2022. 18(5). 438–443

СТРОИТЕЛЬНАЯ МЕХАНИКА ИНЖЕНЕРНЫХ КОНСТРУКЦИЙ И СООРУЖЕНИЙ

STRUCTURAL MECHANICS OF ENGINEERING CONSTRUCTIONS AND BUILDINGS

ISSN 1815-5235 (Print), 2587-8700 (Online)

HTTP://JOURNALS.RUDN.RU/STRUCTURAL-MECHANICS

АНАЛИТИЧЕСКИЕ И ЧИСЛЕННЫЕ МЕТОДЫ РАСЧЕТА КОНСТРУКЦИЙ

ANALYTICAL AND NUMERICAL METHODS OF ANALYSIS OF STRUCTURES

DOI 10.22363/1815-5235-2022-18-5-438-443
UDC 620.193

RESEARCH ARTICLE / НАУЧНАЯ СТАТЬЯ

Predicting the residual life of concrete structures in biocorrosion from the position of the theory of mass transfer

Sergey V. Fedosov[1], **Svetlana A. Loginova**[2]✉, **Anna A. Shalygina**[2]

[1]*Moscow State University of Civil Engineering (National Research University), Moscow, Russian Federation*
[2]*Yaroslavl State Technical University, Yaroslavl, Russian Federation*
✉ sl79066171227@yandex.ru

Article history
Received: July 12, 2022
Revised: September 21, 2022
Accepted: September 25, 2022

For citation
Fedosov S.V., Loginova S.A., Shalygina A.A. Predicting the residual life of concrete structures in biocorrosion from the position of the theory of mass transfer. *Structural Mechanics of Engineering Constructions and Buildings.* 2022;18(5):438–443. http://doi.org/10.22363/1815-5235-2022-18-5-438-443

Abstract. The problem of corrosive destruction of concrete and reinforced concrete structures of industrial buildings affected by aggressive environments does not lose its relevance, because, despite the abundance of modern methods of protection, there are still no radical methods of corrosion control. Corrosive destruction of building materials leads to a strength and load-bearing capacity reduction, loss of aesthetic properties of concrete and reinforced concrete structures and, consequently, to a decrease in the residual life of buildings and structures. The biological factor often acts as an intensifier of corrosive destruction. In this regard, it is reasonable to search for the possibility of predicting the durability of concrete and reinforced concrete structures in aggressive liquid mediums, taking into account the biofactor effect from the standpoint of mass transfer theory. The authors present a model of mass transfer in a concrete structure exposed to aggressive environment and biofouling. The proposed physical and mathematical model considers the properties of concrete and aggressive environment, as well as the kinetics of continuous processes of growth, reproduction and death of microorganisms. The results of numerical experiments on the proposed mathematical model are provided. The application of the received solutions will allow timely monitoring of biocorrosive destruction of concrete and reinforced concrete structures and selecting effective methods of protection.

Keywords: concrete, reinforced concrete, corrosion, biodegradation, residual life, mass transference

Sergey V. Fedosov, Academician of the RAACS, Doctor of Technical Sciences, Professor, Professor of the Department of Technology and Organization of Construction Production, Moscow State University of Civil Engineering (National Research University), 26 Yaroslavskoye Shosse, Moscow, 129337, Russian Federation; ORCID: 0000-0001-6117-7529, Scopus Author ID: 7005670404, eLIBRARY SPIN-code: 1840-8194; mr.fedosow.2011@yandex.ru
Svetlana A. Loginova, Candidate of Technical Sciences, Associate Professor of the Department of Building Structures, Yaroslavl State Technical University, 88 Moskovskii Prospekt, Yaroslav, 150023, Russian Federation; ORCID: 0000-0001-6025-8968, Scopus Author ID: 57215860584, eLIBRARY SPIN-code: 4076-4970; sl79066171227@yandex.ru
Anna A. Shalygina, student, Yaroslavl State Technical University, 88 Moskovskii Prospekt, Yaroslav, 150023, Russian Federation; ORCID: 0000-0002-8263-4546; miss-anna.shalygina@yandex.ru

Прогнозирование остаточного ресурса бетонных конструкций при биокоррозии с позиции теории массопереноса

С.В. Федосов[1], **С.А. Логинова**[2], **А.А. Шалыгина**[2]

[1]*Национальный исследовательский Московский государственный строительный университет, Москва, Российская Федерация*
[2]*Ярославский государственный технический университет, Ярославль, Российская Федерация*
sl79066171227@yandex.ru

История статьи
Поступила в редакцию: 12 июля 2022 г.
Доработана: 21 сентября 2022 г.
Принята к публикации: 25 сентября 2022 г.

