Magazine of Civil Engineering. 2020. 99(7). Article No. 9906

Magazine of Civil Engineering

ISSN 2712-8172

journal homepage: http://engstroy.spbstu.ru/

DOI: 10.18720/MCE.99.6

Mathematical model of concrete biological corrosion

S.V. Fedosov*[a], *S.A. Loginova**[b]
[a] *National Research Moscow State Civil Engineering University, Moscow, Russia*
[b] *Ivanovo State Polytechnic University, Ivanovo, Ivanovo Region, Russia*
** E-mail: sl79066171227@yandex.ru*

Keywords: cement, concrete, bio-corrosion, mathematical model, mass transfer, calcium hydroxide, microorganisms, biofilm.

Abstract. As objects for study samples of cement concrete exposed to biological growth-around have been used. A physical and mathematical model of diffusion processes in system "cement concrete-biofilm-liquid", taking into account the kinetics of the processes of growth, reproduction and death of microorganisms, has been developed. The model of mass transfer in an unlimited two-layer plate in the form of a system of partial differential equations of parabolic type with boundary conditions of the second kind at the boundary of concrete with liquid and the fourth kind at the boundary between concrete and biofilm is considered for the first time. The mathematical model takes into account the kinetics of the change in time of the thickness of the biofilm due to the birth and death of populations of microorganisms. The results of calculations of dimensionless concentrations of "free" calcium hydroxide by the thickness of a concrete structure and biofilm are presented. The results of the numerical experiment showing the influence of mass transfer criteria (Furier, Kirpichov) on the dynamics of corrosive destruction processes have been analyzed. With an increase in the mass transfer criteria of Kirpichov and Furier, large concentration gradients appear. It has been established that carrying out work on cleaning concrete and reinforced concrete underwater structures from biofouling once every 5 years, in conjunction with other scheduled preventive measures, will increase the time between repairs between 1.5 times. Practical recommendations were developed to monitor and increase the corrosion resistance of concrete and reinforced concrete structures in biologically active environments.

1. Introduction

Microbial destruction of concrete and reinforced concrete structures has increasingly attracted scientists' attention as a major problem related to structural integrity and durability of bridge constructions and different hydro facilities. Practically all building materials are subject to microbiological corrosion. It is estimated [1] that not less than 20 % of all corrosion damages are caused by activities of microorganisms.

An analysis of literary sources [2–8] has shown that to date, a large amount of scientific data on corrosion processes in concrete has been accumulated in building materials science: the basic schemes of chemical reactions have been established and investigated; mathematical descriptions of some corrosion processes are given; created a system of regulatory documents on corrosion protection. However, the process of concrete biocorrosion remains a poorly studied problem both in Russia and abroad [2–8]. Mathematical models to predict the durability of concrete structures with biological corrosion are completely absent [3, 5].

Prediction of wear of concrete and reinforced concrete structures resulted from corrosion is a complex task whose solution requires looking for new methods and approaches. It is appropriate to evaluate the effect of different exploitation conditions of a structure on its durability through mathematical modeling and conducting on its basis numerical experiments. The efficiency of methods of mathematical modeling as an integral part of successful predictions of premature wear of structures has been proven by high practical applicability of the obtained results [1–3].

The problem of exposure of underwater concrete and reinforced concrete structures to bio-growth-around is still burning. Although a variety of methods for protection from bio-growth-around are already applied, until now no efficient methods have been found [4, 6]. Traditional methods of corrosion prevention prove to be low-efficient as far as bio-corrosion is concerned.

Fedosov, S.V., Loginova, S.A. Mathematical model of concrete biological corrosion. Magazine of Civil Engineering. 2020. 99(7). Article No. 9906. DOI: 10.18720/MCE.99.6

Studies in the field of microbic influence on concrete [5, 7, 8] showed that microorganisms participating most frequently in bio-destruction of concrete include bacteria, cianobacteria, fungi, seaweed and lichens. Their growth and development depend on composition, porosity, water resistance of material exposed to corrosive destruction as well as on environmental conditions [9]. The danger of microbiological corrosion is related to the fact that microorganisms tend to intensively multiply, easily adapt to changing physical and chemical conditions of the environment. It was found out that most of microbial activity proceeds on the concrete surface. The researchers note a logarithmic reduction of microbial populations with the depth of concrete due to the limited entrance of hydrogen sulfide and oxygen [6].

