



Heat and mass transfer in concrete mixtures during transportation along the route «Manufacturer of liquid – phase solution – consumer of solid-phase concrete»

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Abstract. The durability of concrete is a critical operational parameter that directly determines the service life of concrete structures. Achieving a concrete mixture with specified rheological and strength properties is a vital technological stage, as the quality of the initial material governs the load-bearing capacity of the final reinforced concrete elements. In the technological process, the transformation of concrete mixture components into a liquid non-Newtonian system with distinct rheological characteristics, followed by solidification into a structured composition, depends significantly on the variability of physico-mechanical, thermophysical, and structural-mechanical properties of both individual components and the overall mixture.

Developing comprehensive mathematical models that describe the entire technological cycle—from production to placement—poses a multifactorial challenge aimed at ensuring the design durability of construction structures. Particular emphasis is placed on modeling heat and mass transfer processes within heterogeneous concrete systems, as these non-stationary external influences critically affect the operational characteristics of the final material. Transport and hardening parameters heavily influence structural transformations within the cement stone, ultimately impacting strength and deformation properties. Effective resolution of this problem necessitates modern numerical modeling techniques that incorporate the rheological behavior of concrete mixtures and hydration kinetics.

The proposed mathematical and algorithmic framework underpins efforts to minimize concrete structure degradation by simulating rheological parameters during transportation and placement. A principal achievement is the creation of heat and mass transfer analysis algorithms that integrate predictive models with real-time monitoring data, laying a methodological foundation for future technological process control systems. The solutions further include optimization of logistical parameters under varying temperature and humidity conditions and the establishment of criteria to assess the structural homogeneity of concrete mixtures.

Keywords: heat and mass transfer, concrete mixtures, boundary conditions, rheological properties, process modeling, durability of structures, transportation control, adaptive algorithms, experimental verification, parameter optimization

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1. INTRODUCTION

Transportation of concrete mixtures is a critically important technological process that influences the physico-mechanical and operational characteristics of the constructed building structures. The transportation of concrete mixtures is accompanied by a complex of physico-chemical processes that significantly affect their rheological and structural-mechanical properties. Modern studies indicate a considerable impact of the transportation process on both the properties of concrete mixtures and the structures formed from them (SP 70.13330.2012). During the transportation of the concrete mixture, rheological transformations are observed, characterized by the following patterns: the kinetics of viscosity changes show that dynamic viscosity (η) increases nonlinearly by 15–20% during the first hour of transportation; thixotropic properties of the mixture are disrupted (thixotropy index < 0.7); progressive reduction in the mixture's workability occurs, with the mobility decrease ranging from $(5.55-13.9) \times 10^{-5}$ m/s at a temperature of $+20 \pm 2$ °C; structural changes take place, resulting in the formation of a spatially heterogeneous (anisotropic) structure of the cement paste that leads to violation of isotropy in the rheological properties throughout the volume of the mixture; density changes of the mixture manifest as the formation of defective zones in edge layers and a density decrease at the periphery by 5–7%. These structural transformations are systemic and notably affect the homogeneity of the concrete mixture [1–3]. During transportation, a complex interaction of physico-chemical phenomena occurs, including the cement hydration process, which is activated by mechanical mixing.

1.1. Physical concepts of kinetic features of the processes

The kinetics of hydration of clinker phases in Portland cement [4-7] during the transportation of the concrete mixture are determined by their reactivity, temperature conditions, and mechanical effects caused by mixing [8-9]. The compounds composing Portland cement exhibit varying hydration activities (Fig. 1).

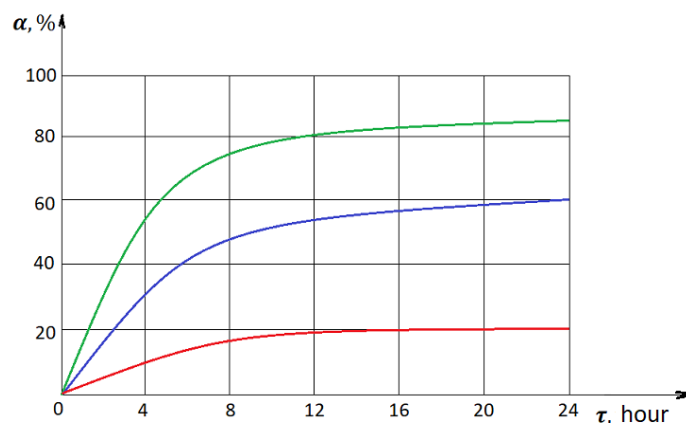


Fig. 1. Illustrates the hydration activity of the Portland cement clinker phases [10]: $\text{—}C_2S$ (belite); $\text{—}C_3S$ (alite); $\text{—}C_3A$ (aluminate).

The greatest reactive activity is exhibited by tricalcium aluminate (C_3A). Upon contact with water, C_3A rapidly undergoes hydration, forming calcium hydroaluminates. In the absence of sufficient sulfate ions (provided by gypsum), this may lead to the phenomenon of false setting. With an optimal gypsum content (3-5% by weight), ettringite forms, stabilizing the system and slowing subsequent hydration.

Alite (tricalcium silicate, C_3S) has a moderate hydration rate. During the first 1-2 hours after mixing, an induction period occurs, followed by active formation of calcium hydrosilicates. This process is accompanied by significant heat release (500-550 kJ/kg), which is especially critical at elevated ambient temperatures. Accelerated hydration of C_3S at temperatures above 30 °C can cause premature reduction in mixture workability.

Belite (dicalcium silicate, C_2S) demonstrates minimal reactivity during the early stages. Its contribution to structure formation becomes noticeable only after 7-14 days. Under transportation conditions (2-3 hours), this phase has practically no effect on the rheological characteristics of the concrete mixture.