Для цитирования
Федосов С.В., Логинова С.А., Шалыгина А.А. Прогнозирование остаточного ресурса бетонных конструкций при биокоррозии с позиции теории массопереноса // Строительная механика инженерных конструкций и сооружений. 2022. Т. 18. № 5. С. 438–443. http://doi.org/10.22363/1815-5235-2022-18-5-438-443

Аннотация. Проблема коррозионного разрушения бетонных и железобетонных конструкций производственных зданий, испытывающих влияние агрессивных сред, не теряет своей актуальности, поскольку, несмотря на обилие современных способов защиты, до сих пор радикальных методов борьбы не существует. Коррозионная деструкция строительных материалов приводит к снижению прочности и несущей способности, потере эстетических свойств бетонных и железобетонных конструкций и, следовательно, к снижению остаточного ресурса зданий и сооружений. Интенсификатором коррозионной деструкции нередко выступает биологический фактор. В связи с этим рационален поиск возможности прогнозирования долговечности бетонных и железобетонных конструкций в агрессивных жидких средах с учетом действия биофактора с позиции теории массопереноса. Приводится модель массопереноса в бетонной конструкции, подверженной воздействию агрессивной среды и биообрастанию. Предложенная физико-математическая модель учитывает свойства бетона и агрессивной среды, а также кинетику непрерывных во времени процессов роста, размножения и гибели микроорганизмов. Приводятся результаты численных экспериментов по предложенной математической модели. Применение полученных решений позволит осуществлять своевременный мониторинг биокоррозионных разрушений бетонных и железобетонных конструкций и подбирать эффективные методы защиты.

Ключевые слова: бетон, железобетон, коррозия, биоразрушение, остаточный ресурс, массоперенос

Introduction

For a long time, they considered that concrete and reinforced concrete structures have an unlimited life, because concrete only gains strength over time [1; 2]. However, during operation, building structures are influenced by various aggressive environments, which eventually result in their destruction. Thus, corrosive destruction of building materials, including biodegradation, is most often found in of food, chemical and other industries' buildings. Figure 1 shows photographic materials from the inspection of corrosively damaged structures of an industrial building.

Currently, there are no guidelines in the building regulations for the design and calculation of structures taking into account corrosive damage. Predicting the life of concrete and reinforced concrete structures, assessing the residual life of their operation is an urgent task, which solution is possible by applying the theory of mass transfer.

The works of V.P. Selyaev [3; 4], V.T. Erofeev [5; 6], V.I. Rimshin [7], B.V. Gusev [8; 9], N.K. Rosenthal [10] and other scientists are devoted to the development of methods for calculating structures exposed to corrosive destruction, modeling of biocorrosive damage.

The most common structural damages during operation in aggressive environments are described in the N.K. Rosenthal's works [10]. The article describes in more detail the process of corrosive destruction of concrete during biofouling.

Федосов Сергей Викторович, академик РААСН, доктор технических наук, профессор кафедры технологии и организация строительного производства, Национальный исследовательский Московский государственный строительный университет, Российская Федерация, 129337, Москва, Ярославское шоссе, д. 26; ORCID: 0000-0001-6117-7529, Scopus Author ID: 7005670404, eLIBRARY SPIN-код: 1840-8194; mr.fedosow.2011@yandex.ru
Логинова Светлана Андреевна, кандидат технических наук, доцент кафедры строительных конструкций, Ярославский государственный технический университет; Российская Федерация, 150023, Ярославль, Московский пр-кт, д. 88; ORCID: 0000-0001-6025-8968, Scopus Author ID: 57215860584, eLIBRARY SPIN-код: 4076-4970; sl79066171227@yandex.ru
Шалыгина Анна Александровна, студент, Ярославский государственный технический университет, Российская Федерация, 150023, Ярославль, Московский пр-кт, д. 88; ORCID: 0000-0002-8263-4546; miss-anna.shalygina@yandex.ru

