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Forecast of the Durability of Shore Structures Made of Reinforced Concrete

S.V. Fedosov[1,2,3,a], B.I. Bulgakov[1,b*], I.V. Krasilnikov[2,4,c], Ngo Xuan Hung[1,5,d], Tang Van Lam[5,e]

[1]Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, 129337, Russia

[2]Scientific Research Institute of Construction Physics of the RAASN, Locomotive Passage, 21, Moscow, 127238, Russia

[3]Volga State University of Technology, Lenin Square, 3, Yoshkar-Ola, 424000, Russia

[4]Ivanovo State Polytecnical University, Sheremetevsky Prospect, 21, Ivanovo, 153000, Russia

[5]Hanoi University of Mining and Geology, 18 Pho Vien, Duc Thang, Bac Tu Liem, Ha Noi, Vietnam

[a]fedosov-academic53@mail.ru, [b]*BulgakovBI@mgsu.ru, [c]korasb@mail.com,
[d]xuanhung1610@gmail.com, [e]lamvantang@gmail.com

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Abstract. This paper considers the basic methods of physical-mathematical modeling that are used to describe the processes of non-stationary mass transfer of "free calcium hydroxide" in concrete structures placed in a liquid environment with a defined flow rate. The boundary value problem of "free calcium hydroxide" mass conductivity in dimensionless variables is obtained. To demonstrate the possibilities of the obtained solution, we will carry out a numerical experiment: in which the fluctuation in the field of dimensionless concentrations $C(\bar{x},Fo_m)$ by the different values of the Fourier number, in accordance with the theory of similarity, will be considered as an indicator of the process time. The study indicated the results of calculating the concentration distributions "free calcium hydroxide" over the dimensionless thickness of the concrete structure at Fourier numbers 0.01; 0.1; 0.2; 0.5 and 1. The study also provides an example of determining the time of reaching the coastal structure surface critical concentration "of free calcium hydroxide" leading to the beginning of high-basic cement concrete. Analysis of the solution also makes it possible to determine the duration of the service life of a reinforced concrete structure, which is determined by the processes occurring at the interface: in concrete - mass conductivity (k), and in the liquid phase - mass transfer (β).

1 Introduction

For countries having border territories along the line of marine (oceanic) waters, the design, construction and operation of structures that have contact with coastal waters are major problems [1,2]. The results of the previous studies [3,4] shown that sea water contains aggressive components which are ions of various elements. The ionic composition of seawater is presented in Table 1.

Table 1. Ionic composition of seawater at salinity 35 %

Cations	mg/l	Equivalent, %	Anions	mg/l	Equivalent, %
Na^+	10760	38.64	Cl^-	19353	45.06
Mg^{2+}	1296	8.81	SO_4^{2-}	2712	4.66
Ca^{2+}	412	1.69	HCO^{3-}	141	0.20
K^+	399	0.84	Br^-	67	0.07
Sr^{2+}	8	0.01			
Total:	12875	49.99	Total:	22273	49.99

In turn, hydraulic structures, the structures of which are washed by coastal waters, are usually made of reinforced concrete [5–8]. At the same time, the task of designers and builders is to find materials and technologies that provide a given service life of the structure and the possibility of organizing repair work.

The destruction of reinforced concrete structures occurs due to corrosion processes caused by diffusion (mass transfer) between the concrete components and the ions of aggressive components of the liquid phase [9–12].

According to the generally accepted international classification proposed by Professor Moskvin V.M. [13–15], the simplest form of the development of corrosion processes in concrete is leaching. At the same time, the aggressive component does not penetrate deeply into the material of the reinforced concrete structure. The rate of the process is determined by the diffusion of calcium hydroxide from the pores of the inner layers of the structure to the outer interface between the phases “solid phase - liquid”, and then by mass transfer from the interface into the bulk of the liquid.

Thus, the objective of this study is to predict the concrete corrosion in coastal structures by using the solutions to the inverse problem of non-stationary mass transfer.

