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ECONOMIC JUSTIFICATION OF MEASURES TO INCREASE THE DURABILITY OF CONCRETE STRUCTURES IN BIOLOGICALLY AGGRESSIVE ENVIRONMENTS

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Abstract. The article assesses the impact of concrete biodegradation on the durability of concrete and reinforced concrete bridge structures. Areas of biocorrosion and other types of concrete corrosion were identified on real bridges. Based on the developed physical and mathematical model, we calculated the service life of reinforced concrete bridge supports and proposed economically advantageous terms for removing biodeposits from concrete. We also calculated the economic efficiency of removing biofouling from concrete and determined that the annual economic effect amounted to 9 % of the cost of the estimated work. If preventative measures against biofouling are carried out at least once every five years, the period for carrying out works to eliminate defects in concrete and reinforced concrete building structures can be increased by 1.5x. We provide recommendations to improve the durability and effective operation of bridge structures.

Keywords: bridge, concrete, corrosion, repair, economic efficiency

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ЭКОНОМИЧЕСКОЕ ОБОСНОВАНИЕ МЕРОПРИЯТИЙ ПО ПОВЫШЕНИЮ ДОЛГОВЕЧНОСТИ БЕТОННЫХ КОНСТРУКЦИЙ В БИОЛОГИЧЕСКИ АГРЕССИВНЫХ СРЕДАХ

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Аннотация. В статье оценивается влияние биодеградации бетона на долговечность бетонных и железобетонных конструкций транспортных сооружений. Рассмотрены примеры реальных объектов, на которых выявлены области совместного протекания биокоррозии и других видов коррозии бетона. На основе разработанной физико-математической модели рассчитаны сроки службы железобетонных опор мостовых сооружений и предложены экономически выгодные условия очистки поверхности бетона от биоотложений. Также в статье представлен расчет экономической эффективности проведения мероприятий по очистке бетона от biообрастаний, по результатам которого годовой экономический эффект составил 9 % от стоимости сметных работ. В случае проведения плановых профилактических мероприятий по очистке от биообрастаний не реже одного раза в пять лет срок проведения капитальных работ по устранению дефектов бетонных и железобетонных конструкций может быть увеличен в полтора раза. На основе расчета даны рекомендации по повышению долговечности и эффективной эксплуатации мостовых конструкций.

Ключевые слова: мост, бетон, коррозия, ремонт, экономическая эффективность

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Introduction

At present, the prevention of bridge collapses remains one of the key areas of scientific research in the transport construction industry. Bridge supports must have sufficient strength and stability [1, 2]. One of the reasons for the collapse of bridge structures is the corrosion destruction of building structures. For example, in 2009, a support of a low-water reinforced concrete road bridge over a stream in the village of Loeva, Ivano-Frankivsk region, was destroyed. The bridge was a reinforced concrete beam structure 6 m long and 12 m wide. The destruction of the reinforced concrete support of the bridge led to the subsequent collapse of the reinforced concrete slab of the carriageway. Fortunately, human casualties were avoided [3].

The degradation of concrete and reinforced concrete building structures is a consequence of corrosion processes occurring in the cement stone. Most often, several types of corrosion act simultaneously in the zones of concrete destruction, for example, carbonization + chloride + biological and other combinations. The result of such joint processes are extensive zones of destruction of structures (Fig. 1) of transport facilities.

And if studies on the effect of carbonization and chloride corrosion, as well as their detection at the field and laboratory stages of inspection of building structures, are quite common in the literature [4, 5], then the issues of identifying and studying biological corrosion are not reflected widely enough. Until now, the prevention of biofouling of underwater concrete and reinforced concrete structures has been carried out mainly by treating surfaces with biocides to destroy or prevent the settling of potential contaminants. However, the environmental safety of a number of biocides against biofouling raises serious concerns, and it becomes necessary to search for alternative methods of protection [6].

Let us consider a particular case of corrosion failure of reinforced concrete bridge supports in the aquatic environment aggravated by biofouling. Favorable conditions for biofouling develop on the rear end of the support in the area of low pressures [7]. A region of variable velocities and pressures is created near the surface of the streamlined body. Most often, biofouling begins with the formation of a biofilm consisting of an accumulation of organic and inorganic compounds and various microorganisms attached to the surface of bridge abutments. The thickness of the resulting biofilm depends on the hydraulic load, the concentration of organic substances, the porosity of the material, and the influence of environmental factors [8, 9].

Turbulent flows in the boundary layer lead to a violation of the integrity of the biofilm. Biomass shedding and growth occur continuously, so in practice the biofilm never has a strictly defined thickness over the entire surface of the structure. The biofilm serves as a substrate for the settlement ofalgae, mollusks, some forms of fungi, etc., which are characteristic of river waters [10]. The composition of biofouling communities varies greatly geographically, seasonally and locally in depth, and is influenced by numerous abiotic and biotic factors. Abiotic factors include the physical and chemical characteristics of water, namely: temperature, pH, dissolved oxygen and organic matter content. Freshwater fouling is usually smaller than marine fouling both in terms of the number of species and biomass, and, consequently, in terms of thickness. The fouling rate primarily depends on the rate of water flow, which determines the possibility of settling and retaining organisms on the substrate, supplying them with nutrients and oxygen, etc.