Figure 1. Corrosion damage to the coating of an industrial building in Moscow

Nowadays, it has been established that biocorrosive destruction of concrete and reinforced concrete structures in its pure form is rare, most often it develops in aggregate with other types of corrosion [11–13]. Additional impact of the bioaggressive environment results in an even greater increase in the material porosity, intensification of diffusion processes in the body of concrete and, as a consequence, stimulation of corrosion destruction in general. Building structures operated in an aquatic environment or an environment of high humidity are particularly often subjected to biocorrosive destruction.

When examining operated concrete and reinforced concrete structures, it is usual to determine their residual life. By mathematical modeling of the corrosion destruction of concrete, taking into account the biofactor, it is possible to establish the essence of the exchange processes occurring between cement stone and biota, predict this exchange and formulate ways to prevent such corrosion damage, thereby saving an impressive amount of money.

Methods

The development of a mathematical description of the biocorrosive destruction of concrete was carried out from the standpoint of the theory of mass transfer. The "concrete – biofilm – liquid" system, which is typical for the case of biofouling of a concrete structure exposed to an aquatic environment during operation, was considered. This system consisted of two unlimited plates in contact with each other. Each of the plates was characterized by the size and properties of the simulated object. The task was to determine the concentration change of the transferred component ($Ca(OH)_2$) over time by the thickness of the concrete structure. A mass transfer model in an unlimited two-layer plate was compiled in the form of a system of partial differential equations of the parabolic type with boundary conditions of the second kind at the boundary of concrete with liquid and of the fourth kind at the boundary between concrete and biofilm [14]. The boundary condition of the second kind characterizes the absence of a flow of matter. The boundary condition of the fourth kind is characteristic for the case of equality of concentrations of the transferred component ($Ca(OH)_2$) and mass flows at the phase boundary. In order to solve the boundary value problem for differential equations, the Laplace integral transformation method was used [15].

Discussion and results

As a result of mathematical modeling, a system of equations (1)–(8) was compiled.

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

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

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

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

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

$$C_1(x,\tau)\big|_{x=0} = mC_2(x,\tau)\big|_{x=0}. \tag{6}$$

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

$$-k_2 \left.\frac{\partial C_2(x,\tau)}{\partial x}\right|_{x=\frac{\delta_2}{\delta_1}} = q_n(\tau), \tag{8}$$

where $C_1(x, \tau)$ – a concentration of the transferred component in the body of concrete, kg of CaO/kg of concrete; $C_2(x, \tau)$ – a concentration of the transferred component in the biofilm, kg of CaO/kg of biomass; $k_{1,2}$ – mass conductivity ratios, m^2/s; δ_1 – a concrete structure thickness, m; δ_2 – a biofilm thickness, m; $C_{1,0}$ – an initial concentration of the transferred component, kg of CaO/kg of concrete; $C_{2,0}$ – a initial concentration of the transferred component, kg of CaO/kg of biomass; ρ_{con}, ρ_{biom} – concrete and biomass densities, kg/m^3; $q_n(\tau)$ – a density of the mass flow leaving the biofilm into the liquid flow, m is a Henry's equilibrium constant, kg of biofilm/kg of concrete.