Bio-destruction of concrete structures contributes to the increase in concrete porosity and acceleration of diffusion processes in it which boosts corrosive processes. The main component that accelerates the general corrosion process in concrete is a mixture of organic acids ($C_6H_8O_7$, $C_4H_6O_5$, etc.), which is the product of the vital activity of microorganisms [7].

The aim of the study is to develop a physical and mathematical model of the diffusion process of the target component of “free” calcium hydroxide in the solid phase of cement concrete and in a biofilm formed by microorganisms in a liquid medium, which will allow solving the boundary-value problem of mass transfer in the system of “cement concrete – biofilm – liquid”, which together will make it possible to develop a calculation method with the aim of monitoring the mass transfer processes in the field of monitoring the biodegradation of cement concrete in liquid media.

An integral part of mathematical modeling is conducting a numerical experiment with the purpose to establish the influence of mass transfer criteria of similarity (Furier, Kirpichov) on the dynamics of corrosive destruction processes.

2. Methods

As objects of the study of corrosive resistance sample cubes with 0.03 m brink made from Portland cement CEM I 42.5 N with 0.3 water/ cement ratio were used. The system under study was composed of tightly fitted plates with a size of 1×3×3 cm. After 28-day preliminary consolidation (consolidation conditions: temperature 20 +/- 2 °C and relative humidity 50–70 %) the samples were contaminated with microorganisms suspensions (Aspergillus niger van Tieghem, Bacillus subtilis) and were kept for 28 days in conditions optimal for their growth. After that the samples were immersed in water with 1000 cm^2 volume. As reactive medium for studies of corrosive processes distilled water (pH = 6.6) was used. Five surfaces of the studied system were isolated. Only one surface remained open for interaction with an aggressive liquid. After certain time intervals, the samples were taken out of the container and the content of Ca^{2+} ions was determined in each of the plate elements, as a result, the concentration distribution curves along the coordinate were built.

In this case, mass transfer processes from the point of view of mathematical formalization are presented as occurring in an unlimited plate. From an experimental point of view, this made it possible to solve not only the problem of studying the kinetics of processes in the liquid phase (determining the time variation of the concentration of Ca^{2+} ions), but also studying the dynamics of processes in the solid phase. Based on the data obtained, the coefficients of mass conductivity and external mass transfer were calculated.

3. Results and Discussion

While conducting experiments it was established that on the 28th day of keeping the samples in water, microorganisms form a biofilm (Fig. 1). Later a gradual increase of biomass takes place.

Figure 1. Pictures of the surface of the cement stone on the 28th day of the experiment.

Forming of biofilms as a rule starts with introducing bacterial cells into the subtract. The growth of heterotrophic organisms that follows is provided in this case due to metabolites of primary organisms and organic compounds from outside [6]. Biofilms change electro-chemical conditions along the border of the division of the phases “concrete – liquid“ that bring about the corrosion [7].

With the beginning of mass transfer processes between the concrete and the liquid environment, the concentration of dissolved $Ca(OH)_2$ in concrete pores begins to decrease causing the dissolution of “free” calcium hydroxide crystals. A decrease in the content of calcium hydroxide as a result of "washing-out" it out of concrete leads to the decomposition of hydrosilicates, hydroaluminates and calcium hydroferrites, etc.

The size of the biofilm is essentially influenced by particularities of hydrodynamics of the liquid flow in the area of reinforced concrete support [1, 3]. It was [3] established that the size of biofilm thickness depends on the opposite processes of biomass birth and death. Kinetics of those processes, in its turn, depends on hydrodynamics of liquid stream flowing around bridge supports [4].

In case of biological corrosion, the proceeds of liquid corrosion are worsened by additional effect of microorganisms-destructors.

Fig. 2 shows physical and mathematical model of mass transfer process of “free” calcium hydroxide from solid phase (concrete) to liquid phase (water) with the account of the effect caused by microorganisms [2].

The system “cement concrete – biofilm – liquid” is represented by two unlimited plates being in touch. The concrete δ_1 thick is covered with biofilm δ_2 thick on the right side (Fig. 2). The task comes down to determining the changes in concentration of “free” calcium hydroxide for time (τ) by the thickness of the structure (x).