The reactivity of tetracalcium aluminoferrite (C_4AF) is intermediate between C_3A and C_2S . Its hydration leads to calcium hydroferrite formation but does not significantly influence the mixture's rheological properties during typical transportation times.

Three key factors substantially affect clinker phase hydration kinetics: temperature (with an exponential increase in hydration rate by 2-3 times per 10 °C rise according to the Van't Hoff rule); water-cement ratio (with hydration acceleration up to $W/C = 0.5$ due to improved diffusion, beyond which effects plateau); and mixing intensity (optimal drum rotation speed of 1-2 rpm ensures necessary mixture homogenization without premature hydration activation).

Based on studies, the hydration of Portland cement (especially tricalcium silicate, C_3S) follows a five-stage kinetic model reflecting sequential phase transformations:

I – Initial stage with immediate cement-water interaction, intense heat release, and primary hydrate phase formation on clinker surfaces.

II – Induction period characterized by slowed reaction rate due to protective hydrate shell formation, supported by calorimetric data.

III – Acceleration stage caused by shell breakdown and autocatalytic process, leading to exponential hydration degree increase.

IV – Deceleration phase linked to diffusion limitations from dense hydrate matrix formation.

V – Slow reaction period dominated by topochemical interaction of residual clinker through formed hydrate layers.

This kinetic model is supported by isothermal calorimetry, thermogravimetric analysis, and electron microscopy findings, which demonstrate clear correlations between hydrate phase morphology and process rate at different stages (Fig. 2) [10-12].

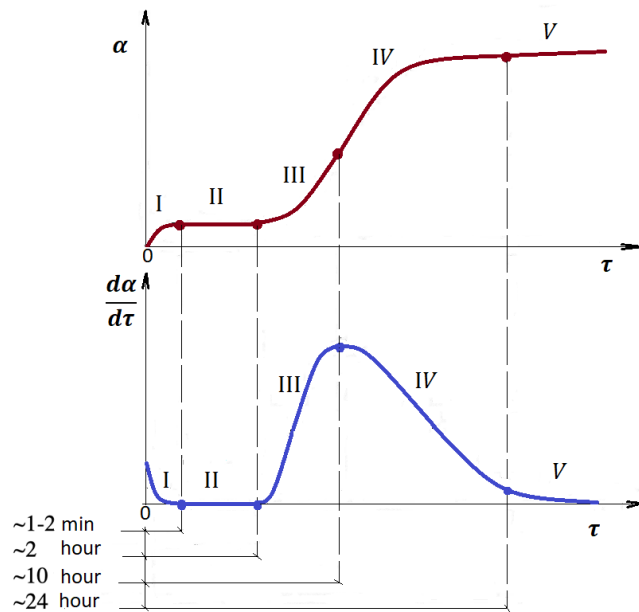


Fig. 2. Hydration periods of Portland cement [10], α – degree of conversion of the initial clinker phases during the interaction with water.

This kinetic model is supported by isothermal calorimetry, thermogravimetric analysis, and electron microscopy findings, which demonstrate clear correlations between hydrate phase morphology and process rate at different stages (Fig. 2) [10-12].

The induction period of cement hydration during transportation is characterized by the system maintaining thixotropic fluid rheological properties. During this phase, marked by a reduced rate of chemical reactions, the necessary technological pause (1.5–3 hours) is provided for transportation operations and subsequent pouring of the mixture into formwork [13-15]. The physicochemical nature of this phenomenon is due to the formation of metastable hydrate shells on the surface of clinker phases (C_3S , C_3A), which temporarily slow down the development of hydration processes while preserving the thixotropic-viscous state of the cement-water dispersion system [16-18].

Currently, there is no universal mathematical model that fully describes the kinetics of Portland cement hydration over the entire time span. Nevertheless, individual stages of the hydration process can be satisfactorily modeled using various theoretical approaches, including the classical Jander and Avrami models, as well as their modifications [19-21]. Each model demonstrates adequate approximation for specific segments of the kinetic curve, enabling a stage-by-stage analysis of hydration with regard to the particular chemical reactions occurring at different time intervals (see Table 1) [22-24].

Table 1. Key models for different hydration phases [10-12].

Stage	Period, h	Processes	Model
Initial stage (I)	First 1 – 2 h	Ion dissolution and primary nucleation	Applicability: until formation of hydrate shells $\frac{d\alpha}{dt} = k_1 \cdot S_0 \cdot (1 - \alpha)^{2/3}$
Induction period (II)	1 – 4 h	Reaction deceleration due to formation of metastable hydrate films. Feature: low reaction rate preparing for the acceleration phase	Feature: low reaction rate, preparation for the acceleration phase $\alpha(t) = \alpha_0 + k_2 \cdot \ln(t)$

The choice of the cement hydration kinetics model depends on three factors: the type of clinker phase (C_3S , C_2S , C_3A), the stage of the hydration process, and the required prediction accuracy. For active phases (C_3A , C_3S) at early stages, surface-controlled models (Avrami) are applied, while for C_2S and later stages, diffusion models (Jander) are used. Multiphase systems require combined approaches (Thomas model), accounting for chemical kinetics and mass transfer through hydrate layers. Prediction accuracy depends on the consideration of temperature effects (Arrhenius equation) and rheological changes in the system [19, 22, 25].

Setting kinetics during transportation is a complex process that requires strict control of mixing parameters and temperature regime. Modern mathematical modeling methods enable prediction of mixture behavior and optimization of logistic schemes to ensure required technological properties. Studies show that over time, concrete mixtures lose their workability non-linearly: the mixture's mobility decreases rapidly in the first minutes after preparation, then the rate of decrease gradually slows. Changes in rheological properties not only complicate placement but also promote segregation processes, which are especially critical during transportation. Upon reaching critical values, heterogeneous phase distribution occurs across the volume, forming concentration gradients. This phenomenon intensifies under prolonged mechanical influence, where vibration and cement hydration exacerbate segregation [8, 12, 26].