The previously published works of the authors [13; 16] describe in detail the process of solving this system of differential equations. By replacing the functions of real variables with their images, that are connected via the Laplace operator, a complex system of differential equations has been reduced to the simplest algebraic operations. The solution of the system in general has taken the form:

$$Z_1(\bar{x}, Fo_m) = \frac{1}{1+NK_kK_\delta}\left\{1 - NK_\delta + NKi_m^*\left[Fo_m + \frac{(1-\bar{x})^2}{2} + \varphi(K_k, N, K_\delta)\right]\right\} +$$
$$+2\sum_{n=1}^{\infty}\frac{1}{\mu_n^2\psi_1^{/}(\mu_n)}\left(\mu_n \sin\mu_n\left[\cos(\mu_n\bar{x})\cos(\mu_n\sqrt{K_k}K_\delta) - \sqrt{K_k}K_\delta\sin(\mu_n\bar{x})\sin(\mu_n\sqrt{K_k}K_\delta)\right] -\right.$$
$$\left.-\frac{N}{\sqrt{K_k}}\cos(\mu_n(1+\bar{x}))\exp(-\mu_n^2 Fo_m)\right.. \tag{9}$$

$$Z_2(\bar{x}, Fo_m) = \frac{1}{1+NK_kK_\delta}\left(1 - NK_\delta + Ki_m^*[\bar{x} - Fo_mK_kK_\delta] + NKi_m^*(\varphi(K_k, N, K_\delta) -\right.$$
$$-\frac{1+K_k\bar{x}^2}{2}) - 2\sum_{m=1}^{\infty}\frac{J}{\mu_m^2\psi_1^{/}(\mu_m)}\left(\mu_m\sin\mu_m\cos\left[\mu_m\sqrt{K_k}(K_\delta - \bar{x})\right] -\right.$$
$$-\frac{\mu_m}{\sqrt{K_k}}\sin(\mu_m\sqrt{K_k}K_\delta)\left[N\cos\mu_m\cos(\mu_m\sqrt{K_k}\bar{x}) + \frac{J}{\sqrt{K_k}}\sin\mu_m\sin(\mu_m\sqrt{K_k}\bar{x})\right] +$$
$$+Ki_H^*\left[N\cos\mu_m\cos(\mu_m\sqrt{K_k}\bar{x}) + \frac{1}{\sqrt{K_k}}\sin\mu_m\sin(\mu_m\sqrt{K_k}\bar{x})\right]\exp(-\mu_m^2K_kFo_m). \tag{10}$$

$$\varphi(K_{k,}N, K_\delta) = \frac{1 + K_k K_\delta (3K_\delta + 3N + NK_k K_\delta^2)}{6(1 + NK_k K_\delta)}. \quad (11)$$

$$J = \int_0^1 Z_{1,0}(\xi)\cos\left[\mu_m (1-\xi)\right] d\xi. \quad (12)$$

$$\mathrm{tg}\mu_m = N\sqrt{K_k}\,\mathrm{tg}(\mu_m \sqrt{K_k} K_\delta), \quad (13)$$

where $Z_1(\bar{x}, Fo_m)$ – a dimensionless concentration of the transferred component over the thickness of the concrete structure; $Z_2(\bar{x}, Fo_m)$ – a dimensionless concentration of the transferred component over the thickness of the biofilm; $\bar{x} = x/\delta_1$ – a dimensionless coordinate; $K_k = k_2 / k_1$, $K_\delta = \delta_2 / \delta_1$, N – a ratio that considers the characteristics of the phases; $Fo_m = (k_1\tau) / \delta_1^2$ – the Fourier criterion; μ_m – the roots of the characteristic equation; Ki_H^* – the Kirpichev mass-exchange criterion.

During the vital activity of microorganisms, the biofilm density changes over time as a result of the growth, reproduction and death of biota [17; 18]. This fact was considered in the mathematical model by introducing the ratio $N = (\rho_{\text{biom}} k_2)/(\rho_{\text{con}} k_1 m)$.

The correctness of the proposed mathematical model was verified by conducting numerical experiments, those results illustrate the influence of similarity criteria (Fourier, Kirpichev) on the dynamics of concrete biodegradation process (Figures 2 and 3). The calculated data obtained had a high similarity with the experimental data received by the authors in earlier studies [15; 19].

Large gradients of the concentrations of the transferred component as a result of changes in the values of the Kirpichev mass-exchange criterion are observed in Figure 2. Figure 3 shows the curves of changes in dimensionless concentrations of the transferred component at different values of the Fourier mass transfer criterion.

