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Safety and longevity technologies of infrastructure, buildings and facilities

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Abstract

Technologies of safety and durability are designed to provide the operation of facilities for the entire period of their functioning without creating a condition dangerous to life and health of people and without harming the environment The results of theoretical and experimental studies form the basis of technologies. In the article mathematical modeling of mass transfer in the processes of corrosion of the first type that occurs in concrete, when exposed to water with low rigidity, when the constituent parts of cement stone are dissolved and washed out by water, has been conducted. The obtained expressions allow to calculate the value of the concentrations of free calcium hydroxide in the thickness of the construction at any time and its content in the liquid phase, that gives the opportunity to predict the dynamics and kinetics of processes of corrosion destruction. The results are presented in graphical form.

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Keywords: Corrosion; Cement concrete; Liquid water environment; Diffusion; Mass transfer; Security; Durability; Henry's law; Mathematical modeling.

1. Introduction

Technologies of safety and durability of infrastructure, buildings and constructions are the set of results of experimental and theoretical studies, design methods, design, constructive and technological solutions that ensure their operation during the entire period of functioning without danger to life and health of people and without harming the environment. Improving the quality and the durability of structures is one of the most important tasks of

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construction. The solution of this problem requires knowledge of the essence of processes in the operation of building structures, primarily the nature of corrosion processes.

Corrosion (lat. corrosio - erosion) is the process of destruction of the material under the action of the external environment. All materials subject to corrosion in varying degrees.

In modern industrial, civil and transport construction the main material responsible for erecting constructions and structures is concrete. The field of concrete application is very extensive: from hydroelectric dams, bearing and enclosing structures of buildings to road surfaces and railway sleepers.

Concrete and cement stone as its matrix part in operating conditions is exposed to corrosion effects of the:

- gaseous environment in the form of polluted atmosphere of ambient air;
- solid media in the form of dusts, polluting the air and deposited on the outer surfaces of the structures;
- soils containing aggressive components;
- liquid medium in the form of aggressive natural or contaminated by technical products surface water and groundwater;
- biologically active environments.

In most cases, multiphase environment affects on the constructions. For example, the air of industrial enterprises often contains suspended liquid phase in the form of fog and solid phase in the form of dust [1].

For the development of corrosion processes the impact of the aggressive environment for concrete components should be permanent, including impact on the inner layers when the boundary of corrosion is moved into the material.

Numerous processes taking place during corrosion of concrete have been classified into three main types, and the main ways of improving the corrosion resistance of concrete were identifies by Professor V.M. Moskvin, who is the founder of the science of corrosion of concrete [1].

The first group (corrosion of the I type) combines the corrosion processes that occur in the concrete under the action of the water when the constituent parts of cement stone are dissolved and washed out. These include water of circulating water supply, condensate, storm water, water of mountain and lowland rivers in flood, swamp water.

At the initial stage calcium hydroxide formed by the hydrolysis of tricalcium silicate dissolves and washed with water. This process is determined by the diffusion of calcium hydroxide from the thickness of concrete to its surface bordering with the environment, by the transition of a substance through the phase boundary solid - liquid and by the dissolution in the liquid medium. After washout of the free calcium hydroxide decomposition of calcium hydrosilicates, and then of calcium hydroaluminates and of calcium ferrite hydrate, begins, that leading to the development of corrosion of other types.

The second group (corrosion of the II type) combines the processes of corrosion developing in the concrete under the action of waters containing chemicals that come in exchange reactions with components of the cement stone (acids and certain salts). The reaction products at the same time or easily dissolved and washed out by water, or in the form of an amorphous mass deposit in the pores and capillaries of the cement stone, acting as inhibitor of corrosion damage at the initial stage.

The third group (corrosion of the III type) combines the processes of corrosion, with the development of which the accumulation of soluble salts occurs in the concrete microplate, and crystallization of these salts causes significant tensile stresses and subsequent destruction.

Crystallization of salts and other secondary processes, developing in the concrete, create internal stress, resulting in failure of the concrete structure. Salts are formed by chemical reactions of the interactions of aggressive environment with the constituent parts of the material, or are brought from outside and are extracted from the solution by the slow evaporation of water from it.

For the all types of corrosion the rate of destruction is determined mainly by the regularities of mass transfer processes in solid and liquid phases and on the phase boundaries.