In a concrete mixer truck, centrifugal forces cause dense components to migrate to the periphery, while cement paste and water concentrate closer to the axis of rotation. This process is described by Stokes' law for particle sedimentation in a centrifugal field [3, 27, 28]. Structural densification of the mixture accompanies reduction in mobility and increase in viscosity, described by the Bingham model [2]. Experiments have established that at rotation speeds above 8–10 rpm, irreversible segregation begins. The optimal mixing regime is 2–6 rpm [2, 3].

A key role in maintaining mixture homogeneity belongs to the design and kinematics of the mixer's blade system. It ensures hydrodynamic mixing and uniform distribution of components through turbulent flows; compensates for centrifugal forces, preventing heavy aggregate migration; and maintains stable rheological properties by disrupting water pockets and evenly distributing moisture.

The efficiency of the blade system is described by the power dependence on blade geometry (attack angle 30–45°, profile curvature) and mixture properties. An optimal design reduces the segregation coefficient to 0.15–0.20 [2, 3, 29, 30]. Excessive mixing leads to overheating and loss of workability, while insufficient mixing results in uneven structure.

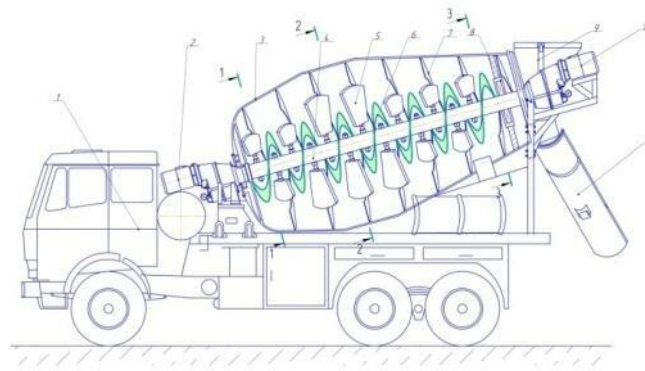


Fig. 3. Gravity-action concrete mixer truck with spiral-blade shaft: 1 – base vehicle; 2 - hydraulic drive for drum control; 3 – drum; 4 – shaft; 5 – shaft blades; 6 – spiral auger; 7 – spiral blades on the drum body; 8 – supports for the spiral-blade shaft mounting; 9 – loading hopper; 10 – hydraulic drive for the shaft with spiral blades; 11 – discharge chute [29, 30].

Disturbances in transportation regimes cause segregation of components (Fig. 3) and uneven distribution of hydrated phases, which may lead to deviation of the water-to-cement ratio from the design value [31]. The resulting heterogeneity in the mixture composition creates conditions for the formation of a defective microstructure, as evidenced by microscopic studies.

Disruptions in transportation regimes initiate a chain of structural changes leading to systemic deterioration of the operational characteristics of concrete structures [32-34]. Compensation for these effects requires a comprehensive approach at all stages—from loading the concrete mixture at the batching plant to its reception at the construction site.

1.2. Problem statement

During the transportation of concrete mixtures, which are heterogeneous multiphase systems, under the influence of variable and often extreme external factors (vibrational loads), complex nonlinear and non-stationary heat and mass transfer processes occur. The activation of these processes leads to changes in the material's rheological properties (decrease in slump values), development of mixture segregation, uneven changes in moisture (φ) and temperature (T) throughout the volume of the mixture, adversely affecting the homogeneity of the structure and the durability of the manufactured construction products and structures.

The key scientific problem lies in the lack of comprehensive and adaptive mathematical models capable of real-time forecasting of internal system states (temperature, moisture, degree of hydration, rheological properties), compensating for stochastic and deterministic disturbances Z_k , as well as implementing optimal control actions (the function $\omega(t)$ – rotational speed of the working element) given nonlinear functional relationships between input variables X_i and output characteristics Y_j of the technological process.

The objective of this work is the synthesis and practical implementation of an adaptive control system based on a comprehensive model of heat and mass transfer in concrete mixtures to minimize structural degradation during transportation. The main computational and experimental task is the optimization of the control profile $\omega(t)$ (drum rotational speed) under variable and non-stationary external influences to ensure the required operational performance in terms of homogeneity, strength, and durability of the concrete structure.

The complex of mathematical models for thermophysical, physico-chemical, and hydromechanical processes in the system under consideration should include several corresponding tasks. These include models for: hydrodynamics (beginning with Newtonian fluid behavior and evolving to Bingham plastic behavior) of the aqueous suspension of cement particles in the rotating volume of the concrete mixer drum; thermal and physico-chemical processes of hydration of cement composites in a polydisperse particle mixture.

Within this scope, the following systemic-mathematical and applied problems are formulated:

1) Formalization of non-stationary heat transfer, moisture mass transfer, and cement hydration kinetics as a system of partial differential equations with boundary conditions of the third kind (Newton) and second kind (Neumann), reflecting the physics of open systems [35, 36].

2) Integration of the Bingham rheological model to adequately describe the viscoplastic properties of the transported mixture and their evolution over time.

3) Numerical optimization of the control profile $\omega(t)$ using Sequential Quadratic Programming (SQP) with technologically justified constraints.

4) Validation of the developed model and control algorithms based on laboratory experiment results using Root Mean Square Deviation (RMSD) analyses for temperature and moisture.

5) Evaluation of control effectiveness on experimental trajectories using an integral quality criterion η , serving as a quantitative measure of the proximity of the implemented control action to the optimal one.

2. METHODS AND MATERIALS

An elementary particle of Portland cement is considered, consisting of four main clinker phases, the content of which varies depending on the cement type and technological production parameters.