Methods

The bridge on a pile foundation was subjected to research. The depth of the river at the location of the bridge is less than 5 m. The speed of the river flow is less than 2 km/h. The pile support of the bridge is represented by a flat two-row system of standard reinforced concrete piles with a solid square section of 0.35 × 0.35 (m) with a reinforced concrete grillage over the pile heads.

Fig. 1. Corrosion damage to reinforced concrete bridge structures in the Ivanovo region

As a result of concrete-liquid contact, the concentration of dissolved $Ca(OH)_2$ in the concrete pores begins to decrease, causing the dissolution of free $Ca(OH)_2$ crystals. As a result, there is a gradual "leaching" of concrete in the zones of contact with water and carbonization of concrete in areas above water.

From the point of view of the theory of mass transfer, the diffusion of "free" $Ca(OH)_2$ (according to the terminology of academician RAASN Fedosov S.V.) to the interface can be described by differential equations (1)–(8):

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

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

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

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

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

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

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

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

The method of integral transformations was used to obtain the solution of the equations (1)–(8) [11]:

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

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

where $C_1(x,\tau)$ – concentration of "free" $Ca(OH)_2$ in terms of CaO in concrete for time "τ" at the point with coordinate x, (kg CaO/kg concrete);

$C_2(x,\tau)$ – the concentration of "free" calcium hydroxide in terms of CaO in the biofilm at time "τ" at an arbitrary point with coordinate "x", (kg CaO/kg biomass);

$k_{1,2}$ – mass conductivity coefficients, m^2/s;

δ_1 – concrete structure thickness, m;

δ_2 – biofilm thickness, m;

$C_{1,0}$ – initial concentration of "free" CaO, kg CaO/kg concrete;

$C_{2,0}$ – initial concentration of "free" CaO, kg CaO/kg biomass;

m – Henry equilibrium constant, kg biomass. /kg concr.;

ρ_{con}, ρ_{biom} – density of concrete and biomass, kg/m^3;

$Z_1(\overline{x},Fo_m)$ – dimensionless concentration of the transferred component along the concrete thickness;

$Z_2(\overline{x},Fo_m)$ – dimensionless concentration of the transferred component along the thickness of the biofilm;

$\overline{x}=x/\delta_1$ – dimensionless coordinate;

$K_k=k_2/k_1$;

$K_\delta=\delta_2/\delta_1$;

q_H – the density of the mass flow leaving the biofilm into the fluid flow;

$N=(\rho_{biom}\cdot k_2)/(\rho_{con}\cdot k_1\cdot m)$ – coefficient taking into account the characteristics of the phases;

$Fo_m=(k_1\cdot\tau)/\delta_1^2$ – Fourier criterion;

$Ki_H^*=\frac{q_H\cdot\rho_{con}\cdot m\cdot K_\delta}{\delta_2\cdot\rho_{biom}\cdot k_2\cdot C_0}$ – Kirpichev's mass transfer criterion;

μ_m – equation roots.

Results and Discussion

In order to establish the service life of the bridge's concrete pillars in river water, according to the proposed mathematical model, the concentration fields of “free” $Ca(OH)_2$ were calculated over the thickness of the concrete pillar after 2, 4, 5, 10 and 15 years of operation. The rate of growth of biomass over time is proportional to the concentration of cells. According to literature sources [10–12], the average increase in the thickness of biofouling during the year of operation of bridge supports in river water is 25–30 mm. Based on this, the biomass densities corresponding to the given time intervals were determined. The calculation results are shown in Fig. 2. As a result, it was concluded that the concentration of “free” $Ca(OH)_2$ on the surface of the concrete support will reach a value corresponding to the beginning of the decomposition of the highly basic components of concrete after 2.1 years.

Currently, GOST does not regulate the timing of the technical cleaning of underwater structures from biofouling. Research and numerical experiments on a mathematical model made it possible to formulate recommendations for carrying out planned work to clean concrete and reinforced concrete underwater structures from biofouling.

Timely implementation of periodic inspections of parts of bridges that are below the water level will reduce the cost of possible repair and restoration work, and scheduled cleaning of underwater structures every 5 years will reduce the rate of their corrosion damage.

Below is a calculation of economic efficiency from carrying out periodic work to clean underwater structures from biofouling.

According to regulatory documents [13], the standard service life of a structure is determined by the formula:

$$T_C = \frac{100}{H_{a.r.}}, \tag{11}$$

where $H_{a.r.}$ – the percentage of annual depreciation deductions for the complete restoration of the structure.

The service life for concrete and reinforced concrete bridges is 100 years, and the general depreciation rate $H_{a.r.}$ = 1.3 %, including 0.3 % for major repairs [13, 14].