The three main types of corrosion, based on the principle of dominating factors, allow to set the overall patterns for each type. This, in turn, facilitates the correct choice of actions necessary to prevent corrosion of the concrete and ensure its durability.

One of the areas in the field of study of the problem of durability of concrete is the study of regularities of corrosion processes both in experimental and in theoretical plans.

At present time, a large number of mathematical models of processes of corrosion of concrete, allowing with the required accuracy to calculate the durability of concrete and reinforced concrete structures are offered by the domestic and foreign researchers.

From the point of view of the theory of chemical processes main "events" occur in diffusion-kinetic area. In these circumstances, the development of mathematical models of processes of corrosion of concrete is based on physical models of diffusion of transmitted components in the porous structure of concrete and on mathematical apparatus of boundary value problems of mass transfer using the differential equations of partial derivatives of parabolic type.

Subject of consideration of authors is liquid corrosion which is possible on hydrotechnical objects (dams, weirs, bridge pillars, tanks), in particular in the conditions of permafrost. It is noted that the piles, on the which the objects in the North are constructed, during warming periods are exposed to intensive influence of groundwater with a high content of aggressive components. The process becomes complicated, and the corrosion rate increases at filtration through the thickness of the concrete. But even for cases of lack of a filtration (cooling towers, reservoirs), the problem remains extremely important [2].

Below mathematical model of processes of diffusion of calcium hydroxide at the corrosion of the I type in the system of reinforced concrete tank - liquid is given.

Mathematically, the mass transfer of calcium hydroxide in a wall of concrete structures is defined by the boundary value problem of form:

$$\frac{\partial C(x,\tau)}{\partial \tau} = k \cdot \frac{\partial^2 C(x,\tau)}{\partial x^2}, \tau > 0, \ 0 \le x \le \delta . \tag{1}$$

Initial condition: $C(x,\tau)\big|_{\tau=0} = C(x,0) = C_0 .$ (2)

Boundary conditions: $\frac{\partial C(0,\tau)}{\partial x} = 0 ;$ (3)

$$k \cdot \frac{\partial C(\delta,\tau)}{\partial x} = \beta\left[C_p(\tau) - C(\delta,\tau)\right], \tag{4}$$

where $C(x,\tau)$ is the concentration of free $Ca(OH)_2$ in concrete at time τ in any point with coordinate x, in terms of CaO, kg CaO/kg of concrete; C_0 is the concentration of free $Ca(OH)_2$ in concrete at the initial moment of time in any point with coordinate x, in terms of CaO, kg CaO/kg of concrete; $C_p(\tau)$ - equilibrium concentration on the surface of the solid, kg CaO/kg of concrete; k - coefficient of mass conductivity in the solid phase, m^2/s; δ - the thickness of the wall of the structure, m; x - coordinate, m; τ - time, s; β - coefficient of mass delivery in the liquid medium, m/s.

According to the weight conservation law, the mass flow of the substance leaving from the concrete surface should be equal to the amount of substance arriving in the liquid phase:

$$-S \cdot \rho_б \cdot k \cdot \frac{\partial C(\delta,\tau)}{\partial x} = V_{ж} \cdot \rho_{ж} \cdot \frac{\partial C_{ж}(\tau)}{\partial \tau}, \tag{5}$$

where the left part is the amount of the transferable component through an internal surface of the tank S, m^2; the right part is the increment of the mass of the component in volume $V_ж$ резервуара, $м^3$; $\rho_б$, $\rho_ж$ are densities of concrete and liquid, respectively, kg/m^3. The sign "minus" indicates a decrease in the concentration of a component in concrete.

The equation (1) is a classic record of the parabolic differential equation of mass conductivity (diffusion in solids). The expression (2) is the initial condition of the problem, showing that in the initial moment of interaction between the liquid and concrete, for example the beginning of filling of the tank, the concentration of free calcium hydroxide on the thickness of a concrete structure is uniform. The boundary condition (3) relates to external border of the construction and is called as the condition of impenetrability, showing that the transferable component doesn't leave through an external surface of concrete. The boundary condition (4) characterizes the condition of mass transfer through the boundary of phases solid - liquid. From within to a body surface the target component is transferred by mass conductivity, and from border it is transferred to liquid by mass delivery, by natural convection in a liquid phase. The differential equation (5) represents the material balance of the transferable component, as its left part reflects the value of density of a stream of mass of the substance coming from the inner layers of concrete to the interphase boundary, and the right part shows the number of substances coming as a result of mass transfer in the liquid volume.