In this study, the elementary particle of Portland cement CEM I 42.5 H with an average content of clinker phases, designated in section 1.1 of this article, is taken as the base model.

2.1. Physical model [37].

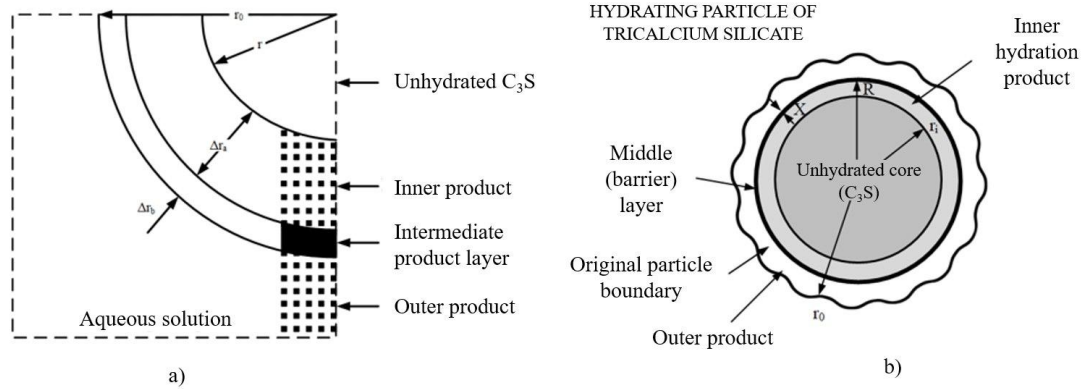


Fig. 4. Schematic of single particle models for C_3S hydration in works [19] (a) and [37] (b): r_0 – radius of the outer surface of the particle; r , r_1 – radius of its unhydrated portion; R – radius of the boundary surface between the inner and middle layers; Δr_a – thickness of the inner product layer; Δr_b or X – thickness of the middle layer (intermediate product layer).

The above analysis of physico-mathematical models of chemical kinetics in heterogeneous solid-phase reaction systems shows that currently there is no strictly defined theory describing the logistic chain of phase and chemical transformations. The lack of data in global scientific and technical literature about the atomic arrangement of elements within the matrix of Portland cement particle structure complicates and limits the possibilities of systematic analysis. However, this also opens the way for stepwise analysis and modeling of heat and mass transfer processes within a scientific framework via different mechanisms of their occurrence.

2.2. Proposed hypothesis:

- *first* postulate: it is assumed that all four main components are uniformly distributed throughout the volume of the particle according to their volumetric proportions. Accordingly, for the components, the following notation is used: C_1 – alite, C_2 – belite, C_3 – aluminate, C_4 – aluminoferrite;

- *second* postulate: it is accepted that the value τ_0 denotes the start time of the mixing process. Accordingly, the time of concrete mixture delivery to the construction site will be denoted as τ_{ET} .

3. RESULTS AND DISCUSSION

In this study, it is assumed that during the hydration process, other components of the cement particle do not participate in the reaction. The chemical interaction of aluminate with water is described by the formula:

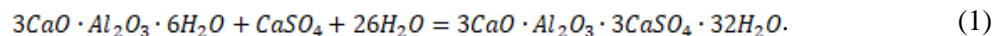


Fig. 5 schematically shows the evolution of the initial stage of cement particle hydration processes.

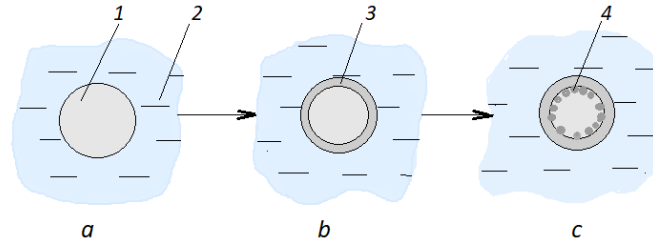


Fig. 5. Illustration of the hydration process of a single Portland cement particle: 1 – spherical particle; 2 – dissolution water; 3 – film of the hydration reaction product; 4 – nuclei of newly formed crystals.

According to the «shrinking core» theory, at the initial moments of interaction between the particle surface and the aqueous solution containing Ca^{2+} ions, a layer of reaction product forms, the quantity of which is determined by the expression:

$$h = 6 \left[1 - \left(1 - \frac{1}{3} k s_0 \tau^* \right) \right], \quad (2)$$

here: h – thickness of the hydration product film formed during the time τ^* , determined experimentally

According to the «Colloid-chemical theory of solidification», developed by academician A.A. Baikov, it is postulated that during the initial stage, there are periods: preparatory (or dissolution); colloidation (hydration).

At the colloidation stage, the liquid phase is considered as a water-cement suspension in which cement particles do not dissolve in the aqueous medium. It is assumed to be saturated with respect to the clinker minerals. Water molecules penetrate into the porous structure of the solid phase. This process is accompanied by the direct formation of reaction products in the solid state, without intermediate dissolution of the original binder.

This case is illustrated in Fig. 5b, and the kinetics of the growth of the hydration product film thickness h is determined by expression (2). The physical picture of the process changes significantly after the formation of the reaction product film. From this point, the limiting stage becomes the diffusion of Ca^{2+} ions through the product layer.

Reaction (1) corresponds to the structural scheme:



According to modern understanding of the kinetics of heterogeneous processes, the overall mass transfer process within the volume of the forming concrete mixture can be illustrated by the following stages:

- *external diffusion* (mass transfer in the liquid phase) from the solvent, which may be at rest (natural convection) or in motion, flowing around solid phase particles (forced convection);
- *internal diffusion* (mass transport in the solid phase) — penetration of the liquid reactant through the pores of the solid reaction product to the surface boundary of the chemical reaction zone;
- *chemical reaction* at the surface of the unreacted core of the particle.