The presented physical and mathematical model of mass transfer in half-limited two-layered plate can be presented as differential equations with boundary conditions of second kind on the border between concrete and liquid and those of the fourth kind on the border between concrete and biofilm.

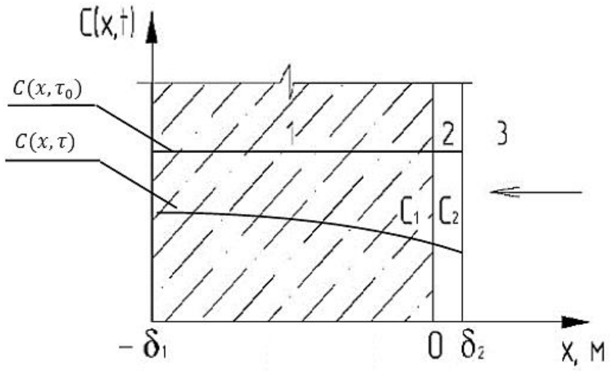

Figure 2. Illustrates the model of concrete structure bio-growth-around: (1) – concrete; (2) – biofilm; (3) – liquid.

$$\frac{\partial C_1(x,\tau)}{\partial \tau} = k_1 \cdot \frac{\partial^2 C_1(x,\tau)}{\partial x^2},\ \tau > 0, -\delta_1 \le x \le 0, \quad (1)$$

$$\frac{\partial C_2(x,\tau)}{\partial \tau} = k_2 \cdot \frac{\partial^2 C_2(x,\tau)}{\partial x^2},\ \tau > 0, 0 \le x \le \delta_2. \quad (2)$$

where $C_1(x,\tau)$ is concentration of “free” calcium hydroxide in relation to CaO in concrete at the time moment at an arbitrary point with coordinate x, (kg CaO/ kg concrete); $C_2(x,\tau)$ is concentration of “free” calcium hydroxide in relation to CaO in biofilm at the time moment at an arbitrary point x, (kg CaO/ kg biomass); $k_{1,2}$ are coefficients of mass conductivity, m^2/s; δ_1 is thickness of concrete structure, m; δ_2 thickness of biofilm, m.

Initial conditions:

$$C_1(x,\tau)\big|_{\tau=0} = C_1(x,0) = C_{1,0} \quad (3)$$

$$C_2(x,\tau)\big|_{\tau=0} = C_2(x,0) = C_{2,0} \quad (4)$$

where $C_{1,0}$ is initial concentration of “free” CaO, kg CaO/ kg concrete;

$C_{2,0}$ initial concentration of free CaO,kg CaO/ kg biomass.

Boundary conditions. Left:

$$\frac{\partial C_1(x,\tau)}{\partial x}\Big|_{x=-\delta_1}=0. \tag{5}$$

At the point of contact of concrete and biofilm. The balance in the system follows the Henry law:

$$C_1(x,\tau)\big|_{x=0}=m\cdot C_2(x,\tau)\big|_{x=0}, \tag{6}$$

where m is Henry equilibrium constant, kg biofilm/ kg concrete.

$$-\rho_{con}\cdot k_1\cdot\frac{\partial C_1(x,\tau)}{\partial x}\Big|_{x=0}=-\rho_{biom}\cdot k_2\cdot\frac{\partial C_2(x,\tau)}{\partial x}\Big|_{x=0}, \tag{7}$$

where ρ_{con},ρ_{biom} are densities of concrete and biomass, kg/m^3.

On right:

$$-k_2\cdot\frac{\partial C_2(x,\tau)}{\partial x}\Bigg|_{x=\frac{\delta_2}{\delta_1}}=q_H(\tau). \tag{8}$$

where $q_H(\tau)$ is density of mass flow leaving the biofilm for the liquid flow.

The system of equations (1) – (2) is of a linear type, coefficients of mass conductivity being variable values in common case and dependent on concentration are brought out of signs of mathematical differentiation operators. With the use of zonal method of calculation or “method of micro-processes“ the whole process is divided into N elementary micro-processes, within each of which coefficients of mass conductivity are meant as constant. So the non-linear problem of mass transfer comes down to the totality of N linear problems.