The costs and expenses incurred during the operation of structures are calculated according to the formula [12, 13]:

$$E_i = \frac{K_i}{\alpha_t} + \sum_{1}^{\gamma_{oo}-1} \frac{C_{oo}}{\alpha_t} + \sum_{1}^{T_c} \frac{C_{cr}}{\alpha_t} + \sum_{1}^{\gamma_{fk}-1} \frac{C_{fk}}{\alpha_t},$$

$$\gamma_{kr} - 1 = \frac{T_c}{T_{kr}} - 1, \gamma_{fk} - 1 = \frac{T_c}{T_{fk}} - 1, \tag{12}$$

where K_i – specific capital investments in the repair base or the cost of fixed production assets used in the production of repair and construction work;

C_{oo} – the cost of one overhaul;

C_{cr} – the cost of one average annual current repair;

C_{fk} – costs associated with the restoration and maintenance of the quality and durability of structures, as well as with the maintenance of structures, not included in the capital and current repairs;

t – years of major repairs or the cost of restoring and maintaining the quality and durability of building structures during the operation of structures;

T_{kr} – the frequency of overhauls of structures;

T_{fk} – the frequency of carrying out the costs of restoring and maintaining the quality and durability of building structures.

The value of the coefficient $\frac{1}{\alpha_t}$ at different periods of implementation of costs and the reduction standard E = 0.1 are tabular values, where “t” is the time in years between the moment of production of costs and the start of operation of structures.

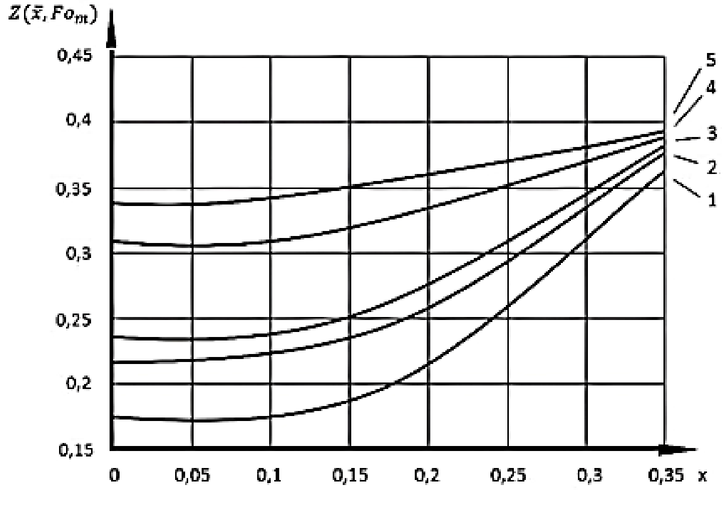

Fig. 2. Concentration fields in a concrete bridge abutment with the Fourier criterion Fo_m equal to: 1 – 0.16; 2 – 0.32; 3 – 0.4; 4 – 0.8; 5 – 1.2; which corresponds to 2, 4, 5, 10 and 15 years of operation

At the same time, the cost of annual current repairs is determined by the formula:

$$С_{cr} = \frac{(С_d - С_{fk})}{T_{kr}}. \qquad (13)$$

The annual economic effect from the use of the measure is calculated by the formula [15–17]:

$$E_r = (E_1 - E_2) \cdot A_2, \qquad (14)$$

where E_1 – reduced costs;

E_2 – the same, for a design of increased quality and durability;

A_2 – is the annual volume of implementation of the proposed measure to improve quality and durability.

According to regulatory documents [16, 18–20], the restoration of the original transport and operational qualities of the structure must be carried out every 15–30 years.

With a frequency of overhauls of 20 years, the coefficient $\mu_{cr} = 0.174$; at age 30, $\mu_{tr} = 0.1$. Then at $t = 20$ years $1/\alpha_t = 0.513$; at $t = 30$ years $1/\alpha_t = 0.035$; at $t = 40$ years $1/\alpha_t = 0.022$; at $t = 60$ years $1/\alpha_t = 0.003$; at $t = 80$ years $1/\alpha_t = 0.001$; at $t = 90$ years $1/\alpha_t = 0.001$; at $t = 100$ years $1/\alpha_t = 0.001$.

The given costs per 100 m^2 of concrete surface are:

$E_1 = E_{n1} + E_{e1} = 58164,19 + 41067,12 = 99231,31$ rub.

$E_2 = E_{n2} + E_{e2} = 58164,19 + 30121,05 = 88285,24$ rub.

The annual economic effect will be

$$E_r = (E_1 - E_2) \cdot A_2 =$$

$$= (99231,31 - 88285,24) \cdot 0,08 \approx 9\ \%.$$

Conclusions

The expected economic effect in current prices for the Ivanovo region from timely scheduled preventive work against biofouling amounted to 9% of the cost of estimates.

As a result of the study, it was found that cleaning from biofouling with a frequency of every 5 years, in conjunction with other measures of planned preventive work, will increase the time between repairs by 1.5 times.

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