Considering that phase interactions within the concrete mixer volume occur at low hydrodynamic flow velocities, the mass transfer equation in the surface layer can be written as follows:

$$\frac{\partial C_A}{\partial \tau} = \frac{\partial}{\partial x} \left[D_A \frac{\partial C_A(x, \tau)}{\partial x} \right] - u(x, \tau) \frac{\partial C_A(x, \tau)}{\partial x}, \quad (4)$$

here: $C_A(x, \tau)$ is the concentration of the defining component, which varies both with the process time τ and along the generalized coordinate normal to the particle surface x . It is also assumed that at the initial stage of hydration processes, the time intervals for external diffusion mass transfer and the formation of the first layer of reacted product are very small. In this case, it can be assumed that the size of the reaction product zone is significantly smaller than the size of the cement particle $h/R \ll 1$, where R is the particle radius. This, in turn, allows the mass transfer process at the second stage to be considered as occurring within the body of an unlimited plate-shaped geometry.

Rewrite equation (4) in the following form:

$$\frac{\partial C_A(r, \tau)}{\partial \tau} = \frac{\partial}{\partial x} \left[k(r, \tau) \frac{\partial C_A(r, \tau)}{\partial r} \right] - q_V(r, \tau), \quad (5)$$

$$q_V(x, \tau) = u(x, \tau) \frac{\partial C_A(x, \tau)}{\partial x}, \quad (6)$$

here: $C_A(x, \tau)$ is the concentration of component A in the liquid phase; $k(x, \tau)$ is the mass conductivity coefficient (internal diffusion coefficient in the solid body); $q_V(r, \tau)$ is the mass source term from the chemical reaction, in $kg/(m^3 \cdot s)$.

For the case of an unlimited plate, the boundary value problem of mass conductivity with an active mass source in nondimensional form is represented by the following system of equations:

$$\frac{\partial U(\bar{r}, Fo_m)}{\partial Fo_m} = \frac{\partial^2 U(\bar{r}, Fo_m)}{\partial \bar{r}^2} + Po_m(\bar{r}, Fo_m); Fo_m > 0; 0 \leq \bar{r} \leq 1; \quad (7)$$

$$U(\bar{r}, Fo_m)|_{Fo_m=0} = U_0(\bar{r}); \quad (8)$$

$$\left. \frac{\partial U(\bar{r}, Fo_m)}{\partial \bar{r}} \right|_{\bar{r}=0} = 0; \quad (9)$$

$$\left. \frac{\partial U(\bar{r}, Fo_m)}{\partial \bar{r}} \right|_{\bar{r}=1} = Ki_m. \quad (10)$$

here: $U(\bar{r}, Fo_m) = \frac{C_A(r, \tau) - C_{A0}}{C_{A0}}$ is the dimensionless concentration.

The dimensionless time characteristic of the diffusion-kinetic process (according to the fundamentals of mass transfer theory) is the value of the mass transfer Fourier criterion (Fo), which quantifies the similarity of unsteady mass transfer processes and is defined as:

$$Fo_m = \frac{k\tau}{(R-r_1)^2}. \quad (11)$$

External diffusion mass transfer between cement particles and mixing water is characterized by the mass transfer Kirpichev criterion (Ki), which quantifies the intensity of mass transfer relative to characteristic system parameters. It is defined as:

$$Ki_m = \frac{q_{sur}(R-r_1)}{k \cdot C_0 \cdot \rho_c}. \quad (12)$$

The dimensionless mass source term due to the chemical reaction occurring in the solid phase is:

$$Po_m(\bar{r}, Fo_m) = \frac{q_V(r, \tau)(R-r_1)^2}{k \cdot C_0 \cdot \rho_c}. \quad (13)$$

The solution to the boundary value problem (7) – (10), obtained by the Laplace integral transform method for small values of the Fourier numbers (Fo) [35], has the form:

$$U(\bar{r}, Fo_m) = Ki_m(1 \pm \bar{r})erfc\left[\frac{(1 \pm \bar{r})}{2\sqrt{Fo_m}}\right] - 2Ki_m\sqrt{\frac{Fo_m}{\pi}}\exp\left[-\frac{(1 \pm \bar{r})^2}{4Fo_m}\right] + \frac{1}{\sqrt{\pi Fo_m}}\int_0^1 U_0(\xi)\exp\left[-\frac{(1 \pm \bar{r} + \xi)^2}{4Fo_m}\right]d\xi + 2\sqrt{Fo_m}\int_0^1 Po_m(\xi)ierfc\left[\frac{(1 \pm \bar{r} + \xi)}{2\sqrt{Fo_m}}\right]d\xi \quad (14)$$

Some calculation results for the above-defined mathematical boundary problems of non-stationary mass transfer are illustrated by the data in Fig. 6 and 7.

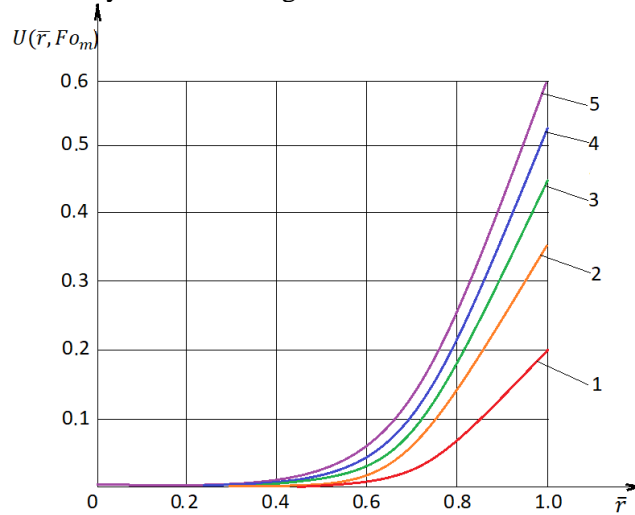


Fig. 6. Profiles of dimensionless concentrations across the thickness of the hydrated product layer: $\bar{r} = \frac{r}{R}$ (in the notation of Fig. 4); $Fo_m = 0.05$; Ki_m : 1-1; 2-3; 3-5; 4-6; 5-7.