2 Methods

It is unfeasible to develop mathematical models if there is no deep knowledge of the processes mechanism, experimental data illustrating the impacts of diverse factors on the kinetics and dynamics of processes and test the theory under practical conditions [16,17].

From the viewpoints of the mass transfer theory, it is realistic to find out the solutions to these complicated issues. The principles of mass transfer can be applied to any natural phenomena. They facilitate the design of building structures meeting the operational requirements, make material selection optimal, and enable evaluation of the structures’ state. There is no doubt that the study of mass transfer processes occurring during corrosion failure is an urgent task at present, scientifically and practically [18,19].

The theoretical basis for carrying out research in this direction is the theory of heat and mass transfer and its mathematical logic expressions are represented as a system of partial differential equations describing the phenomena of heat, mass and pressure transfer in solids under various kinds of boundary conditions. Characteristics of the substance transfer on the interface between the solid and the gas (or liquid) surrounding are indicated in the studies of academician A.V. Lykov [20,21].

3 Results

In this case, it is assumed that the target component, which is "free calcium hydroxide" in the processes of cement concrete corrosion, is removed from the surface of the reinforced concrete product by a liquid medium as a result of convective mass transfer [22,23]. If the medium is stationary (for example, in a tank), then the mass transfer will be characterized by natural convection, and if the surface of the structure cools down at a certain speed of fluid movement (for example, in cooling towers when the heat exchangers of power plants are cooled), then there will be a forced fluid flow [24,25]. In both cases, the mass transfer of the target component will be determined by two processes: mass transfer from the inner layers to the interface and mass transfer from the inter-face to the liquid phase [26].

4 The model of the problem of mass transfer with initial and boundary conditions for an unbounded plate concrete (reinforced concrete) can be schematically illustrated in Fig. 1.

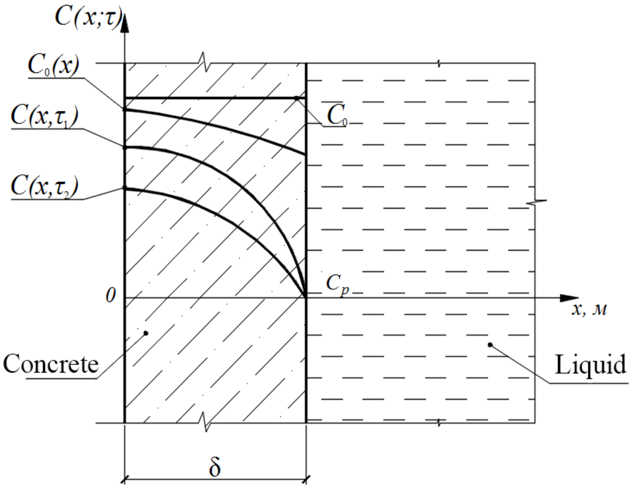

Fig. 1. On the physical and mathematical formulation of the problem

The problem of mass transfer of calcium hydroxide from a concrete structure into an aqueous substance can be formulated by the following system of equations:

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

$$C(x,0) = C_0; \tag{2}$$

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

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

Where:

C_0 is the initial concentration of free calcium hydroxide in concrete, in terms of calcium oxide, kg CaO/kg concrete;

$C(x,\tau)$ is the concentration of free calcium hydroxide in concrete at the moment τ at any point with the coordinate x, in terms of calcium oxide, kg CaO/kg concrete;

k is coefficient of mass conductivity in the solid phase (diffusion), m^2/s;

β is mass transfer coefficient in a liquid medium, m/s;

C_p is the equilibrium concentration of the transferred component on the surface of a solid; kg CaO/kg concrete;

δ is wall thickness of the structure, m.

The Eq. (1) is the differential equation of non-stationary mass transfer in the body of a reinforced concrete structure.

The Eq. (2) defines the initial condition of the process: the distribution of calcium hydroxide concentrations at the time instant taken as the initial one. The third and fourth expressions define the conditions at the interface.