A distinctive feature of the mathematical model (1) - (4) is not the constancy of the value of the equilibrium concentration on a surface of the solid C_p, and its dependence on the concentration of the component in the liquid phase of the $C_{ж}$. The simplest form of this dependence is the Henry's law:

$$C_p(\tau) = mC_{жс}(\tau), \tag{6}$$

where m is the Henry's law constant, kg liquid /kg of concrete.

The equation (6) characterizes an isotherm of adsorption (desorption) of substance at low concentrations (fig. 1). According to it the Henry's law is formulated as follows: the amount of adsorption at low concentrations of substance in solution is directly proportional to concentration. At adsorption (desorption) on solid adsorbents the scope of the Henry's law is small due to the heterogeneity of a surface. In figure 1, curve 1 shows the real curve of equilibrium for a system concrete - water, line 2 illustrates Henry's law. Zone I is the area of validity of Henry's law (the area of low concentrations); zone II is the area where Henry's law is no longer valid. The straight line 3 approximates the behavior of the equilibrium line in zone II.

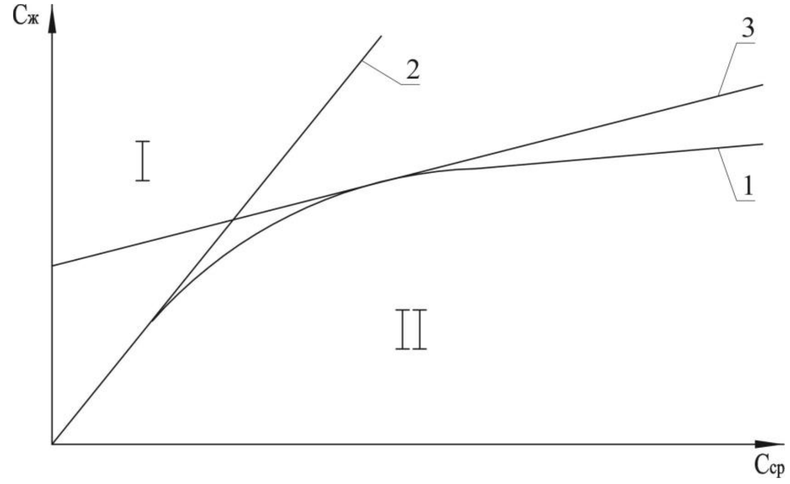

Fig. 1. Equilibrium in the system concrete - water: 1 - desorption curve; 2 - straight line illustrating Hooke's law; 3 - approximation of the equilibrium line in zone II.

It is obvious that in the closed system, than more long there is a process, and liquid is more and more sated with a transferable component, intensity of a mass transfer more and more decreases, and divergences between lines more and more grows. Therefore, the error of the calculations based on the Henry's law will increase.

For the first time the idea about possibility of joint consideration of a mass transfer in the closed system solid - liquid was stated at research of processes of adsorption by professor of the Ivanovo Institute of Chemistry and Technology K.N. Belonogov in the sixties of the last century and with his consent was published by professor of the Lvov Polytechnical Institute L.S. Akselrud in the monograph [3].

To facilitate understanding of the solution we will use the criteria of similarity and will introduce dimensionless variables of the form:

$$Z(\bar{x},Fo_m)=\frac{C_0-C(x,\tau)}{C_0},\ \bar{x}=\frac{x}{\delta},\ Fo_m=\frac{k\cdot\tau}{\delta^2},\ Bi_m=\frac{\beta\cdot\delta}{k},\ Z_{жс}(Fo_m)=\frac{C_0-mC_{жс}(\tau)}{C_0}. \tag{7}$$

We will denote also: $K_m=\frac{m\cdot S\cdot\delta}{V_{жс}}\cdot\frac{\rho_б}{\rho_{жс}}=\frac{m\cdot G_б}{G_{жс}}$. (8)

where K_m is a coefficient considering the characteristics of the phases; $G_б$ is the mass of the concrete tank, kg; $G_{жс}$ is the mass of liquid in the tank, kg.