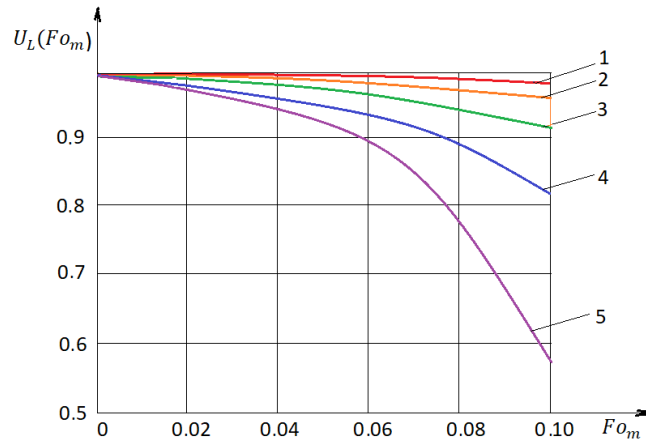


Fig. 7. Kinetic curves of the dimensionless concentration of the hydration product in the solution zone (see Fig. 4): Ki_m : 1-1; 2-3; 3-5; 4-6; 5-7.

It should be noted that according to Fig. 2, the first stage of aluminates hydration lasts 1-2 minutes. This result also allows the assumption that, in the forming layer of hydrated reaction product from r_1 to R (see Fig. 4), the concentration of reaction product components changes linearly from the value C_{sur} (at the cement particle surface) to zero (at line r_1).

Curves in Figure 6 show dimensionless concentration profiles in the reaction product layer on the surface. Interestingly, under the analyzed conditions, nearly 80% of this layer is reacted.

Data in Fig. 7 illustrate the change in concentration of the final product leaving the particle surface into the volume of the liquid phase in the solution zone.

Obviously, these curves reflect only qualitative system behavior for the specific example. For quantitative results, data on cement polydispersity and experimental mass transfer parameters are necessary.

The following figure (Fig. 8) presents data illustrating the kinetics of the average concentration change of the transported component within the reactive layer of concrete. Notably, at low intensities of external mass transfer ($Ki_m < 3$), a linear concentration distribution is observed. This indicates an approximate equality of the diffusion fluxes corresponding to both internal and external mass transfer mechanisms.

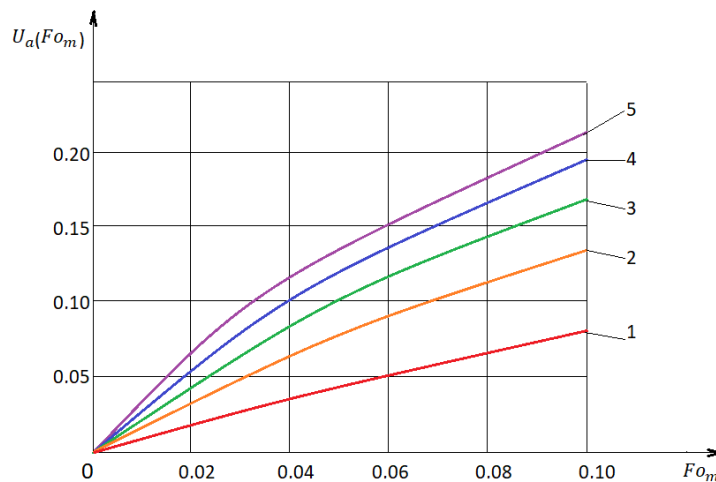


Fig. 8. Kinetics of the change in average dimensionless concentration, Ki_m : 1 – 1; 2 – 3; 3 – 5; 4 – 6; 5 – 7.

The curves in Figure 8 depict the temporal evolution of the dimensionless average integral concentration (over the volume of the reacted zone) of the target component (the subscript «a» denotes «average») as a function of the intensity of external mass transfer into the liquid phase. Notably, when comparing these data with those of Fig. 6 and 7, it is evident that intensive mass transfer between phases is characterized by a monotonic change in the average concentration values.

Fig. 9 illustrates the dynamics of mass transfer in the solid phase under the influence of internal mass sources.

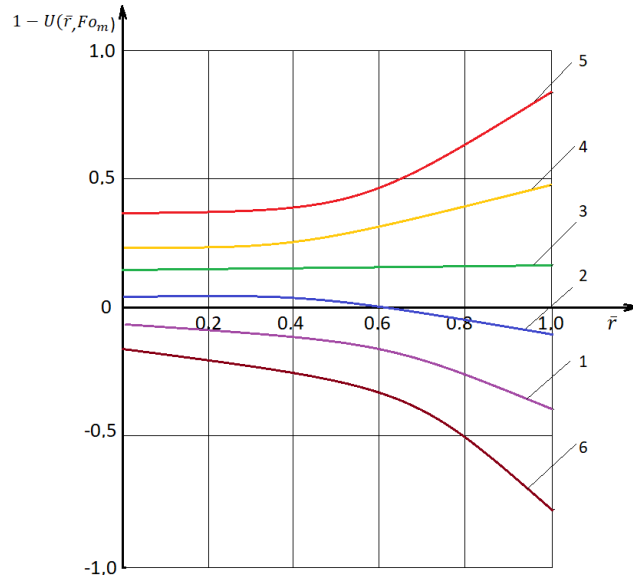


Fig. 9. Influence of the magnitude of the internal mass source (P_{o_m}) on the profiles of dimensionless concentrations: $F_{o_m} = 0.2$; $Ki_m = 1$; P_{o_m} : 1 – 0; 2 – 0.2; 3 – 1; 4 – 0.5; 5 – 2; 6 – –0.5.