The Eq. (3), also called the "non-penetration condition", determines the fact that calcium hydroxide does not diffuse into the liquid medium from the concrete mass.

The Eq. (4) characterizes the interaction of the surface layer of the structure with a liquid medium. This is a condition of the third kind, also called "Newton's condition".

The use of dimensionless variables allows you to go to the following formulas:

$$C(\bar{x}, Fo_m) = \frac{C(x,\tau) - C_p}{C_0 - C_p},\ \bar{x} = \frac{x}{\delta},\ Fo_m = \frac{k\tau}{\delta^2},\ Bi_m = \frac{\beta\delta}{k}. \tag{5}$$

Where:

$C(\bar{x}, Fo_m)$ is dimensionless concentration of the transferred component across the concrete thickness;

$\bar{x}$ is dimensionless coordinate;

Fo_m is Fourier mass transfer criterion;

Bi_m is Bio mass transfer criterion.

In this case, the system of Eqs. (1), (2), (3) and (4), also called the "boundary value problem of non-stationary mass transfer", is transformed to the from:

$$\frac{\partial C(\bar{x}, Fo_m)}{\partial Fo_m} = \frac{\partial^2 C(\bar{x}, Fo_m)}{\partial \bar{x}^2}, \ Fo_m > 0, \ 0 \le \bar{x} \le 1. \tag{6}$$

$$C(\bar{x}, 0) = 1. \tag{7}$$

$$\frac{\partial C(0, Fo_m)}{\partial \bar{x}} = 0, \tag{8}$$

$$\frac{\partial C(1, Fo_m)}{\partial \bar{x}} = -Bi_m C(1, Fo_m). \tag{9}$$

The purpose of solving this boundary value problem is to find a function $C(\bar{x}, Fo_m)$ that allows one to calculate the concentration profiles of the transferred component over the thickness of the structure, which also change over time. This is the so-called “direct problem of the dynamics of the mass transfer process” [27]. The solution to the abovementioned problems is indicated in the [26,28].

$$C(\bar{x}, Fo_m) = 2Bi_m \sum_{m=1}^{\infty} \frac{\cos(\mu_m \bar{x}).\exp(-\mu_m^2 Fo_m)}{\mu_m \left[\sin(\mu_m)(1+Bi_m) + \mu_m.\cos(\mu_m)\right]}. \tag{10}$$

Where μ_m is roots of the characteristic equation:

$$tg(\mu_m) = \frac{Bi_m}{\mu_m}, \text{ or } ctg(\mu_m) = \frac{\mu_m}{Bi_m}. \tag{11}$$

The calculation of the concentration fields of the transferred component according to the Eq. (10) is accompanied by the search for the roots of the characteristic Eq. (11). The scheme for determining the roots of the characteristic equation is shown in Fig. 2.

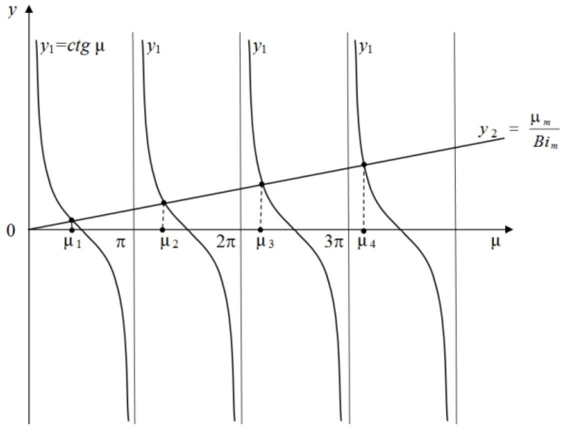

Fig. 2. Scheme for determining the roots of the characteristic Eq. (11)

Some results of calculations by Eq. (10) are shown in Fig. 3.