Then the boundary value problem of mass conductivity in a dimensionless form can be represented by the following system of equations:

$$\frac{\partial Z(\bar{x},Fo_m)}{\partial Fo_m}=\frac{\partial^2 Z(\bar{x},Fo_m)}{\partial\bar{x}^2},\ Fo_m>0,\ 0\le\bar{x}\le 1. \tag{9}$$

Initial condition: $Z(\bar{x},0)=0$. (10)

Boundary conditions: $\frac{\partial Z(0,Fo_m)}{\partial\bar{x}}=0$; (11)

$$\frac{1}{Bi_m}\cdot\frac{\partial Z(1,Fo_m)}{\partial\bar{x}}=\left[Z_p(Fo_m)-Z(1,Fo_m)\right]. \tag{12}$$

In the equation (12) $Z_p(Fo_m)$ is the same as that $Z_{жс}(Fo_m)$.

Then the condition of the mass transfer of concrete and liquid will finally takes the form:

$$-\frac{\partial Z_{жс}(Fo_m)}{\partial Fo_m}=K_m\cdot\frac{\partial Z(1,Fo_m)}{\partial\bar{x}}. \tag{13}$$

In this case the initial condition (2) changes to uneven distributed:

$$C(x,\tau)\big|_{\tau=0}=C_0(x), \tag{14}$$

or in dimensionless form:

$$Z_0(\bar{x})=\frac{C_0-C(x)}{C_0}. \tag{15}$$

The solution of the system was performed by the method of integral transformation of, i.e., the initial system of equations was displayed in area of complex numbers, in which the solution of the system was obtained, and then a decision transfer in area of originals was made.

When solving the system of equations (9) - (12) for small numbers of Fourier, the expressions allowing to calculate the profile of the dimensionless concentration of the transferable component on the thickness of the concrete at any time point (16) and the concentration of the transferred component in a liquid phase (17) in the initial stages of the corrosion process of the first type [4] are received:

$$\frac{Z(\bar{x},Fo_m)}{Z_{жс}(0)}=-\frac{Bi_m}{\sqrt{Bi_m^2-4K_m}}\sum_{i=1}^{2}(-1)^i\exp\left[-a_i(1-\bar{x})+a_i^2 Fo_m\right]\times erfc\left(\frac{1-\bar{x}}{2\sqrt{Fo_m}}-a_i\sqrt{Fo_m}\right). \tag{16}$$

$$\frac{Z_{ж c}(Fo_m)}{Z_{ж c}(0)} = 1 - \frac{K_m Bi_m}{\sqrt{Bi_m^2 - 4K_m Bi_m}} \sum_{i=1}^{2} (-1)^{i+1} \left\{ 2\sqrt{\frac{Fo_m}{\pi}} + a_i \int_0^{F_{0m}} \exp(a_i^2 Fo_m) \times erfc(-a_i \sqrt{Fo_m}) dFo_m \right\}. \qquad (17)$$

when $a_i = \frac{-Bi_m \pm \sqrt{D}}{2}$, i=1, 2.

The obtained solutions allow to determine the value of the concentration of the transferable component (free calcium hydroxide) in thickness of construction in the initial periods of corrosion destruction of cement concrete and, besides, allow to calculate the content of this substance in the liquid phase and an average value on thickness and volume of the structure, i.e. allow to calculate the kinetics of the process for solid and liquid phases.

Theoretical calculations for the presented mathematical model are shown by the authors in previous publications [5-8].

Some results of calculations for the obtained expressions are given in figures 2 and 3. Figure 2 illustrates data of calculations of profiles of dimensionless concentration depending on mass transfer criterion Bi_m (Bio). The analysis of profiles of concentration on the thickness of concrete at Fo_m=0,05 shows that the main contribution of the mass transfer process is concentrated in the surface layer at the interface solid - liquid. At increase in mass-exchanged criterion of Bio there are big gradients of concentration. The increase in Bi_m by 5 times causes growth of the concentration gradient in 2.5÷3 times.