Since on the left border of concrete structure there is no substance flow, the boundary condition (5) is represented as a condition of the second kind.

Boundary conditions (6) and (7) are conditions of the fourth kind and illustrate the fact that at the point of plates' contact the concentrations of “free” calcium hydroxide are equal and densities of mass flows are equal as well.

To solve the system (1) – (8) Laplas's method of integral transformations was used which got a good reputation while solving problems on heat mass transfer [10–13].

Mathematically the problem of mass transfer (1) – (8) in a dimensionless form can be presented as the following system of equations (9) – (16):

$$\frac{\partial Z_1(\bar{x},Fo_m)}{\partial Fo_m}=\frac{\partial^2 Z_1(\bar{x},Fo_m)}{\partial \bar{x}^2}, Fo_m>0,\ -1\le\bar{x}\le 0. \tag{9}$$

$$\frac{\partial Z_2(\bar{x},Fo_m)}{\partial Fo_m}=\frac{\partial^2 Z_2(\bar{x},Fo_m)}{\partial \bar{x}^2}\cdot K_k, Fo_m>0, 0\le\bar{x}\le K_\delta. \tag{10}$$

Initial conditions:

$$Z_1(\bar{x},Fo_m)\big|_{Fo_m=0}=Z_{1,0}(\bar{x}); \tag{11}$$

$$Z_2(\bar{x},Fo_m)\big|_{Fo_m=0}=Z_{2,0}(\bar{x}). \tag{12}$$

Boundary conditions:

$$\frac{\partial Z_1(\bar{x},Fo_{m)}}{\partial \bar{x}}\Big|_{\bar{x}=|-1|}=0, \tag{13}$$

$$Z_1(\bar{x},Fo_m)\big|_{\bar{x}=0}=Z_2(\bar{x},Fo_m)\big|_{\bar{x}=0}, \quad (14)$$

$$\frac{\partial Z_1(\bar{x},Fo_m)}{\partial \bar{x}}\Big|_{\bar{x}=0}=N\cdot\frac{\partial Z_2(\bar{x},Fo_m)}{\partial \bar{x}}\Big|_{\bar{x}=0}, \quad (15)$$

$$\frac{\partial Z_2(\bar{x},Fo_m)}{\partial \bar{x}}\Big|_{\bar{x}=K\delta}=Ki_H^*, \quad (16)$$

where $Z_1(\bar{x},Fo_m)$ is dimensionless concentration of the transferred component by the thickness of concrete; $Z_2(\bar{x},Fo_m)$ is dimensionless concentration of the transferred component by the thickness of biofilm; $\bar{x}=x/\delta_1$ is dimensionless coordinate; $K_k=k_2/k_1; K_\delta=\delta_2/\delta_1; q_H$ are density of mass flow leaving the biofilm for liquid flow; m is Henry' s constant (kg biofilm/ kg concrete); $N=(\rho_{biom}\cdot k_2)/(\rho_{con}\cdot k_1\cdot m)$ is coefficient considering characteristics of phases; $Fo_m=(k_1\cdot\tau)/\delta_1^2$ is Furier criterion; $Ki_H^*=\dfrac{q_H\cdot\rho_{con}\cdot m\cdot K_\delta}{\delta_2\cdot\rho_{biom}\cdot k_2\cdot C_0}$ is Kirpichov's mass transfer criterion.

It is possible to take into account the complex mechanism of growth, reproduction, and death of microorganisms by introducing the coefficient N, which takes into account changes in the biomass density.

Kinetic equations describing the growth, reproduction and death of microorganisms, taking into account natural mortality, taking into account the stochastic nature of these processes, for a system of isolated cells can be represented as [13, 14]:

$$\frac{dm}{dt}=\mu(t)m=U_1(m,C), \quad (17)$$

$$\frac{dm}{dt}=\beta S(t)\psi(t)=U_2(m,C), \quad (18)$$

where $m(t)$ is the mass of an individual cell at time t (m is a determinate value); t is the cell division time; $U_{1,2}(m, C)$ is cell growth rate; C is the concentration of the substrate; β is the mass transfer coefficient; $\beta = D_M/d$, D_M is the molecular diffusion coefficient depending on the temperature of the culture fluid; d is the thickness of the “boundary film”, depending on the hydrodynamic situation in the vicinity of the cell; $S(t)$ the outer surface of the cell at time t.