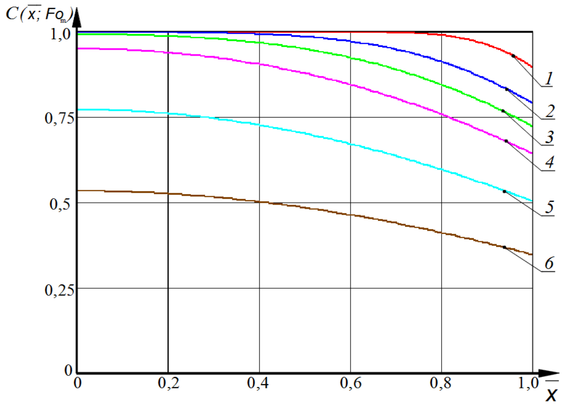

Fig. 3. The profiles of dimensionless concentrations $C(\overline{x}, Fo_m)$ over the thickness of the concrete structure at Fourier numbers: $Bi_m = 1$, Fo_m= 1 – 0.01; 2 – 0.05; 3 – 0.1; 4 – 0.2; 5 – 0.5; 6 - 1

5 Discussion

To solve the problem of protecting a reinforced concrete structure from the aggressive effects of the marine environment, it is necessary to use the obtained expression to solve the “inverse problem of non-stationary mass transfer” in order to find conditions under which the processes of mass transfer would be carried out with a minimum leaching rate. It is possible to control this process by influencing the structure of the concrete in the structure. Obviously, the time parameter is the Fourier mass transfer criterion: $Fo_m = \frac{k\tau}{\delta^2}$. It is also obvious that the time τ is included in the exponential function, which is a factor in each term of the Fourier series. Therefore, the solution of the “inverse mass transfer problem” is possible only with the use of the iteration method [28,29].

The methodology for solving the inverse problem of mass conductivity involves the following steps:

1. Selecting the time step $\Delta\tau$ and assigning the symbol τ_1 to it.
2. Determining of the first value of the Fourier mass transfer number:

$$Fo_{m1} = \frac{k\tau_1}{\delta^2}. \tag{12}$$

3. Determination of the value of the dimensionless concentration at the solid-liquid interface: $C(1, Fo_1) = C(1)$ according to the Eq. (10).
4. Comparison of the calculated value C(1) with the critical value of C_{cr}, at which the decomposition of the main components of concrete begins, leading to the loss of its mechanical strength.
5. Under the condition $C(1) – C_{cr} > \varepsilon$, where ε is the specified error of the calculation result, the values of time and the Fourier number are recalculated:

$$\tau_2 = \tau_1 + \Delta\tau, \tag{13}$$

$$Fo_{m2} = \frac{k\tau_2}{\delta^2}. \tag{14}$$

6. Then the sequence of actions is repeated according to points 3-5 until the specified value of the error ε is reached.

As an illustration, a specific example of the calculation is given below, with the following initial data:

a) the thickness of the structure of the hydraulic structure: $\delta = 0.3$ m;

b) the coefficient of mass conductivity of calcium hydroxide in concrete can be taken equal to 5.10^{-10} m^2/s [16];

c) the dimensionless concentration C_{cr}, at which the critical value at the interface is reached, is 0.35.

Calculations using the proposed method in the Eq. (10) show that this critical value is achieved when the value of the Fourier mass transfer number is equal to one unit (curve 6 in Fig. 3). Based on the accepted designations, the time calculation will be made according to the Eq. (15):

$$\tau_{кр} = \frac{\delta^2 Fo_{m,кр}}{k} = \frac{0.3^2 x1}{5x10^{-10}} = 1.8x10^8 \text{ (s)} = 2083 \text{ (d)} = 5.7 \text{ (y)}. \qquad (15)$$

6 Conclusions

Analysis of the solution also makes it possible to determine the duration of the service life of a reinforced concrete structure, which is determined by the processes occurring at the interface: in concrete - mass conductivity (k), and in the liquid phase - mass transfer (β). The first depends on the structural and mechanical characteristics of the reinforced concrete structure; the second - on the conditions of interaction at the phase boundary. All of these determine the directions of scientific research of researchers.

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