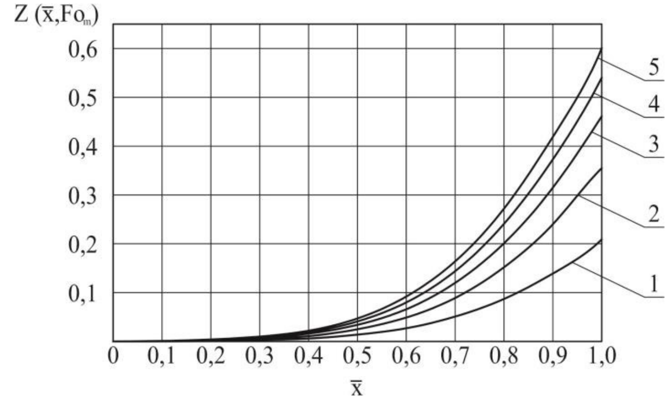

Fig.2. Profiles of dimensionless concentrations on the thickness of the concrete when Fo_m=0,05 with different values of Bi_m: 1-1; 2-2; 3-3; 4-4; 5-5.

Figure 3 shows the kinetic curves of accumulation of the substance in the liquid corresponding to this case.

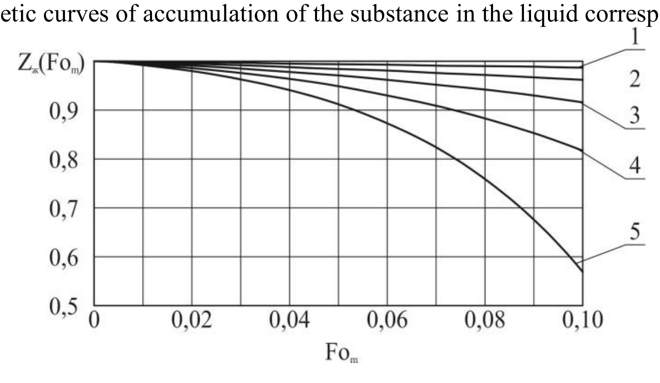

Fig. 3. The kinetics of changes of concentration of the transferable component in phase at the following values of Bi_m: 1-1; 2-2; 3-3; 4-4; 5-5.

The unconditional positive moment of the obtained dependences is the possibility of the solution of the return task, when the available experimental data will allow to predict the numerical value of free calcium hydroxide by means of this model that finally allows to predict durability and reliability of infrastructure, buildings and constructions with the minimum error.

Further results of practical application of the solution of this task at inspection of reinforced concrete structures of the fire tank are given.

As a result of inspection damages of corrosion character were revealed: condensate smudges with signs of leaching of a cement stone (wall saltpeter), lack of a protective layer of concrete and corrosion of reinforcement.

The only condition for extending the service life of the reservoir is creation of an effective protective layer of concrete. For a practical evaluation of service life of the protective layer calculations for the developed mathematical model were executed.

In calculations the following thickness of a protective layer δ were accepted by mm: 30, 45, 60, 80 и 90.

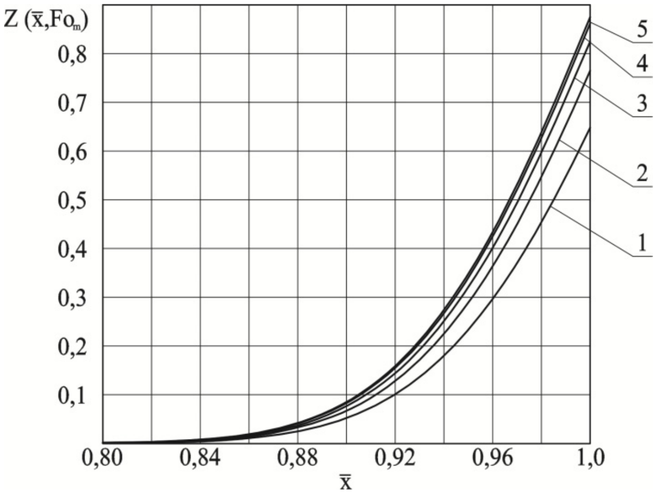

Fig. 4. Profiles of the dimensionless concentrations in the protective layer of concrete with thickness, mm: 1-30; 2-45; 3-60; 4-80; 5-90.

According to the results of the carried-out calculations (Fig. 4-5)) the concentration of calcium hydroxide on the surface of the protective layer will reach the value corresponding to the beginning of decomposition of high-basic components of concrete at mass transfer criteria Fo_m is equal to: 0,0495; 0,0192; 0,0808; 0,0709 и 0,0042.