After system of equations (9) – (16) was transferred in the area of complex numbers where the solution of the system was obtained and then the solution was transferred in the area of the originals. The general solution of the mass conductivity problem describing the dynamics of concentration fields looks as follows:

$$Z_1(\bar{x},Fo_m)=\frac{1}{1+NK_kK_\delta}\left\{1-NK_\delta+NKi_H^*\left[Fo_m+\frac{(1-\bar{x})^2}{2}+\phi(K_k,N,K_\delta)\right]\right\}+$$
$$+2\sum_{n=1}^{\infty}\frac{1}{\mu_n^2\psi_1^/(\mu_n)}(\mu_n\sin\mu_n\left[\cos(\mu_n\bar{x})\cos(\mu_n\sqrt{K_k}K_\delta)-\sqrt{K_k}K_\delta\sin(\mu_n\bar{x})\sin(\mu_n\sqrt{K_k}K_\delta)\right]- \quad (19)$$
$$-\frac{N}{\sqrt{K_k}}\cos(\mu_n(1+\bar{x}))\exp(-\mu_n^2Fo_m).$$

$$Z_2(\bar{x},Fo_m)=\frac{1}{1+NK_kK_\delta}(1-NK_\delta+Ki_H^*\left[\bar{x}-Fo_mK_k,K_\delta\right]+NKi_H^*(\phi(K_k,N,K_\delta)-$$
$$-\frac{1+K_k\bar{x}^2}{2})-2\sum_{m=1}^{\infty}\frac{J}{\mu_m^2\psi_1^/(\mu_m)}(\mu_m\sin\mu_m\cos\left[\mu_m\sqrt{K_k}(K_\delta-\bar{x})\right]-$$
$$-\frac{\mu_m}{\sqrt{K_k}}\sin(\mu_m\sqrt{K_k}K_\delta)\left[N\cos\mu_m\cos(\mu_m\sqrt{K_k}\bar{x})+\frac{J}{\sqrt{K_k}}\sin\mu_m\sin(\mu_m\sqrt{K_k}\bar{x})\right]+ \quad (20)$$
$$+Ki_H^*\left[N\cos\mu_m\cos(\mu_m\sqrt{K_k}\bar{x})+\frac{1}{\sqrt{K_k}}\sin\mu_m\sin(\mu_m\sqrt{K_k}\bar{x})\right]\exp(-\mu_m^2K_kFo_m),$$

where μ_m is roots of characteristic equation:

$$\phi(K_k, N, K_\delta) = \frac{1 + K_k K_\delta (3K_\delta + 3N + NK_k K_\delta^2)}{6(1 + NK_k K_\delta)}, J = \int_0^1 Z_{1,0}(\xi) \cos\left[\mu_m(1-\xi)\right] d\xi,$$
$$tg\mu_m = N\sqrt{K_k} tg(\mu_m \sqrt{K_k} K_\delta). \quad (21)$$

The expressions (19) and (20) make it possible to calculate the dynamics of mass transfer of the target component of the structure's inner layers towards the border of the division of the phases (concrete/ biofilm) [15, 16].

Table 1. The change in the values of the concentration of "free" calcium hydroxide in the solution of the pores of the sample from time to time and coordinates.

Time			Concentration, $kg_{CaO}/kg_{bet} \cdot 10^4$ at the point with the coordinate					
			Experimental values			Estimated Values		
			x_1 = 0.005 m	x_2 = 0.015 m	x_3 = 0.025 m	x_1 = 0.005 m	x_2 = 0.015 m	x_3 = 0.025 m
1	τ_1	14 days	2.47	2.23	1.93	2.52	2.29	1.99
2	τ_2	28 days	2.38	1.98	1.76	2.42	2.01	1.79
3	τ_3	42 days	2.16	1.81	1.48	2.26	1.97	1.62
4	τ_4	56 days	1.88	1.53	1.23	2.01	1.67	1.39
5	τ_5	70 days	1.68	1.45	1.20	1.81	1.53	1.25

For the evaluation of the influence of mass transfer parameters, a numerical experiment was conducted illustrating the influence of similarity criteria (Furier, Kirpichov) on the dynamics of corrosive destruction process [17].

