastering mortars in technological systems of construction machines as interrelated stages within a unified technological cycle. Based on analytical description of construction mixture motion in the gravitational mixer working volume and pipeline system, regularities of material flow velocity parameter formation depending on mixing kinematic regimes and transport conditions are established.

Relations enabling evaluation of mixer drum angular rotation velocity influence on structural-mechanical characteristics of construction mixtures and their motion velocity in the pipeline are obtained. It is shown that increasing mixing intensity reduces medium internal motion resistance and contributes to higher transport efficiency during pumping by pump equipment. Interrelation between construction mixture mixing process parameters and transport process parameters is established, enabling consideration of these processes as elements within a unified dynamic technological system for construction machine set operation.

The obtained results can be applied during justification of rational mixing and conveying equipment operating regimes for preparation and delivery of concrete mixes and plastering mortars in construction practice.

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ДИНАМІКА ПРОЦЕСІВ ПРИГОТУВАННЯ ТА ПЕРЕКАЧУВАННЯ БЕТОННИХ СУМІШЕЙ І ШТУКАТУРНИХ РОЗЧИНІВ У ТЕХНОЛОГІЧНИХ СИСТЕМАХ БУДІВЕЛЬНИХ МАШИН

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У статті досліджено динаміку процесів приготування та перекачування бетонних сумішей і штукатурних розчинів у технологічних системах будівельних машин як взаємопов'язаних стадій єдиного технологічного циклу, ефективність функціонування яких визначається узгодженістю кінематичних, енергетичних і реологічних параметрів робочого процесу. Розглянуто закономірності формування кінематичних параметрів руху частинок суміші в гравітаційному змішувачі та встановлено їх вплив на структурно-механічні характеристики будівельних середовищ, що визначають умови подальшого транспортування матеріалу трубопровідними системами. Запропоновано аналітичний підхід до опису руху бетонних сумішей і штукатурних розчинів як бінгамівських середовищ з урахуванням граничного напруження зсуву та пластичної в'язкості, що дозволяє враховувати особливості їх реологічної поведінки під час перекачування насосним обладнанням. Отримано аналітичні залежності зміни швидкості руху потоку, перепаду тиску та витрати матеріалу від режимних параметрів роботи змішувального обладнання, геометричних характеристик трубопровідної системи та фізико-механічних властивостей суміші. Встановлено взаємозв'язок між інтенсивністю перемішування компонентів будівельної суміші, ступенем її структурної однорідності та енергетичними витратами на транспортування матеріалу в технологічних системах будівельних машин. Показано, що узгодження параметрів процесів змішування та перекачування дозволяє підвищити стабільність подачі суміші, зменшити гідравлічні втрати в трубопроводах і забезпечити раціональні режими функціонування технологічного обладнання. Отримані результати можуть бути використані під час проєктування змішувально-транспортуючих систем будівельних машин, а також при розробленні технологій механізованої подачі бетонних сумішей і штукатурних розчинів, зокрема у сучасних системах будівельного 3D-друку.

Ключові слова: бетон, бетонна суміш, змішування, транспортування, насос, реологія, математичне моделювання, розчин, 3D-друк, витрата матеріалу.

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