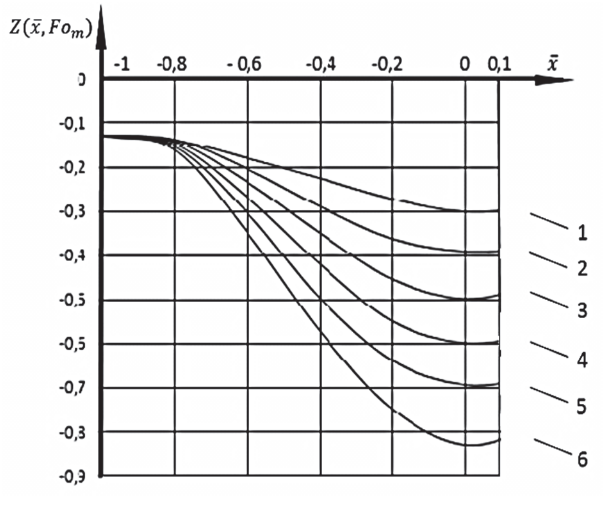

Figure 2. Profiles of dimensionless concentrations of the transferred component over the thickness of concrete and biofilm at $K_k = 1$, $K_\delta = 0.1$, $N = 1$; $Fo_m = 1$ with different values Ki_H^*:
1 = –0.5; 2 = –1; 3 = –1.5; 4 = –2; 5 = –2.5; 6 = –3

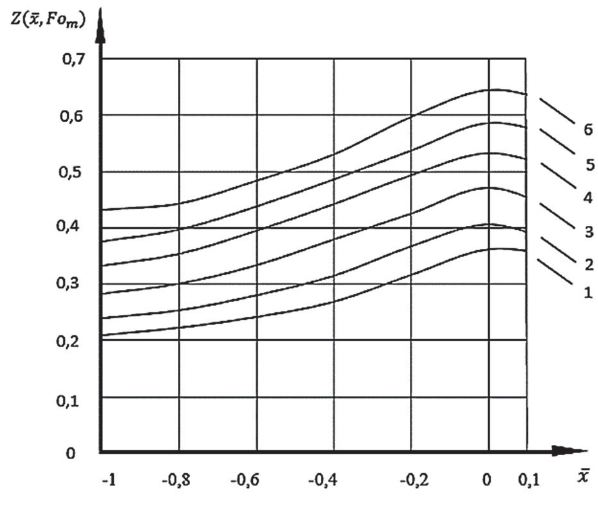

Figure 3. Profiles of dimensionless concentrations of the transferred component over the thickness of concrete and biofilm at $K_k = 1$, $K_\delta = 0.1$, $N = 1$, $Ki_H^* = 0.5$ with different values Fo_m:
1 = 0.5; 2 = 1; 3 = 1.5; 4 = 2; 5 = 2.5; 6 = 3

Conclusion

The obtained solutions (9)–(13) provide for determining the concentration values of the transferred component over the thickness of both the concrete structure and in the biofilm itself, at any time. At the same time, the obtained relationships make it possible to predict the numerical value of the transferred component over the thickness of the concrete structure according to the available experimental data. The generality of the mathematical model allows us to extend it to predict the durability of various types of concrete. Based on this, it becomes possible to determine the residual life of building structures during operation in aggressive environments.

References

1. Pukhonto L.M. *Durability of reinforced concrete constructions of engineering structures*. Moscow: ASV Publ.; 2004. (In Russ.)

2. Timoshin A.A., Orlova T.S. Analysis of the economic sustainability of industrial enterprises in the context of digitalization and risk control. *Scientific Review: Theory and Practice.* 2021;6(86):1589–1600. (In Russ.) https://doi.org/10.35679/2226-0226-2021-11-6-1589-1600

3. Selyaev P.V., Kechutkina E.L., Babushkina D.R., Gryaznov S.Yu. Modeling of the work of reinforced concrete structures taking into account the combined action of mechanical loads and aggressive media. *Expert: Theory and Practice.* 2021;1(10):19–24. (In Russ.) https://doi.org/10.51608/26867818_2021_1_19

4. Selyaev V.P., Selyaev P.V., Kechutkina E.L., Bezrukova E.S. *Kinetic models of interaction of cement and polymer concretes with chemically active media.* Saransk; 2020. (In Russ.)