Fig. 3 illustrates the dependence of dimensionless concentrations on Kirpichov's mass transfer criterion. It was established that with the increase in Kirpichov's mass transfer criterion large gradients of concentration appear. Curves (picture 4) illustrate the dynamics of dimensionless concentrations of the transferred component with different values of Furier mass transfer criterion.

The obtained dependencies make it possible to solve the reverse problem when the available experimental data allow with the help of this model to predict the numerical value of "free" calcium hydroxide by the thickness of the structure and the film [13, 16, 18].

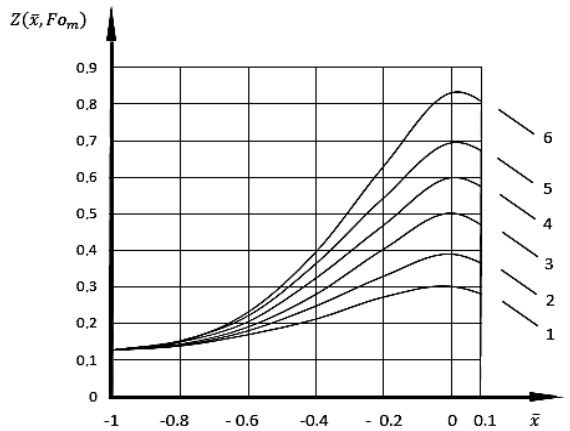

Figure 3. Profiles of dimensionless concentrations by the thickness of concrete and biofilm with $K_k = 1; K_\delta = 0.1; N = 1; Fo_m = 1$ **and different values** Ki_H^* **:**1 – 0.5; 2 – 1; 3 – 1.5; 4 – 2; 5 – 2.5; 6 – 3.

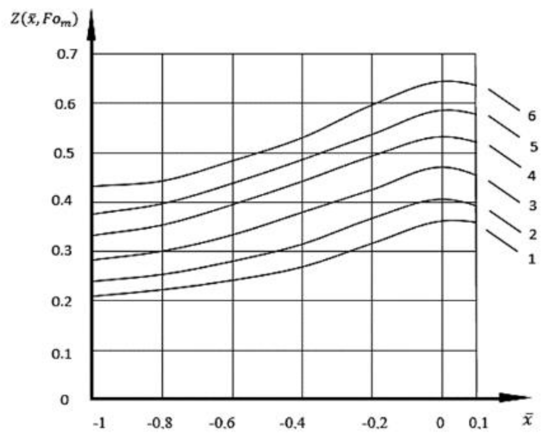

Figure 4. Profiles of dimensionless concentrations by thickness of concrete and biofilm with $K_k = 1; K_\delta = 0.1; N = 1; Ki_H^* = 0.5$ **and different values** Fo_m : 1 – 0.5; 2 – 1; 3 – 1.5; 4 – 2; 5 – 2.5; 6 – 3.

The results of mathematical modeling are confirmed by the results of experimental studies of concrete biocorrosion of the scientific school of Professor V.T. Erofeeva [8]. The obtained expressions allow to determine concentration values of the transferred component by thickness of both the concrete structure, and in the biofilm itself at any period of time, and also make it possible to calculate concentration of "free" calcium hydroxide in liquid phase, the kinetics of the process in solid, liquid phases and in biofilm which eventually allows with minimal error to predict durability and reliability of building structures [19–23]. However, those calculations are possible only with availability of objective information about characteristics of mass transfer – coefficients of mass conductivity and mass giving away of particular corrosive processes that can be obtained in the course of experimental studies.

Based on the results of mathematical modeling, practical recommendations were developed to monitor and increase the corrosion resistance of concrete and reinforced concrete structures in biologically active environments, which were used during the industrial examination of LLC «Basic Engineering» (Ivanovo, Russia) [24]. The economic effect amounted to 8.9 % of the estimated cost of work.

In the future, the generality of the mathematical description will make it possible to disseminate the developed mathematical model and the proposed calculation method for various types of concrete biocorrosion, taking into account experimentally determined mass transfer coefficients depending on the taxonometric composition of biofouling.