The model representations, although not always precisely accounting for the actual physicochemical processes occurring within the modeled system, qualitatively capture the underlying physics of the phenomena, thereby ensuring the reliability of the mathematical simulation results. Several points merit emphasis.

First, curve 1 illustrates the «classical» results of diffusion-driven mass transfer processes in the absence of an active mass source (P_{o_m}).

Second, lines 2, 3, 4, and 5 represent the distribution of dimensionless concentrations corresponding to increasing internal volumetric mass source intensities within the concrete.

It is noteworthy that, in the example analyzed, the escalation of the internal mass source strength is not compensated by the external mass transfer into the liquid phase.

Third, curve 6 depicts conditions under which the concrete is subject to a negative volumetric mass source, reflecting the phenomenon of substance absorption within the solid phase. Evidently, this contributes to the accelerated attainment of phase equilibrium at the interface.

Finally, another intriguing aspect realizable via the approach developed herein is a common methodological paradigm in digital mathematical modeling, where the model boundary of the reaction front advances from the surface inward within the reacting cement particle.

In this framework, the reacting particle continues to be modeled as comprising two zones (an unreacted core and a chemical reaction zone), with the volumetric mass source intensity characterized by a Dirac delta function:

$$\delta(\bar{r}_{bo}, \xi) = \begin{cases} 1, & \bar{r}_{bo} \leq \xi \leq 1 \\ 0, & 0 \leq \xi \leq \bar{r}_{bo} \end{cases} \quad (15)$$

here: $\delta(\bar{r}_{bo}, \xi)$ – Dirac delta function; ξ – current dimensionless coordinate; \bar{r}_{bo} – coordinate of the zone of action (or absence thereof) of the mass source; the subscript «bo» (boundary) denotes belonging to the formal boundary separating the zones.

For the given case, the solution to the boundary mass transfer problem can be formulated in the following final form:

$$U(\bar{r}, Fo_m) = Ki_m \cdot \left[\frac{1-3\bar{r}^2}{6} - Fo_m + \frac{2}{\pi^2} \sum_{m=1}^{\infty} \frac{(-1)^m}{m^2} \cos(\pi m \bar{r}) \exp(-\pi^2 m^2 Fo_m) \right] +$$

$$Po_m [(Fo_m + 3\bar{r}^2 + 2)(1 - \bar{r}_{bo}) + \bar{r}_{bo}^2 (3 - 2\bar{r}) - 1] +$$

$$\frac{2Po_m}{\pi^3} \sum_{m=1}^{\infty} \frac{1}{m^3} \int_0^1 \sin(\pi m \bar{r}_{bo}) \cos(\pi m \bar{r}) \exp(-\pi^2 m^2 Fo_m). \quad (16)$$

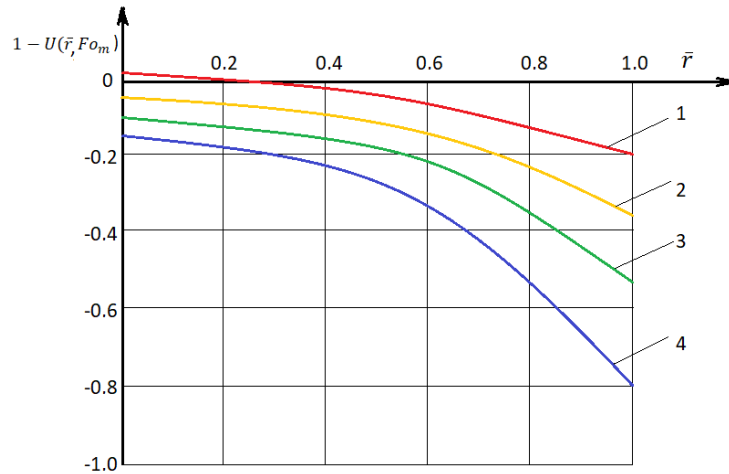


Fig. 10. Concentration profiles at various values of the Dirac delta function: 1) $Po_m = 0.5$; $\bar{r}_{gp} = 0.1$. 2) $Po_m = 0.5$; $\bar{r}_{gp} = 0.5$. 3) $Po_m = -0.5$; $\bar{r}_{gp} = 0.9$. 4) $Po_m = -0.5$; $\bar{r}_{gp} = 0.1$.

A few words about transport features: Transporting concrete mix to the construction site is a technologically regulated process including several sequential stages (Fig. 11). Initially, the prepared concrete mix, meeting design parameters (workability, strength grade, water-cement ratio), is loaded into a truck mixer equipped with a rotating drum to maintain homogeneity. Loading is done via concrete plant dispensers with mandatory quality control (sample testing, mix passport verification). Continuous mixing during transport at 2-6 rpm prevents filler sedimentation and premature setting. Delivery time is regulated by standards (SP 70.13330, GOST 7473) and generally does not exceed 90 minutes from mixing, dictated by cement hydration kinetics.

Based on the above analysis of physical, chemical, and mathematical features, the following logistic chain of «technological stages» of the studied system was obtained.