5. Erofeev V.T., Al Dulaimi S.D.S., Dergunova A.V. Improving the durability and environmental friendliness of buildings and structures in the textile industry by using materials modified with a microbiological additive. *News of Higher Educational Institutions. Technology of the Textile Industry.* 2021;3(393):141–146. (In Russ.) https://doi.org/10.47367/0021-3497_2021_3_141

6. Erofeev V.T., Yelchishcheva T.F., Vatin N.I., Mitina E.A., Rodin A.I., Erofeeva I.V. Design of structures of external walls of buildings under adverse environmental influences. *Industrial and Civil Construction*. 2020;8:4–15. (In Russ.) https://doi.org/10.33622/0869-7019.2020.08.04-15

7. Rimshin V.I., Shubin I.L., Erofeev V.T., Avetisyan A.A. Automation of the life cycle of buildings during reconstruction and major repairs. *Housing Construction.* 2022;7:6–12. (In Russ.) https://doi.org/10.31659/0044-4472-2022-7-6-12

8. Gusev B.V., Fayvusovich A.S. Calculated dependencies for predicting the technical condition of reinforced concrete structures. *Industrial and Civil Construction.* 2021;6:4–12. (In Russ.) https://doi.org/10.33622/0869-7019.2021.06.04-12

9. Gusev B.V., Faivusovich A.S. Mathematical theory of processes of concrete corrosion. *Industrial and Civil Construction*. 2019;7:58–63. (In Russ.) https://doi.org/10.33622/0869-7019.2019.07.58-63

10. Rosenthal N.K., Chekhov G.V. Corrosion and protection of reinforced concrete structures in biologically active media. *Bulletin of Construction SIC.* 2013;7–8:111–118. (In Russ.)

11. Morozov V.I., Antsygin O.I., Savchenko A.P. Calculating and modeling the operation of structures with corrosion damages. *Bulletin of Civil Engineers.* 2009;1:25–30. (In Russ.)

12. Wasim M., Duc Ngo T., Abid M. Investigation of long-term corrosion resistance of reinforced concrete structures constructed with various types of concretes in marine and various climate environments. *Construction and Building Materials.* 2020;237:117701. https://doi.org/10.1016/j.conbuildmat.2019.117701

13. Fedosov S.V., Loginova S.A. Mathematical model of concrete biological corrosion. *Magazine of Civil Engineering.* 2020;99(7):9906. https://doi.org/10.18720/MCE.99.6

14. Zaikina S.M. Generalized integral Laplace transform and its application to solving some integral equations. *Journal of Samara State Technical University. Series: Physical and Mathematical Sciences.* 2014;1(34):19–24. (In Russ.) https://doi.org/10.14498/vsgtu1265

15. Chaulagain H. Common structural deficiencies of RC buildings in Nepal. *BSMC Journal of Local Development.* 2016;1(1):130–141.

16. Loginova S.A. Principles of mathematical modeling of corrosion processes in aggressive environments. *Smart Composites in Construction*. 2022;3(1):47–57. (In Russ.) https://doi.org/10.52957/27821919_2022_1_47

17. Yang Y., Wang M. Pore-scale modeling of chloride ion diffusion in cement microstructures. *Cement and Concrete Composites.* 2018;85:92–104. https://doi.org/10.1016/j.cemconcomp.2017.09.014

18. Davis J.L., Nica D., Shields K., Roberts D.J. Analysis of concrete from corroded sewer pipe. *International Biodeterioration and Biodegradation.* 1998;42(1):75–84. https://doi.org/10.1016/S0964-8305(98)00049-3

19. Salihovic A., Ademovic N. Nonlinear analysis of reinforced concrete frame under lateral load. *Coupled System Mechanics.* 2017;6(4):523–537. https://doi.org/10.12989/csm.2017.6.4.523