4. Conclusion

1. A physical and mathematical model of diffusion process of target component of “free” calcium hydroxide in solid phase of cement concrete and biofilm formed in liquid medium has been developed which allows to obtain a solution of the boundary problem of mass transfer in the system “cement concrete – biofilm – liquid” which in totality makes it possible to monitor the processes of mass transfer in the field of controlling bio-destruction of cement concretes.

2. A numerical experiment has been conducted to illustrate the influence of similarity criteria (Furier, Kirpichov) on the intensity of the process of corrosive mass transfer. With an increase in the mass transfer criteria of Kirpichov and Furier, large concentration gradients appear.

3. Practical recommendations were developed and implemented to monitor and increase the corrosion resistance of concrete and reinforced concrete structures in biologically active environments. It has been established that carrying out work on cleaning concrete and reinforced concrete underwater structures from biofouling once every 5 years, in conjunction with other scheduled preventive measures, will increase the time between repairs between 1.5 times. The economic effect was 8–15 % of the estimated cost of work.

4. Since abiotic environmental factors change over time, only the joint application of the obtained solutions using the zonal calculation method will allow continuous monitoring of bio-corrosion damage and manage them in the field of scheduled preventive repairs.

References

1. Tsivilis, S., Batis, G., Chaniotakis, E., Grigoriadis, G., Theodossis, D. Properties and behavior of limestone cement concrete and mortar. Cement and Concrete Research. 2000. 30. Pp. 1679–1683. DOI: 10.1016/S0008-8846(00)00372-0
2. Levandovskiy, A.N., Melnikov, B.E., Shamkin, A.A. Modeling of porous material fracture. Magazine of Civil Engineering. 2017. 69(1). Pp. 3–22. DOI: 10.18720/MCE.69.1
3. Travush, V.I., Karpenko, N.I., Erofeev, V.T., Rodin, A.I., Smirnov, V.F., Rodina, N.G. Development of Biocidal Cements for Buildings and Structures with Biologically Active Environments. Power Technology and Engineering. 2017. 4(51). Pp. 377–384. DOI: 10.1007/s10749-017-0842-8
4. Newale, R., Sartape, Y., Ramane, A., Telrandhe, S., Vairal, S., Girish, J. Structural Audit, Repair and Rehabilitation of Building. International Journal of Innovative Research in Science. 2017. 6(3). Pp. 4679–4693. DOI: 10.15680/IJIRSET.2017.0603255
5. Selyaev, V.P., Neverov, V.A., Selyaev, P. V., Sorokin, E. V., Yudina, O.A. Predicting the durability of concrete structures, including sulfate corrosion of concrete. Magazine of Civil Engineering. 2014. 1(45). Pp. 41–52. DOI: 10.5862/MCE.45.5
6. Pepe, O., Sannino, L., Palomba, S., Anastasio, M., Blaiotta, G., Villani, F., Moschetti, G. Heterotrophic microorganisms in deteriorated medieval wall paintings in southern Italian churches. Microbiological Research. 2010. 165(1). Pp. 21–32. DOI: 10.1016/j.micres.2008.03.005
7. Han, F., Zhang, Z. Hydration, mechanical properties and durability of high-strength concrete under different curing conditions. Journal of Thermal Analysis and Calorimetry. 2018. 132. Pp. 823–834. DOI: 10.1007/s10973-018-7007-3
8. Erofeev, V., Rodin, A., Rodina, N., Kalashnikov, V., Irina, E. Biocidal Binders for the Concretes of Unerground Constructions. Procedia Engineering. 2016. 165. Pp. 1448–1454. DOI: 10.1016/j.proeng.2016.11.878
9. Brenna, A., Bolzoni, F., Beretta, S., Ormellese, M. Long-term chloride-induced corrosion monitoring of reinforced concrete coated with commercial polymer-modified mortar and polymeric coatings. Construction and Building Materials. 2013. 48. Pp. 734–744. DOI: 10.1016/j.conbuildmat.2013.07.099
10. Patel, R.A., Perko, J., Jacques, D., De Schutter, G., Ye, G., Van Bruegel, K. Effective diffusivity of cement pastes from virtual microstructures: Role of gel porosity and capillary pore percolation. Construction and Building Materials. 2018. 165. Pp. 833–845. DOI: 10.1016/j.conbuildmat.2018.01.010
11. Kolchunov, V.I., Dem’yanov, A.I. The modeling method of discrete cracks in reinforced concrete under the torsion with bending. Magazine of Civil Engineering. 2018. 81(5). Pp. 160–173. DOI: 10.18720/MCE.81.16
12. Fedosov, S.V., Roumyantseva, V.E., Konovalova, V.S., Loginova, S.A. Mathematical modeling of diffusion processes of mass transfer of «Free calcium hydroxide» during corrosion of cement concretes. International Journal for Computational Civil and Structural Engineering. 2018. DOI: 10.22337/2587-9618-2018-14-3-161-168
13. Luo, J., Chen, X., Crump, J., Zhou, H., Davies, D.G., Zhou, G., Zhang, N., Jin, C. Interactions of fungi with concrete: Significant importance for bio-based self-healing concrete. Construction and Building Materials. 2018. 164. Pp. 275–285. DOI: 10.1016/j.conbuildmat.2017.12.233
14. Flemming, H.C., Wingender, J., Szewzyk, U., Steinberg, P., Rice, S.A., Kjelleberg, S. Biofilms: An emergent form of bacterial life. Nature Reviews Microbiology.2016. 14. Pp. 563–575. DOI: 10.1038/nrmicro.2016.94
15. Lushnikova, V.Y., Tamrazyan, A.G. The effect of reinforcement corrosion on the adhesion between reinforcement and concrete. Magazine of Civil Engineering. 2018. 80(4). Pp. 128–137. DOI: 10.18720/MCE.80.12