The time values correspond to the calculated values of mass transfer criterion of the Fourier: Fo_m=0.0495 - 12 years; Fo_m=0.0192 - 7.7 years; Fo_m=0.0808 - 4.5 years; Fo_m=0.0709 - 5 years; Fo_m=0.0042 - 3.5 years.

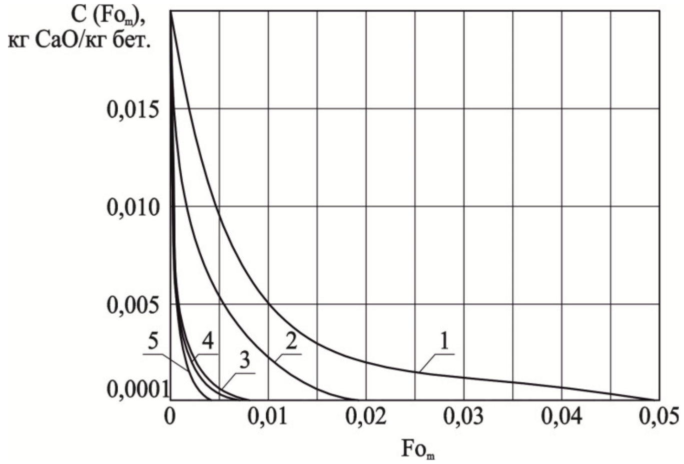

Fig. 5. The change of the concentration of calcium hydroxide on the surface of the protective layer with thickness, mm: 1-30; 2-45; 3-60; 4-80; 5-90.

The analysis of calculation results allows to draw the following conclusions. The durability of the protective layer with thickness of 50÷100 mm (not more than 7.7 years) is insufficient to ensure the reserve maintenance period of service of the reservoir, which is equal to 10 years according to the requirements of the operational organization. On the other hand, the period of protective action in 12 years is provided at a coating thickness of 30 mm. It should be noted that during this period there would be no need to renew or repair the protective layer.

Application of the developed mathematical model during the survey of building structures of the tank allowed economically proved to appoint means of protection from corrosion and to establish the optimal timing of repair work.

References

[1] V. M. Moskvin, Corrosion of concrete. M.: Stroiizdat, 1952. 342 p.

[2] S. V. Fedosov, V. E. Roumyantseva, N. L. Fedosova, V. L. Smeltsov, Modeling of mass transfer in processes liquid corrosion of concrete of the first type // Building materials. 2005. №7. pp. 60-62.

[3] G. A. Akselrud, V. M. Lisianski, Extraction (system solid - liquid), M.: Chemistry, 1974. 256 p.

[4] S. V. Fedosov, V. E. Roumyantseva, V. A. Khrunov, L. N. Aksakovskaya, Modeling of a mass transfer in the processes of corrosion of concretes of the first type (small values of the Fourier number) // Building materials. 2007. №5. pp. 70-71.

[5] S. V. Fedosov, V. E. Roumyantseva, V. A. Khrunov, N. S. Kasyanenko, V. L. Smeltsov, Prediction of durability of building structures from position of numerical and experimental studies of the processes of corrosion of concrete // Bulletin of the Volgograd SUAC, the series of "Construction and architecture", the section "Construction materials and products". 2009. №14 (33). pp. 117-122.

[6] S. V. Fedosov, V. E. Roumyantseva, V. A. Khrunov, M. E. Shesterkin, Issues of prediction of durability of building constructions // Construction and reconstruction. 2011. №5 (37). pp. 63-69.

[7] S. V. Fedosov, V. E. Roumyantseva, N. S. Kasyanenko, V. A. Khrunov, Mass transfer in the system "concrete - aggressive liquid phase", complicated by chemical reaction at the interface // Bulletin of the Department of construction Sciences. №15. Orel-Moscow-Kursk, 2011. pp. 216-219.

[8] R. A. Kayumov, S. V. Fedosov, V. E. Roumyantseva, V. A. Khrunov, Yu. V. Manokhina, I. V. Krasilnikov, Mathematical modeling of corrosion mass transfer of heterogeneous systems "liquid corrosive environment - cement concrete". Special cases of the solution // Proceedings of the KSUAC. 2013. №4 (26). pp. 343-348.