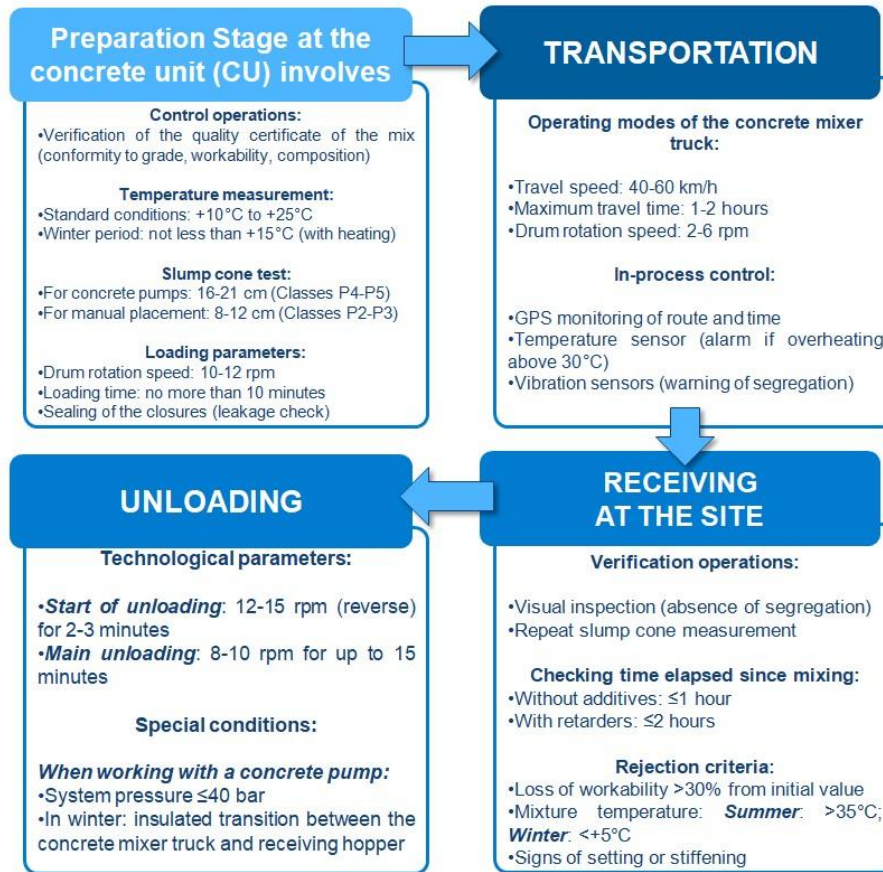


Fig. 11. Scheme of concrete mixture transportation.

Upon arrival at the construction site, the accompanying documentation is checked, and a visual assessment of the mix's workability is conducted (using slump or spread cone tests). Unloading is carried out either directly into the formwork through the concrete mixer truck chute or with the use of concrete pumps, vibration chutes, or hopper conveyors depending on the site conditions (height, accessibility, volume). A critical parameter at this stage is minimizing the time intervals between delivery and placement, as the thixotropic properties of the concrete mix deteriorate under prolonged mechanical action. After unloading, the transport unit is washed to remove residual mix, preventing hardening inside the drum and ensuring readiness for the next transport cycle.

The authors see the task of the next article in developing key aspects:

- *firstly*, the hydration process is accompanied by a significant heat effect («heat release»). This, in turn, complicates both the physical process and mathematical models of mass transfer due to the Arrhenius equation coefficients' dependence on temperature.

- *secondly*, it is known that in the early stages of hydration, passivation occurs, whereby other components' hydration stages are sequentially activated. Alite (C_3S) exhibits the first activity. According to some sources [5-7, 10-12], it reacts from the initial mixing moment, but its activity increases with time, practically beyond the transportation time to the construction site.

This heat release during hydration is critical for cement strength development. Approximately half of the total heat is released within the first 1-3 days, about 75% within a week, and over 80% within six months. The heat release depends on the cement's chemical composition and must be accounted for in physical and mathematical models. The passivation and sequential hydration of components significantly affect the kinetics and final properties of the hydrating cement.

4. CONCLUSIONS

Research shows that transportation of concrete mix is a critically important technological stage during which combined vibrational and thermal effects activate coupled nonlinear heat and mass transfer and hydration processes. There is a complex nature of degradation processes leading to systemic structural deterioration of the material. This degradation manifests as nonlinear reduction in rheological properties, particularly workability decreasing at rates up to $13.9 \cdot 10^{-5}$ m/s, development of component segregation, formation of anisotropic structure with a density gradient at the periphery up to 5-7%, as well as uneven distribution of temperature and moisture throughout the mix volume.

The analysis identified key factors that decisively influence the kinetics of the studied processes. It was established that the temperature regime is crucial: an increase of 10 °C accelerates hydration by 2-3 times according to the Van't Hoff rule, which is especially relevant during transportation under elevated temperatures. The mixing regime also plays a leading role: drum rotation speeds above 8-10 rpm provoke irreversible segregation, while maintaining an optimal range of 2-6 rpm preserves mix homogeneity. Furthermore, hydration kinetics are governed by the sequential stages from surface control to diffusion, with hydration of the C_3A phase having the most significant impact on rheological properties at the initial transportation stage.

To address these issues, a methodological framework was developed based on an adaptive control system. The core of this system is a comprehensive mathematical model integrating transient heat and mass transfer equations with third-kind boundary conditions, Bingham rheological models describing the evolution of viscoplastic properties, and kinetic models (Yandera, Avrami) for cement hydration stages.

Within the study, an optimization algorithm was proposed and validated to compensate for disturbances, based on Sequential Quadratic Programming (SQP), optimizing the drum rotation control $\omega(t)$. Model validation against experimental data confirmed its adequacy with high RMSD accuracy for temperature and humidity fields.

The practical significance lies in demonstrating that adaptive control based on this model minimizes structural heterogeneity of the concrete mix at placement, ensuring adherence to key parameters (workability, homogeneity, strength) and thereby directly enhancing the durability of concrete structures. The results lay a foundation for real-time systems for logistic control and operational management of transportation process parameters.

Further research prospects include deepening the developed model by incorporating exothermic heat release of hydration reactions, passivation modeling, simultaneous hydration of multiple clinker phases (especially C_3S), and integrating micro-level models describing microstructure evolution within the macromodel of transportation.

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