16. Mullard, J.A., Stewart, M.G. Corrosion-induced cover cracking: New test data and predictive models. ACI Structural Journal. 2011. 108(1). Pp. 71–79. DOI: 10.14359/51664204
17. Fedosov, S.V., Rumyantseva, V.E., Krasilnikov, I.V., Konovalova, V.S., Evsyakov, A.S. Mathematical modeling of the colmatation of concrete pores during corrosion. Magazine of Civil Engineering. 2018. 83(7). Pp. 198–207. DOI: 10.18720/MCE.83.18
18. Vu, K., Stewart, M.G., Mullard, J. Corrosion-induced cracking: Experimental data and predictive models. ACI Structural Journal. 2005. 102(5). Pp. 719–726. DOI: 10.14359/14667
19. Chromková, I., Čechmánek, R. Influence of biocorrosion on concrete properties. Key Engineering Materials. 2018. 760. Pp. 83–90.
20. Ksiazek, M. Biological corrosion of the sandstone of the quay of the river of Odra in Wrocław. Engineering Failure Analysis. 2014. 44. Pp. 338–344. DOI: 10.1016/j.engfailanal.2014.05.003
21. Wei, S., Jiang, Z., Liu, H., Zhou, D., Sanchez-Silva, M. Microbiologically induced deterioration of concrete - A review. Brazilian Journal of Microbiology. 2013. 44. Pp. 1001–1007. DOI: 10.1590/S1517-83822014005000006
22. Loto, C.A. Microbiological corrosion: mechanism, control and impact–a review. International Journal of Advanced Manufacturing Technology. 2017. 92(9-12). Pp. 4241–4252. DOI: 10.1007/s00170-017-0494-8
23. Vupputuri, S., Fathepure, B.Z., Wilber, G.G., Sudoi, E., Nasrazadani, S., Ley, M.T., Ramsey, J.D. Isolation of a sulfur-oxidizing Streptomyces sp. from deteriorating bridge structures and its role in concrete deterioration. International Biodeterioration and Biodegradation. 2015. Pp. 128–134. DOI: 10.1016/j.ibiod.2014.11.002
24. Fedosov, S.V., Roumyantseva, V.E., Krasilnikov, I.V., Narmania, B.E. Formulation of mathematical problem describing physical and chemical processes at concrete corrosion. International Journal for Computational Civil and Structural Engineering. 2017. 13(2). Pp. 45–49. DOI: 10.22337/2587-9618-2017-13-2-45-49

Contacts:

Sergey Fedosov, FedosovSV@mgsu.ru
Svetlana Loginova, sl79066171227@yandex.ru